National Technical University of Athens

School of Rural. Surveying and Geoinformatics Engineering

Department of Infrastructure and Rural Development

Methodologies for the integrated analysis and assessment of shared-space urban roads

For the degree of Doctor of Philosophy by

Panagiotis G. Tzouras
Dipl. Rural and Surveying Engineering NTUA
MSc Civil Engineering, Track: Transport and Planning TU Delft

Athens, November 2023

Εθνικό Μετσόβιο Πολυτεχνείο

Αγρονόμων και Τοπογράφων Μηχανικών – Μηχανικών Γεωπληροφορικής

Τομέας Έργων Υποδομής και Αγροτικής Ανάπτυξης

Μεθοδολογίες ολοκληρωμένης ανάλυσης και αξιολόγησης αστικών οδών συνύπαρξης

Για την απόκτηση Διδακτορικού Διπλώματος από τον

Παναγιώτη Γ. Τζούρα
Διπλ. Αγρονόμο και Τοπογράφο Μηχανικό ΕΜΠ
MSc Civil Engineering, Track: Transport and Planning TU Delft

Αθήνα, Νοέμβριος 2023

Doctoral advisor committee:

Dr. Konstantinos Kepaptsoglou, Associate Professor, NTUA (Chair)
Dr. Ioannis Kaparias, Associate Professor, University of Southampton
Dr. Efthimios Bakogiannis, Assistant Professor, NTUA

Exam committee:

Dr. Konstantinos Kepaptsoglou, Associate Professor, NTUA
Dr. Ioannis Kaparias, Associate Professor, University of Southampton
Dr. Efthimios Bakogiannis, Associate Professor, NTUA
Dr. Nikolaos Geroliminis, Professor, Ecole Polytechnique Fédérale de Lausanne
Dr. Eleni Vlahogianni, Professor, NTUA
Dr. Alexandros Nikitas, Professor, University of Huddersfield
Dr. Ioanna Spyropoulou, Associate Professor, NTUA

Acknowledgements

The research work was supported by the Hellenic Foundation for Research and Innovation (HFRI) under the 3rd Call for HFRI PhD Fellowships (Fellowship Number: 5785).

H.F.R.I.
Hellenic Foundation for Research & Innovation

Preface

«Ν 'αγαπάς την ευθύνη, να λες εγώ μοναχός μου θα σώσω τον κόσμο.
Αν χαθεί, εγώ θα φταίω»
Nikos Kazantzakis

Dear reader, in the preface and only in the preface, allow me to express some words from the heart in my native language in Greek.

Πάνε περίπου έξι χρόνια από τότε που διαπραγματεύτηκα για πρώτη φορά τους δρόμους συνύπαρξης. Ήταν τότε, όταν σε μάθημα του μεταπτυχιακού προγράμματος στο Ντελφτ, προσπαθούσαμε να σχεδιάσουμε ένα σύστημα για αυτόνομα οχήματα που θα ανταποκρινόταν στις απαιτήσεις του πολύπλοκου αυτού οδικού περιβάλλοντος. Βέβαια το διδακτορικό μου βασίζεται σε πρόταση που είχα γράψει στο αεροπλάνο της επιστροφής από την Ολλανδία, σε μία σχετικά δύσκολη στιγμή για εμένα. Η πρόταση είχε γραφτεί με γνώμονα τα προβλήματα τις ελληνικής πόλης και την απουσία χώρου ώστε να φτιάξουμε τις ποδηλατικές υποδομές που απολάμβανα εκεί. Ένιωθα βαθιά την ευθύνη να προχωρήσω την έρευνα αυτή και να εξετάσω/προσφέρω λύσεις για την ελληνική πόλη.

Στον δρόμο αυτό, βρέθηκε ο Δρ. Κωνσταντίνος Κεπαπτσόγλου που αποφάσισε να στεγάσει εμένα και την ιδέα μου, άσχετα αν απείχε από τα κύρια ερευνητικά του ενδιαφέροντα. Του υποσχέθηκα μόνο ότι θα βάλω περισσότερο modeling στην πρόταση αυτή και μάλιστα μοντέλα πρακτόρων...που να ήξερα! Τον ευχαριστώ πολύ για όλα. Ήταν και είναι ένας πραγματικός μέντορας στα δύσκολα μονοπάτια που κάθε φορά (γιατί δεν ξέρω;) επιλέγω. Με στήριξε με τον δικό του τρόπο σε όλη αυτή τη διαδρομή, δίνοντας πάντα τα κατάλληλα κίνητρα ώστε να συνεχίσω να προσπαθώ. Εδώ θα πρέπει να ευχαριστήσω και το Ελληνικό Ίδρυμα Έρευνας και Καινοτομίας (ΕΛ.Ι.Δ.Ε.Κ) που χρηματοδότησε από ένα σημείο και μετά την πρόταση μου. Η υποτροφία ήταν σημαντική προκειμένου να βρω χρόνο και να ολοκληρώσω το διδακτορικό μου. Ένα ευχαριστώ νομίζω ότι χρωστώ στον Δρ. Ευθύμιο Μπακογιάννη που μου πρόσφερε την πρώτη μου δουλειά στην Ελλάδα στο ερευνητικό πεδίο του συγκοινωνιακού και πολεοδομικού σχεδιασμού. Ήταν αυτό που ξεκλείδωσε τον επαναπατρισμό μου και την επιστροφή μου στο Πολυτεχνείο. Η αλήθεια είναι ότι έμαθα πολλά από αυτόν με ό,τι αποκαλούμε πράξη ή μάλλον πολιτική των μεταφορών. Πάντα λέω ότι το να παρουσιάζεις σε ένα επιστημονικό συνέδριο είναι ένα παιχνίδι για παιδιά μπροστά στο να μπαίνεις σε μία δημόσια διαβούλευση, με όλες αυτές τις διαφορετικές φωνές. Δεν ξεχνώ βέβαια τον Δρ. Ιωάννη Καπαριά, που φυσικά τα paper για τους δρόμους συνύπαρξης ήταν από τα πρώτα που διάβασα. Χωρίς αυτά, πολύ απλά δεν θα υπήρχε διδακτορική πρόταση. Γνωριστήκαμε μέσα από συνέδρια, αλλά η αλήθεια είναι ότι όποτε ζήτησα επιστημονική υποστήριξη μου την πρόσφερε απλόχερα.

Ειδική μνεία οφείλω στον Καθηγητή Δρ. Αλέξανδρο Νικήτα που πίστεψε στο concept του μελλοντικού αστικού δρόμου συν-επιβλέποντας τότε την έρευνα που πραγματοποιήθηκε. Τον ευχαριστώ για τη στήριξη του και ξέρω ότι αυτή θα είναι συνεχής. Ευχαριστώ και την Καθηγήτρια Δρ.

Ελένη Βλαχογιάννη για τη συνεργασία μας στην ανάλυση των εμπειρικών δεδομένων αλλά και για τις πολύτιμες συμβουλές της. Είναι επίσης ιδιαίτερη τιμή για μένα να συμμετέχει στην εξεταστική επιτροπή ο Καθηγητής Δρ. Νικόλαος Γερολιμίνης. Τον ευχαριστώ πολύ. Να αναφερθώ και στην Δρ. Ιωάννα Σπυροπούλου, στην οποία θαυμάζω το συνεχές ενδιαφέρον της για την εκπαίδευση των νέων. Και αυτό με έφερε εδώ, τότε που ο υψηλός κυκλοφοριακός φόρτος σήμαινε κίνηση για μένα. Τέλος, αν αναρωτηθεί κάποιος από που προκύπτει η ελληνική μετάφραση του όρου shared space, θα πρέπει να βρει τον Ομότιμο Καθηγήτη Δρ. Θάνο Βλαστό. Ο δρόμος συνύπαρξης είναι δικιά του επινόηση. Ακόμα διατηρώ την ανταλλαγή mail που κάναμε, σε περίπτωση που το έχει ξεχάσει.

Θα ήθελα στη συνέχεια να αναφερθώ στους άμεσους συνεργάτες. Άλλωστε αποτελούν συνδιαμορφωτές πολλών από αυτών που παρουσιάζονται στη διατριβή αυτή. Πάντα θεωρούσα ότι η απόκτηση γνώσης και η δημιουργία νέας έρχονται μόνο μέσα από τη διαδικασία αλληλεπίδρασης, από πολλά λάθη που (και βέβαια) έκανα και αρνητικές κριτικές. Με τον Δρ. Στέφανο Τσιγδινό με συνδέουν πολλά πέρα από τα paper που συγγράψαμε. Μας συνδέουν τα όνειρα που ξεκινήσαμε τα διδακτορικά μας, η όρεξη για έρευνα και οι ατελείωτες συζητήσεις μας. Τον ευχαριστώ πολύ από καρδιάς. Ευχαριστώ επίσης και τον Χρήστο Καρολεμέα, που έκανε το screen που χρειαζόμουν ώστε να ξεκλειδωθώ ερευνητικά, τότε στην εποχή της πανδημίας που τα ερευνητικά ενδιαφέροντα της ομάδας μας υποχρηματοδοτούνταν. Τον κατηγορώ όμως (με την καλή έννοια) που μου κόλλησε το μικρόβιο της ενασχόλησης με τα μοντέλα πρακτόρων. Στην προσπάθεια αυτή, ο Δρ. Λάμπρος Μητρόπουλο ήταν ο έτερος συνοδοιπόρος. Μαζί παιδευτήκαμε με την μικροκινητικότητα, αλλά με σημαντικό τελικά αποτέλεσμα. Θα αναφερθώ και στην Δρ. Χριστίνα Ηλιοπούλου, η οποία αποτελούσε και αποτελεί φωτεινό παράδειγμα για εμένα. Άλλωστε, έτυχε να παρουσιάζει το διδακτορικό της τότε που εγώ άρχιζα. Στο διδακτορικό αυτό, ένωσα τις δυνάμεις μου και με πολλούς άλλους νέους συναδέλφους. Μία από αυτούς ήταν η Mariana Batista από το TU Braunschweig που μοιράστηκε το σετ δεδομένων της ώστε να πραγματοποιήσουμε μία από κοινού ανάλυση. Είχαμε μία φανταστική συνεργασία. Thank you, Mariana! Ευχαριστώ επίσης την Βαλεντίνα, την Ευτυχία και την Ελένη, που συνεργαστήκαμε κατά τη φάση των διπλωματικών τους και βοήθησαν στην έρευνα αυτή.

Ποιος μένει; Μα φυσικά οι άνθρωποι που βρίσκονται όλα αυτά τα χρόνια δίπλα μου. Οι γονείς μου, Γιώργος και Αλεξάνδρα και ο αδερφός μου Χρήστος. Ξέρω ότι αυτά τα τέσσερα χρόνια περάσαμε πολύ δύσκολες στιγμές, αλλά τώρα είμαστε καλά και μπορούμε να δούμε με αισιοδοξία το μέλλον. Ευχαριστώ την (too be soon σύζυγο μου) Νικολίνα Λεκατσά. Η βοήθεια της δεν αφορά μόνο τον γραμματικό/συντακτικό έλεγχο που έκανε αλλά την ειλικρινή και έμπρακτη στήριξη που τώρα στο τέλος μου πρόσφερε, παραμερίζοντας κάποιες φορές, χωρίς να πρέπει, τα δικά της θέλω.

Abstract

Shared space refers to that part of urban road space that all road users including pedestrians, cyclists, vehicles, and disabled people are encouraged and legally enabled to occupy with little physical or visual separation. It can be considered as a potential design that will solve the road space allocation problem that many dense cities face. Indeed, the narrow streets limit the available space to safely segregate traffic flows. Yet, in the literature, no assessment study attempted to explore the direct/indirect impacts of shared space considering the entire transport system and multiple perspectives of the problem. Therefore, the main objective of this research is to develop integrated methodologies to evaluate shared space as a design concept for the future. The perspectives considered in this comprehensive approach are a) concept potential and acceptability, b) road users' traffic behavior, c) road users' safety perceptions, d) transport system efficiency, and e) accessibility and equity.

The first process aims to evaluate the potential of shared space to transform the future urban road. A systematic literature review, interviews with experts, and the Q-method are applied to collect and analyze different perspectives around it. The second research process focuses on assessing the feasibility of road users' coexistence in the same road environment by modeling empirical data coming from four different shared spaces. The pedestrian crossing rate and drivers' speed compliance are major factors to describe the coexistence. The examination of safety perceptions in shared space is performed in the third research process. Based on image-based double-stated preferences, the way that perceived safety influences mode/route choices is investigated. Last, all developed models are integrated into MATSim to evaluate the efficiency, accessibility, and equity of an extensive shared space network. Two simulation experiments in Berlin and Athens were conducted.

The results of the qualitative approach show three dilemmas that will form future urban roads: prioritization of modes? Human first or not? b) Share or segregate (and therefore regulate or not) and c) design systems or roads? The results of the empirical analysis show a noticeable proportional increase in pedestrian crossings in the shared space, while car drivers follow a more homogeneous driving behavior with lower speeds. Shared space is divided into three abstract zones: circulation, activity, and safe zone. The provision of more space to pedestrians further encourages pedestrian crossing. The same happens with car drivers, where large circulation zones induce high-speed compliance rates. Regarding safety perceptions, the idea of shared spaces emerges as a potential solution, offering a balance for all road users. Interestingly, there is a broader consensus about the safety benefits of shared spaces, especially when compared to car-dominated road designs.

In this study, it became evident that safety perceptions vary among road users and even individuals. The influence of these concerns on mode choice also diverges significantly. This results in a complex reality, best approached using agent-based models. The simulation data revealed a direct correlation between reduced speed limits and an uptick in the utilization of public transport leading to a noticeable decrease in congestion points. Nevertheless, it can be concluded that the key factor for the success of lowering speed limits is drivers' compliance. In scenarios with no compliance, the impact of shared space is negligible. Overall, shared space networks pave the way for a more equitable transport ecosystem, where each traveler, irrespective of their chosen mode, can anticipate a consistent trip characterized by fewer unsafe interruptions or discontinuities. Although the approach of segregation can cause serious modal shifts leading to a more sustainable future, it gives rise to greater spatial inequities.

Rather than configuring streets to accommodate autonomous vehicles, transport, and urban planners should set requirements that the vehicles should adapt to. Shared space can be one. These areas do not have to stand in isolation either; they can integrate with segregated cycle networks, thereby developing a new hierarchy in road infrastructure. A successful shared space is more than instituting a 30 km/h speed limit. It is about designing environments that guide users towards compliance.

Highlights

- Shared space as a concept creates some significant contradictions among mobility experts.
- A noticeable proportional increase in pedestrian crossing was observed in shared space sections.
- Car drivers react to the increased interactions by following a more homogeneous driving behavior.
- The provision of more abstract space to pedestrians further encourages pedestrian crossing.
- On the contrary, large abstract circulation zones result in non-compliance with the reduced speed limits.
- A broad consensus exists about the safety benefits of shared spaces compared to car dominated roads.
- Lower speed limits in the inner urban road network led to increase of public transport ridership.
- The effectiveness of shared spaces in mitigating congestion will be determined by speed compliance.
- Shared space networks pave the way for a more equitable transport ecosystem.
- Yet, the usage and the mean accessibility of sustainable transport modes was not noticeably improved.

Keywords

shared space; future urban road; road networks; road environment; coexistence; perceived safety; mobility choices; agent based models; accessibility; sustainability; transport equity.

Περίληψη

Ο δρόμος συνύπαρξης αναφέρεται σε εκείνο το μέρος του οδικού χώρου, στο οποίο όλοι οι χρήστες του, συμπεριλαμβανομένων των πεζών, των ποδηλάτων, των οχημάτων και των ατόμων με αναπηρία, ενθαρρύνονται να τον καταλαμβάνουν νόμιμα, με ελάχιστο φυσικό ή οπτικό διαχωρισμό. Θεωρείται ως ένας δυνητικός σχεδιασμός, ο οποίος θα επιλύσει το πρόβλημα του χώρου, που αντιμετωπίζεται από πολλές πυκνές πόλεις σήμερα. Πράγματι, οι στενοί δρόμοι περιορίζουν τον διαθέσιμο χώρο για τον ασφαλή διαχωρισμό των κυκλοφοριακών ροών. Ωστόσο, στη βιβλιογραφία δεν υπάρχει κάποια μελέτη αξιολόγησης, που να εξετάζει τις άμεσες ή έμμεσες επιπτώσεις των δρόμων συνύπαρξης, λαμβάνοντας υπόψη ολόκληρο το μεταφορικό σύστημα και πολλές διαφορετικές οπτικές. Άρα, ο κύριος στόχος της έρευνας αυτής ήταν η ανάπτυξη ολοκληρωμένων μεθοδολογιών για την αξιολόγηση του δρόμου συνύπαρξης ως έννοιας σχεδιασμού για το μέλλον. Οι οπτικές που λήφθηκαν υπόψη σε αυτήν την πλήρη προσέγγιση είναι: α) δυναμική και κοινωνική αποδοχή της έννοιας, β) κυκλοφορία και συμπεριφορά των χρηστών της οδού, γ) αντιλήψεις ασφάλειας των χρηστών του δρόμου, δ) αποδοτικότητα του συστήματος μεταφορών και ε) προσβασιμότητα και ισότητα.

Η πρώτη ερευνητική διαδικασία επιχειρούσε να αξιολογήσει τη δυνατότητα των δρόμων συνύπαρξης να μετασχηματίσουν τον αστικό δρόμο του μέλλοντος. Εφαρμόστηκε μια συστηματική ανασκόπηση της βιβλιογραφίας, διενεργήθηκαν συνεντεύξεις με ειδικούς και εφαρμόστηκε η μέθοδος Q για τη συστηματική συλλογή και ανάλυση των διαφορετικών απόψεων. Επίσης, καταγράφηκαν οι απόψεις του κοινού με πείραμα δεδηλωμένων προτιμήσεων. Η δεύτερη ερευνητική διαδικασία επικεντρώθηκε στην εξέταση της εφικτότητας της συνύπαρξης των διάφορων χρηστών της οδού στον ίδιο χώρο. Πραγματοποιήθηκε μοντελοποίηση των εμπειρικών δεδομένων, τα οποία συλλέχθηκαν από τέσσερις διαφορετικούς δρόμους συνύπαρξης από διαφορετικές πόλεις. Ο ρυθμός διαβάσεων των πεζών και η συμμόρφωση των οδηγών στα νέα όρια ταχύτητας αποτέλεσαν τους κύριους παράγοντες ώστε να περιγραφεί η συνύπαρξη. Η εξέταση των αντιλήψεων ασφάλειας πραγματοποιείται στην τρίτη ερευνητική διαδικασία. Βάσει ενός διπλού πειράματος δεδηλωμένων προτιμήσεων που βασίζεται σε εικόνες, διερευνάται ο τρόπος με τον οποίο η αντιληπτή ασφάλεια επηρεάζει την επιλογή μέσου και διαδρομής. Τέλος, όλα τα αναπτυγμένα μοντέλα ενσωματώνονται στη MATSim, που είναι ένα μοντέλο πρακτόρων, για να αξιολογηθεί η αποδοτικότητα, η προσβασιμότητα και η κοινωνική ισότητα ενός εκτεταμένου δικτύου δρόμων συνύπαρξης. Διεξήχθησαν δύο πειράματα προσομοίωσης, ένα στο Βερολίνο και ένα στην Αθήνα.

Τα αποτελέσματα της ποιοτικής προσέγγισης απέδειξαν τρία διλήμματα που θα διαμορφώσουν τους μελλοντικούς αστικούς δρόμους: α) πρώτα ο άνθρωπος ή όχι; β) συνύπαρξη ή διαχωρισμός κυκλοφοριακών ροών (και επομένως κυκλοφοριακές ρυθμίσεις ή όχι); και γ) σχεδίαση συστημάτων ή δρόμων; Τα αποτελέσματα της εμπειρικής ανάλυσης δείχνουν μια σημαντική αναλογική αύξηση στις διαβάσεις των πεζών στους δρόμους συνύπαρξης, ενώ οι οδηγοί αυτοκινήτων ακολουθούν μια πιο ομοιογενή συμπεριφορά οδήγησης με χαμηλότερες ταχύτητες. Ο δρόμος συνύπαρξης φαίνεται να διαιρείται σε τρεις αφηρημένες ζώνες: κυκλοφορίας, δραστηριότητας και ασφαλής ζώνη. Η παροχή περισσότερου χώρου στους πεζούς ενθαρρύνει περαιτέρω την κάθετη διάσχιση του δρόμου. Το ίδιο συμβαίνει με τους οδηγούς αυτοκινήτων, όπου οι μεγάλες ζώνες κυκλοφορίας προκαλούν χαμηλότερη συμμόρφωση στα νέα όρια ταχύτητας. Όσον αφορά στις αντιλήψεις ασφάλειας, η ιδέα των δρόμων συνύπαρξης εμφανίζεται ως μια μέση λύση, η οποία προσφέρει ισορροπία σε όλους τους χρήστες του δρόμου. Ενδιαφέρον παρουσιάζει το γεγονός ότι υπάρχει ευρύτερη συμφωνία όσον αφορά στα οφέλη ασφάλειας των δρόμων συνύπαρξης, ιδίως όταν συγκρίνονται με τους κλασικούς σχεδιασμούς αστικών δρόμων, στους οποίους επικρατεί το αυτοκίνητο.

Σε αυτή τη διδακτορική διατριβή, έγινε εμφανές ότι η αντιληπτή ασφάλεια διαφέρει μεταξύ των χρηστών του δρόμου, ακόμα και μεταξύ ατόμων. Η επίδραση αυτών των ανησυχιών στην επιλογή του τρόπου μετακίνησης επίσης διαφέρει σημαντικά. Αυτό οδηγεί σε μια πολύπλοκη πραγματικότητα, η οποία προσεγγίζεται καλύτερα με τη χρήση μοντέλων πρακτόρων. Τα δεδομένα προσομοίωσης αποκάλυψαν μια άμεση συσχέτιση μεταξύ της μείωσης των ορίων ταχύτητας και της αύξησης της χρήσης της δημόσιας συγκοινωνίας, οδηγώντας στην ελαχιστοποίηση των σημείων κυκλοφοριακής συμφόρησης. Παρόλα αυτά, μπορούμε να συμπεράνουμε ότι το κύριος παράγοντας για την επιτυχία της μείωσης των ορίων ταχύτητας είναι το επίπεδο συμμόρφωσης των οδηγών. Σε περιπτώσεις όπου δεν υπάρχει συμμόρφωση, η επίδραση των δρόμων συνύπαρξης είναι αμελητέα. Συνολικά, τα δίκτυα δρόμων συνύπαρξης ανοίγουν τον δρόμο για ένα πιο ισότιμο σύστημα μεταφορών, όπου κάθε μετακινούμενος, ανεξάρτητα από τον επιλεγμένο τρόπο μετακίνησής του, μπορεί να πραγματοποιήσει ένα συνεχές ταξίδι που χαρακτηρίζεται από λίγες εκπλήξεις ανασφάλειας. Παρόλο που η προσέγγιση του διαχωρισμού μπορεί να προκαλέσει αξιοσημείωτες μεταβολές στον τρόπο μετακίνησής μας οδηγώντας σε ένα πιο βιώσιμο μέλλον, δημιουργεί μεγαλύτερες χωρικές ανισότητες.

Αντί οι μελετητές να διαμορφώνουν δρόμους ώστε να λειτουργήσουν τα αυτόνομα οχήματα, ο συγκοινωνιακός και ο πολεοδομικός σχεδιασμός θα πρέπει να θέσει τις απαιτήσεις, βάσει των οποίων τα οχήματα αυτά θα σχεδιαστούν. Ο δρόμος συνύπαρξης μπορεί να είναι μια από αυτές τις απαιτήσεις. Οι δρόμοι συνύπαρξης δεν θα βρίσκονται σε απομόνωση· θα ενσωματωθούν σε δίκτυα ποδηλατοδρόμων, δημιουργώντας έτσι μια νέα ιεραρχία στην οδική υποδομή. Ένας επιτυχημένος δρόμος συνύπαρξης είναι κάτι περισσότερο από την εγκαθίδρυση ενός ορίου ταχύτητας 30 χλμ./ώρα. Πρόκειται για τον σχεδιασμό του οδικού περιβάλλοντος, που δια βίου καθοδηγεί τους χρήστες του προς συμμόρφωση και συνύπαρξη.

Καλύτερα σημεία

- Ο δρόμος συνύπαρξης ως ιδέα δημιουργεί αντιφάσεις στους ειδικούς της κινητικότητας.
- Μία αξιοσημείωτη αύξηση των διαβάσεων πεζών παρατηρήθηκε στο τμήματα δρόμων συνύπαρξης.
- Οι οδηγοί αντιδρούν σε αυτές τις πολύπλοκες αντιδράσεις με μία πιο ομοιογενής οδηγική συμπεριφορά.

- Η παροχή περισσότερου νοητού χώρου στον πεζό ενθαρρύνει τις διαβάσεις των πεζών.
- Αντίθετα, οι μεγάλες νοητές ζώνες κυκλοφορίας οδηγούν σε μη συμμόρφωση στα νέα όρια ταχύτητας.
- Υπάρχει γενική συμφωνία σχετικά με κέρδη ασφάλεια του δρόμους συνύπαρξης σε σχέση με δρόμους κυριαρχημένους από το αυτοκίνητο.
- Χαμηλότερα όρια ταχύτητα στο εσωτερικό οδικό δίκτυο οδήγησαν σε υψηλότερη επιβατική κίνηση στα μέσα μαζικής μεταφοράς.
- Η αποτελεσματικότητα του δρόμου συνύπαρξης στην άμβλυνση της συμφόρηση θα καθοριστεί από τη συμμόρφωση των οδηγών
- Τα δίκτυα δρόμων συνύπαρξης ανοίγουν τον δρόμο για ένα πιο δίκαιο μεταφορικό οικοσύστημα
- Όμως, η χρήση και η μέση προσβασιμότητα των βιώσιμων μέσων μετακίνησης δεν βελτιώθηκε σημαντικά.

Λέξεις κλειδιά

δρόμοι συνύπαρξης, μελλοντικός αστικός δρόμος, οδικά δίκτυα, οδικό περιβάλλον, συνύπαρξη, αντιληπτή ασφάλεια, επιλογές μετακίνησης, μοντέλα πρακτόρων, προσβασιμότητα, βιωσιμότητα, ισότητα μεταφορών.

Εκτεταμένη σύνοψη

Αντικείμενο έρευνας

Η διδακτορική αυτή διατριβή ερευνά τους δρόμους συνύπαρξης. Εξ ορισμού, οι δρόμοι αυτοί επιτρέπουν τη συνύπαρξη όλων των χρηστών της οδού (ποδηλάτες, πεζοί, αυτοκίνητα, κ.λπ.) στο ίδιο περιβάλλον με μικρό φυσικό ή οπτικό διαχωρισμό. Πρόκειται για μία ιδέα που στοχεύει στην αύξηση των καθημερινών κοινωνικών δραστηριοτήτων και στη βελτίωση της άνεσης στη μετακίνηση του πεζού, ενώ παράλληλα περιορίζει τη γρήγορη κίνηση της μηχανοκίνητης κυκλοφορίας. Βέβαια, η συγκεκριμένη διατύπωση δημιουργεί σημαντικές αντιθέσεις στην επιστημονική κοινότητα. Πολλοί συνδέουν τον δρόμο συνύπαρξης με το νόμο της ζούγκλας, όπου ο πιο ισχυρός επικρατεί. Πράγματι, στο παρελθόν πολλές πολιτικές υπέρ της οδικής ασφάλειας υποστήριξαν τον διαχωρισμό των κυκλοφοριακών ροών και την κατασκευή ειδικών υποδομών για το κάθε μέσο μετακίνησης. Η εφαρμογή μειωμένων ορίων ταχύτητας, δηλαδή 30 ή ακόμα και 15 χλμ./ώρα, φαίνεται να συνεισφέρουν στην ασφαλή συνύπαρξη των χρηστών της οδού, κυρίως διότι μειώνεται η πιθανότητα ενός τροχαίου συμβάντος με πολύ σοβαρό ή θανάσιμο τραυματισμό του ευάλωτου χρήστη. Από την άλλη, ήδη στο Ηνωμένο Βασίλειο έχει ζητηθεί να πραγματοποιηθεί περισσότερη έρευνα γύρω από τους δρόμους αυτούς εστιασμένη στην ασφάλεια των ατόμων με αναπηρία και δυσκολία στη μετακίνηση. Η εισαγωγή των αυτόνομων οχημάτων σε αυτό το πολύπλοκο οδικό περιβάλλον ίσως λειτουργήσει ως μία επιπρόσθετη δικλείδα ασφαλείας, εφόσον βέβαια οι επερχόμενες νέες τεχνολογίες αποδειχθούν αρκετά ικανές να αντιμετωπίσουν όλες αυτές τις αλληλεπιδράσεις, καλύτερα από ότι ο άνθρωπος.

Η έρευνα αυτή δεν στρέφει την προσοχή της στο πεδίο της ασφάλειας, αλλά σε αυτούς, που αντιμάχονται τη μείωση των ορίων ταχύτητας και κατά επέκταση τους δρόμους συνύπαρξης. Η υπόθεση που συχνά διατυπώνεται είναι ότι η αποδοτικότητα του μεταφορικού δικτύου θα υποβαθμιστεί σημαντικά. Με άλλα λόγια, οι μετακινούμενοι θα χρειάζονται πολλαπλάσιο σε σχέση με πριν χρόνο προκειμένου να μετακινηθούν, καθώς οι ταχύτητες στο αστικό δίκτυο θα είναι χαμηλές. Ο συγκοινωνιακός σχεδιασμός οφείλει κάθε φορά να αντισταθμίζει την ασφάλεια με την αποδοτικότητα του συστήματος. Όμως υπάρχει μία αντίστροφή υπόθεση: οι χαμηλές ταχύτητες στο εσωτερικό αστικό δίκτυο περιορίζουν στην πράξη τη γρήγορη μετάβαση με το αυτοκίνητο στον προορισμό, που οδηγεί σε χαμηλότερη ζήτηση για μετακίνηση με αυτοκίνητο και άρα σε λιγότερα σημεία κυκλοφοριακής συμφόρησης και καθυστερήσεις. Για πρώτη φορά, η έρευνα αυτή εστιάζει σε δίκτυα δρόμων συνύπαρξης, τα μοντελοποιεί, προκειμένου να ελέγξει την εγκυρότητα της υπόθεσης αυτής.

Οι δρόμοι συνύπαρξης μπορούν να αποτελέσουν έναν πιθανό σχεδιασμό, ο οποίος θα επιλύσει το πρόβλημα της κατανομής του οδικού χώρου, που πολλές πυκνές πόλεις στον κόσμο αντιμετωπίζουν. Οι ελληνικές πόλεις είναι μεταξύ αυτών. Πράγματι, ο φυσικός διαχωρισμός των κυκλοφοριακών ροών δεν είναι πάντα μία εφικτή επιλογή, καθώς το στενό πλάτος του μέσου ελληνικού δρόμου αποτελεί έναν πολύ σημαντικό περιορισμό. Στη θεωρία, οι δρόμοι συνύπαρξης φαίνονται να είναι μία χαμηλού κόστους και ενδεδειγμένη εναλλακτική για να αντιμετωπιστούν οι υφιστάμενες προκλήσεις, αλλά και για να γίνουν οι δρόμοι πιο ζωντανοί και βιώσιμοι. Συνεπώς, υπάρχουν παραπάνω από ένας λόγοι να ερευνηθούν και να δώσουν απαντήσεις σε ένα κεντρικό ερευνητικό ερώτημα:

Κ.Ε. *Είναι ο δρόμος του μέλλοντος δρόμος συνύπαρξης;*

Η απάντηση του ερωτήματος δεν είναι τόσο απλή, όσο μπορεί να φαντάζει. Ο δρόμος συνύπαρξης δημιουργεί ένα πολύπλοκο μεταφορικό σύστημα. Οι επιπτώσεις των δικτύων δρόμων συνύπαρξης θα πρέπει να εξεταστούν λαμβάνοντας υπόψη πολλά διαφορετικά πεδία. Εδώ μπαίνει η αναγκαιότητα για την ανάπτυξη ολοκληρωμένων μεθοδολογιών αξιολόγησης και ανάλυσης των δικτύων δρόμων συνύπαρξης. Το τελευταίο αποτελεί και τον κύριο στόχο της έρευνας. Φυσικά, τα εργαλεία αυτά βοηθούν και στη μοντελοποίηση της βιώσιμης κινητικότητας και στην ενδεδειγμένη αξιολόγηση των μέτρων, τα οποία λαμβάνονται κάθε φορά. Οι οπτικές που εντάσσονται σε αυτή την πλήρη προσέγγιση είναι: α) δυναμική και κοινωνική αποδοχή της έννοιας, β) κυκλοφορία και συμπεριφορά των χρηστών της οδού, γ) αντιλήψεις ασφάλειας των χρηστών του δρόμου, ε) αποδοτικότητα του συστήματος μεταφορών και στ) προσβασιμότητα και ισότητα. Βάσει αυτών, δημιουργούνται τα ακόλουθα υπό-ερωτήματα, τα οποία η συγκεκριμένη διδακτορική διατριβή διαπραγματεύεται:

Υπ.Ε.1. *Ποιες είναι οι κυρίαρχες απόψεις μεταξύ των ειδικών σχετικά με τους δρόμους συνύπαρξης;*

Υπ.Ε.2. *Είναι οι δρόμοι συνύπαρξης μία κοινωνικά αποδεκτή ιδέα;*

Υπ.Ε.3. *Ποιες είναι διαφορές στη συμπεριφορά των χρηστών της οδού σε ένα δρόμο συνύπαρξης και σε έναν τυπικό αστικό δρόμο;*

Υπ.Ε.4. *Είναι εφικτό όλοι οι χρήστες της οδού να συνυπάρξουν; Ένα ναι, κάτω από ποιες συνθήκες μπορεί αυτό να επιτευχθεί;*

Υπ.Ε.5. *Θα αισθανθούν οι πεζοί ή οι ποδηλάτες περισσότερο ασφαλείς σε ένα δρόμο συνύπαρξης από ότι σε ένα τυπικό αστικό δρόμο;*

Υπ.Ε.6. *Πώς οι αντιλήψεις ασφάλειας σε ένα δρόμο συνύπαρξης θα επηρεάσουν την προσβασιμότητα του κάθε μέσου μετακίνησης;*

Υπ.Ε.7. *Μπορεί ένα δρόμος συνύπαρξης να βελτιώσει την αποδοτικότητα του οδικού δικτύου;*

Υπ.Ε.8. *Μπορεί ένα δίκτυο δρόμων συνύπαρξης να συνεισφέρει στη βιώσιμη κινητικότητα, στη βελτίωση της προσβασιμότητας και στην ισότητα των χρηστών της οδού;*

Μεθοδολογικό πλαίσιο

Ένα σημαντικό εύρος μεθοδολογιών εφαρμόζεται για την απάντηση των ερευνητικών ερωτημάτων που διατυπώθηκαν. Παράλληλα αναπτύσσονται και νέα εργαλεία ανοιχτού κώδικα που αφορούν τους δρόμους συνύπαρξης.

Για τη διαμόρφωση της εικόνας του δρόμου τους μέλλοντος, πραγματοποιείται συστηματική βιβλιογραφική ανασκόπηση σε διάφορες ιδέες σχεδιασμού. Βάσει των ευρημάτων από την βιβλιογραφία, δημιουργείται ένα πλαίσιο συμμετοχικής ιεράρχησης διαφορετικών δηλώσεων σχετικά με το δρόμο του μέλλοντος και τους δρόμους συνύπαρξης. Αξιοποιείται η μέθοδος Q, όπου 50 ειδικοί, στον τομέα του πολεοδομικού και συγκοινωνιακού σχεδιασμού από όλη την Ευρώπη, ταξινομούν τις διάφορες δηλώσεις βάσει του επιπέδου συμφωνίας τους. Η μέθοδος Q, η οποία είναι μία περισσότερο ποσοτική παρά ποιοτική αξιολόγηση, αναδεικνύει τις οπτικές που επικρατούν. Φυσικά, μεταξύ αυτών, πιθανότατα υπάρχουν αντιφάσεις, οι οποίες διαμορφώνουν διλλήματα για περισσότερη έρευνα στο μέλλον.

Η μελέτη της κοινωνικής αποδοχής διαφορετικών σχεδιασμών ανακατανομής του οδικού χώρου διενεργείται με ένα πείραμα δεδηλωμένων προτιμήσεων με χρήση κλίμακας Likert. Η κλίμακα Likert εκφράζει το επίπεδο αποδοχής, ενώ οι ανεξάρτητες μεταβλητές αναφέρονται σε διαφορετικούς παράγοντες σχεδιασμού. Ο διαμοιρασμός του ερωτηματολογίου γίνεται στο κοινό με συμμετοχή 131 ατόμων. Η μεθοδολογία εδώ εμπεριέχει την ανάπτυξη ενός μοντέλου τακτικής λογιστικής παλινδρόμησης με τυχαίες επιδράσεις και παράγοντες αλληλεπίδρασης. Ως μελέτη περίπτωσης, χρησιμοποιείται η Λεωφ. Πανεπιστημίου και διερευνάται η αποδοχή της δημιουργίας ενός δρόμου συνύπαρξης με δύο λωρίδες κυκλοφορίας.

Η συμπεριφορά των χρηστών σε δρόμους συνύπαρξης μελετάται εμπειρικά με συλλογή δεδομένων από το πεδίο και ανάπτυξη στατιστικών μοντέλων παλινδρόμησης. Οι στρατηγικές συλλογής δεδομένων συνδυάζουν μετρήσεις με ραντάρ, φυσικούς παρατηρητές και κάμερες. Χρησιμοποιείται μία ιδιαίτερη μελέτη περίπτωσης από την Ελλάδα, η οδός Αμαλίας στο Ναύπλιο, που διαθέτει τόσο μία διατομή δρόμου συνύπαρξης όσο και μία τυπική διατομή. Στο σετ εντάσσονται τρεις διαφορετικές περιπτώσεις δρόμων συνύπαρξης στην Γερμανία: η Frankfurter Street στο Bad Rothenfeld, η Lange Street στο Hessisch Oldensorf και η Marktplatz στο Königslutter am Elm. Για να συγχωνευτούν τα δύο σετ δεδομένων χρησιμοποιούνται τεχνικές εναρμόνισης δεδομένων, ενώ εφαρμόζονται αναβαθμισμένες τεχνικές οπτικοποίησης τους. Στο τέλος προκύπτουν διαφορετικά μοντέλα γραμμικής παλινδρόμησης, τα οποία αξιοποιούνται και για την πραγματοποίηση ποσοτικών συγκρίσεων και προβλέψεων. Γενικότερα, στην εμπειρική ανάλυση εφαρμόζεται η υπόθεση ότι πεζοί και οδηγοί οχημάτων ανταγωνίζονται μεταξύ τους σχετικά με το ποιος θα κυριαρχήσει σε ένα δρόμο συνύπαρξης. Αυτό το παίγνιο μπορεί να μοντελοποιηθεί με δύο βασικούς παράγοντες: α) διαβάσεις των πεζών (ή αναλογία διαβάσεων ανά πεζό), που συνδέονται με την ελευθερία που αισθάνεται ο ευάλωτος χρήστης και β) οι κυκλοφοριακές ταχύτητες ή η συμμόρφωση του οδηγού με τα νέα μειωμένα όρια ταχύτητας.

Η εξέταση των αντιλήψεων ασφάλειας πραγματοποιείται με την διεξαγωγή ενός διπλού πειράματος δεδηλωμένων προτιμήσεων που βασίζεται σε εικόνες. Στο πρώτο εξετάζεται η αντιληπτή ασφάλεια τεσσάρων διαφορετικών μέσων μετακίνησης: αυτοκίνητο, ηλεκτρικό ποδήλατο, ηλεκτρικό πατίνι και περπάτημα. Χρησιμοποιούνται διαφορετικές διατομές δρόμων δημιουργώντας τις σκηνές που διαδραματίζονται οι αλληλεπιδράσεις των χρηστών· μία από αυτές είναι και ο δρόμος συνύπαρξης.

Στις σκηνές αυτές εντάσσονται στατικά και κινούμενα εμπόδια και η επίδραση τους μελετάται υπολογίζοντας μοντέλα τακτικής λογιστικής παλινδρόμησης. Παράλληλα διενεργείται προσομοίωση Monte-Carlo για να διερευνηθεί η ετερογένεια σχετικά με τις αντιλήψεις ασφάλειας που εκφράστηκαν από τους 129 συμμετέχοντες αυτής της πειραματικής διαδικασίας. Στην δεύτερη διαδικασία, οι συμμετέχοντες δηλώνουν ποιο μέσο θα χρησιμοποιούσαν λαμβάνοντας υπόψη και τον χρόνο και το κόστος. Εδώ δημιουργούνται μοντέλα επιλογής μέσου, σημαντικά για την περιγραφή των επιλογών μετακίνησης στο πρώτο/τελευταίο μίλι. Εφαρμόζεται και εδώ μεικτή λογιστική παλινδρόμηση, καθώς οι προσφερόμενες επιλογές δεν είναι ανεξάρτητες μεταξύ τους. Στην προσέγγιση αυτή, εισάγεται η έννοια της αξίας της (αντιληπτής) ασφάλειας που εκφράζει πόσα παραπάνω χιλιόμετρα, οι διάφοροι χρήστες της οδού, είναι αποφασισμένοι να κάνουν προκειμένου να αποφύγουν ένα ανασφαλές οδικό τμήμα. Συνεπώς, η αξία του δρόμου συνύπαρξης αντί μίας τυπικής διατομής αξιολογείται έμμεσα βάσει αυτής της αναλογίας. Φυσικά, η αναλογία αυτή μπορεί να συνδεθεί και με την προσβασιμότητα του κάθε μέσου μετακίνησης.

Στην τελική αξιολόγηση των δρόμων συνύπαρξης, δημιουργούνται και εκτελούνται δύο πειράματα προσομοίωσης με μοντέλα πρακτόρων. Το πρώτο πείραμα, αυτό της φυσικής προσομοίωσης, χρησιμοποιείται το ανοιχτό σενάριο του Βερολίνου της Γερμανίας και το υφιστάμενο πλαίσιο προσομοίωσης της MATSim. Προετοιμάζονται διαφορετικά σενάρια, τα οποία εμπεριέχουν αλλαγές στα όρια ταχύτητας διαφορετικών ιεραρχικών επίπεδων του οδικού δικτύου. Συνεπώς, η προσφορά μεταβάλλεται. Εκεί ενημερώνεται η χωρητικότητα του κάθε οδικού συνδέσμου, υποθέτοντας ένα τριγωνικό διάγραμμα φόρτου πυκνότητας. Η ταχύτητα ελεύθερης ροής, που είναι παράγοντας της χωρητικότητας, υπολογίζεται μεν από το όριο ταχύτητας, αλλά και από το επίπεδο συμμόρφωσης των οδηγών στα νέα όρια. Τα επίπεδα συμμόρφωσης εκλέγονται βάσει της προηγούμενης εμπειρικής ανάλυσης σε δρόμους συνύπαρξης. Τα σενάρια εισάγονται στην προσομοίωση και αναλύονται τα εξαγόμενα δεδομένα. Με την ανάλυση αυτή, αξιολογείται η αποδοτικότητα του μεταφορικού συστήματος συνολικά για τη μητροπολιτική περιοχή του Βερολίνου.

Στο πείραμα νοητής προσομοίωσης, γίνεται επέκταση του μοντέλου της MATSim. Συγκεκριμένα, αναβαθμίζεται η συνάρτηση βαθμολόγησης των πλάνων (ή χρησιμότητας) ώστε να λαμβάνει υπόψη τον παράγοντα της αντιληπτής ασφάλειας. Χρησιμοποιούνται τα μοντέλα από το προηγούμενο πείραμα δεδηλωμένων προτιμήσεων προκειμένου αυτή να βαθμονομηθεί. Για το πείραμα αυτό, δημιουργείται ένα πειραματικό οδικό δίκτυο στο κέντρο της Αθήνας, ενώ η ζήτηση περιγράφεται με ένα συνθετικό (πειραματικό πάλι) πληθυσμό. Στην προσομοίωση, εισάγονται τέσσερα σενάρια ανακατανομής του οδικού χώρου. Η σύνδεση με την έννοια της προσβασιμότητας και της ισότητας γίνεται μετά στην ανάλυση των δεδομένων προσομοίωσης. Ειδικότερα, θεωρείται ότι ως δείκτης της προσβασιμότητας η απόκλιση της τελικής επιλογής από τη πιο σύντομη διαδρομή μεταξύ δύο σημείων (δηλαδή η ευθεία γραμμή). Φυσικά, ο παράγοντας της αντιληπτής ασφάλειας, αλλά και τα νέα όρια ταχύτητας, συμβάλουν στη μείωση ή αύξηση των αποκλίσεων αυτών. Στη συνέχεια, δημιουργούνται καμπύλες Lorenz για να μελετηθεί η ισότητα, δηλαδή κατά πόσο η προσβασιμότητα κατανέμεται δίκαια σε όλους τους πράκτορες.

Σημαντικές παρατηρήσεις και συμπεράσματα

Στο σημείο αυτό, θα δοθούν οι κυριότερες παρατηρήσεις ανά ερευνητικό υπό-ερώτημα που τέθηκε παραπάνω. Όλες αυτές αποτελούν σημαντικές απαντήσεις στο κύριο ερευνητικό ερώτημα, το οποίο έχει περισσότερο φιλοσοφικό περιεχόμενο.

Υπ.Ε.1. *Ποιες είναι οι κυρίαρχες απόψεις μεταξύ των ειδικών σχετικά με τους δρόμους συνύπαρξης;*

- Ο δρόμος συνύπαρξης παρουσιάζει πολλές ομοιότητες με σενάρια πύκνωσης των διαγραμμισμένων διαβάσεων πεζών στον αστικό δρόμο. Εντάσσεται στο ευρύτερο πλαίσιο των μέτρων ήπιας κυκλοφορίας.

- Δίνει προτεραιότητα στις αλληλεπιδράσεις των ανθρώπων και κατά πολλούς ειδικούς αποτελεί μία λύση έναντι ενός δυστοπικού οδικού περιβάλλοντος, όπου τα αυτόνομα οχήματα κυριαρχούν.

- Ο δρόμος συνύπαρξης δημιουργεί πολλές αντιφάσεις με άλλες προσεγγίσεις σχεδιασμού - μέτρα της βιώσιμης κινητικότητας. Αυτές εντοπίστηκαν στην έρευνα με τους ειδικούς, οδηγώντας στη δημιουργία διακριτών ομάδων.

Υπ.Ε.2. *Είναι οι δρόμοι συνύπαρξης μια κοινωνικά αποδεκτή ιδέα;*

- Το κοινό απαιτεί τον ασφαλή διαχωρισμό των κυκλοφοριακών ροών στους δρόμους, δηλαδή τη σωστή αξιοποίηση του χώρου και τη δημιουργία κατάλληλων διαδρόμων για κάθε μέσο μετακίνησης.

- Η μείωση των ορίων ταχύτητας, που επιβάλλεται σε ένα δρόμο συνύπαρξης, αποτελεί ένα μέτρο πίεσης για το κοινό.

- Σε δρόμους που υπάρχει επαρκής χώρος για τον πεζό, η περαιτέρω αύξηση του οδηγεί σε χαμηλή κοινωνική αποδοχή.

Υπ.Ε.3. *Ποιες είναι διαφορές στη συμπεριφορά των χρηστών της οδού σε ένα δρόμο συνύπαρξης και σε έναν τυπικό αστικό δρόμο;*

- Στην εμπειρική ανάλυση, παρατηρήθηκε ότι για κάθε δευτερόλεπτο αύξησης του χρονικού διάκενου μεταξύ των αυτοκινήτων, ο ρυθμός διάβασης των πεζών αυξάνεται επίσης σε δρόμους συνύπαρξης.

- Παρά τον υψηλό φόρτο πεζών που διασχίζουν τον δρόμο, η διακύμανση των κυκλοφοριακών ταχυτήτων μειώθηκε σημαντικά. Πρόκειται για μία αντίδραση των οδηγών υπέρ της ασφάλειας ώστε να ανταπεξέλθουν στις πολλαπλές αλληλεπιδράσεις,

- Όμως, στο τυπικό οδικό τμήμα της οδού Αμαλίας στο Ναύπλιο, οι οδηγοί φαίνεται να μην παραχωρούν προτεραιότητα στους πεζούς στη διαγραμμισμένη διάβαση, καθώς η μέση ταχύτητα παραμένει αυξημένη και δεν επηρεάζεται από τις κινήσεις των πεζών.

- Χρησιμοποιώντας τα ανεπτυγμένα μοντέλα για πρόβλεψη, φανερώθηκε ότι στα σενάρια με υψηλό φόρτο οχημάτων, ο φόρτος των διαβάσεων πεζών δεν μειώνεται σημαντικά.

Υπ.Ε.4. *Είναι εφικτό όλοι οι χρήστες της οδού να συνυπάρξουν; Ένα ναι, κάτω από ποιες συνθήκες μπορεί αυτό να επιτευχθεί;*

- Ο δρόμος συνύπαρξης φαίνεται στην πράξη να διαχωρίζεται σε τρεις νοητές ζώνες: ζώνη δραστηριοτήτων, ζώνη κυκλοφορίας και ασφαλής ζώνη. Αυτό αποδείχθηκε από την εξέταση τεσσάρων διαφορετικών δρόμων συνύπαρξης.
- Τότε η συνύπαρξη θα πρέπει να περιγράφεται ως η κατάσταση κατά την οποία ο πεζός νιώθει ελεύθερος να διασχίσει τον δρόμο όποτε και σε όποιο σημείο θέλει, ενώ παράλληλα η ταχύτητα κυκλοφορίας των οχημάτων παραμένει σταθερή σύμφωνα με το νέο μειωμένο όριο ταχύτητας.
- Δίνοντας περισσότερο χώρο στον πεζό, δηλαδή αυξάνοντας τη νοητή ζώνη δραστηριοτήτων ή την ασφαλή ζώνη, ο πεζός διασχίζει αναλογικά περισσότερες φορές τον δρόμο παρενοχλώντας την κυκλοφορία οχημάτων.
- Δίνοντας περισσότερο χώρο στα οχήματα, οι ταχύτητες αυξάνονται πέρα από το όριο, ενώ η κίνηση των πεζών γίνεται σε διαμορφωμένα κανάλια, τα οποία βρίσκονται στις άκρες του δρόμου.

Υπ.Ε.5. *Θα αισθανθούν οι πεζοί ή οι ποδηλάτες περισσότερο ασφαλείς σε ένα δρόμο συνύπαρξης από ότι σε ένα τυπικό αστικό δρόμο;*

Υπ.Ε.6. *Πως οι αντιλήψεις ασφάλειας σε ένα δρόμο συνύπαρξης θα επηρεάσουν την προσβασιμότητα του κάθε μέσου μετακίνησης;*

- Η διπλή έρευνα δεδηλωμένων προτιμήσεων αποκάλυψε ότι οι χρήστες της οδού νιώθουν περισσότερο ασφαλείς σε δρόμους με διαχωρισμό των ροών. Όμως ο δρόμος συνύπαρξης παρουσιάζεται ως μία μέση λύση.
- Είναι εξαιρετικά αξιοσημείωτο ότι η ετερογένεια στις αξιολογήσεις αντιληπτής ασφάλειας μειώθηκε όταν παρουσιάστηκαν σενάρια με δρόμους συνύπαρξης. Αντίθετα σε σενάρια που το αυτοκίνητο κυριαρχεί (τυπικός ελληνικός δρόμος), η ετερογένεια ήταν υψηλή.
- Είναι ακόμα σημαντικό ότι σενάρια που εμπεριείχαν διαγραμμισμένη διάβαση πεζού δεν αξιολογήθηκαν ως πιο ασφαλή σε σχέση με αυτά απουσία αυτής.
- Στο πείραμα φανερώθηκε ότι σε μετακινούμενους χωρίς κουλτούρα υπέρ των ενεργών μετακινήσεων, το αίσθημα ανασφάλειας περιορίζει την πραγματική προσβασιμότητα των μέσων μικροκινητικότητας, όπως το ηλεκτρικό ποδήλατο και πατίνι.
- Οι δρόμοι συνύπαρξης ίσως αποτελέσουν ασφαλείς διόδους για την εξυπηρέτηση ποδηλατικών μετακινήσεων. Αυτό σημαίνει λιγότερες παρακάμψεις από την πιο γρήγορη διαδρομή.
- Αυτό όμως δεν μπορεί να αποδειχθεί χωρίς την εφαρμογή μοντέλων προσομοίωσης. Πράγματι η διαφορετικότητα των αντιλήψεων ασφάλειας δημιουργεί μια πολύπλοκη πραγματικότητα.

Υπ.Ε.7. *Μπορεί ένα δρόμος συνύπαρξης να βελτιώσει την αποδοτικότητα του οδικού δικτύου;*

- Από το πρώτο πείραμα προσομοίωσης με μοντέλο πρακτόρων προέκυψε ότι η εφαρμογή χαμηλότερων ορίων ταχύτητας σε εκτενή κλίμακα στο Βερολίνο οδηγεί σε σημαντική αύξηση των μετακινήσεων με Δημόσια Συγκοινωνία.

- Παρατηρήθηκε μείωση των οχηματοχιλιομέτρων με αυτοκίνητο και των σημείων κυκλοφοριακής συμφόρησης στις ώρες αιχμής. Άρα στην περίπτωση αυτή η αποδοτικότητα του συστήματος δεν θυσιάζεται στο βωμό της ασφάλειας.

- Είναι πολύ σημαντικό ότι το αυτοκίνητο χρησιμοποιήθηκε από τους πράκτορες για μεγαλύτερα ταξίδια.

- Βέβαια, στις τελευταίες παρατηρήσεις, κρίσιμος παράγοντας επιτυχίας είναι η εναρμόνιση της συμπεριφοράς των οδηγών με τα μειωμένα όρια ταχύτητας. Ο δρόμος συνύπαρξης πιθανώς να αποτελεί ένα αποτελεσματικό μέτρο για αυτό.

Υπ.Ε.8. *Μπορεί ένα δίκτυο δρόμων συνύπαρξης να συνεισφέρει στη βιώσιμη κινητικότητα, στη βελτίωση της προσβασιμότητας και στην ισότητα των χρηστών της οδού;*

- Στο δεύτερο πείραμα προσομοίωσης στην Αθήνα, αναδείχθηκε ότι τα δίκτυα δρόμων συνύπαρξης συμβάλουν στην ισότητα. Αυτό σημαίνει ότι όλοι οι χρήστες της οδού από όλα τα σημεία της πόλης απολαμβάνουν ίδιο επίπεδο αντιληπτής ασφάλειας. Αυτό οδηγεί σε μία ισόρροπη κατανομή της προσβασιμότητας.

- Με εφαρμογή σεναρίων προς το διαχωρισμό των ροών και κατασκευή ποδηλατικών υποδομών, η μέση προσβασιμότητα αυξάνεται αλλά όχι το ίδιο αναλογικά σε όλους.

- Ακόμα παρατηρήθηκε μία σημαντική βελτίωση των ποσοστών των μετακινήσεων με μέσα μικροκινητικότητας στα σενάρια διαχωρισμού των ροών. Αυτό έχει θετικές συνέπειες και στη βιωσιμότητα του μεταφορικού συστήματος.

Συνεισφορά έρευνας και πρακτικές προτάσεις

Μεγάλο τμήμα της έρευνας αυτής συνδέθηκε με την ανάπτυξη μεθοδολογιών προκειμένου να απαντηθούν τα ερευνητικά ερωτήματα. Εκεί εντοπίζεται και η συνεισφορά της διατριβής στην επιστημονική γνώση γύρω από τον συγκοινωνιακό σχεδιασμό. Συγκεκριμένα, η διατριβή αυτή αποτελεί μία από τις πρώτες προσπάθειες μοντελοποιήσης της βιώσιμης κινητικότητας και των μέτρων που συνδέονται με αυτή. Για πρώτη φορά, εισάγονται οι έννοιες της αντιληπτής ασφάλειας και αυτή της αξίας της ασφάλειας σε μοντέλα επιλογής μέσου. Από την στοχαστική ανάλυση αυτή αποδείχθηκε ότι στα μέσα μικροκινητικότητας η αντιληπτή ασφάλεια είναι ένας ιδιαίτερα καθοριστικός παράγοντας. Φυσικά, αποτελεί και παράγοντα επιτυχίας του σχεδιασμού των δρόμων συνύπαρξης. Η αποτυχία του δρόμου συνύπαρξης θα ήταν δεδομένη αν δημιουργούσε αρνητικά συναισθήματα ασφάλειας στους ευάλωτους χρήστες της οδού. Έγινε εισαγωγή των νέων μοντέλων επιλογής μέσου στο μεθοδολογικό πλαίσιο της MATSim παρουσιάζοντας μία επέκταση ανοιχτού κώδικα για το συγκεκριμένο μοντέλο πρακτόρων. Άλλωστε, η διδακτορική διατριβή αυτή είναι η πρώτη μέχρι σήμερα (Οκτώβριος 2023) στην Ελλάδα που διαπραγματεύεται ένα μεσοσκοπικό μοντέλο πρακτόρων για τις μεταφορές και αναπτύσσει κατάλληλες μεθοδολογίες. Σε επίπεδο οδικού συνδέσμου, η διδακτορική διατριβή εισάγει για πρώτη φορά την ιδέα περί ανταγωνισμού των χρηστών της οδού σχετικά με το ποιος θα επικρατήσει στον δρόμο συνύπαρξης. Η προσέγγιση αυτή ακολουθείται τόσο κατά τον σχεδιασμό των μετρήσεων όσο και κατά την ανάλυση των εμπειρικών δεδομένων. Εκεί αποτυπώνεται ότι ο δρόμος συνύπαρξης δεν είναι μία μοναδική ιδέα σχεδιασμού αλλά μία ευρύτερη έννοια. Μπορεί να έχει διάφορες παραλλαγές που αποτυπώνονται με τη διαφορετική νοητή κατανομή του χώρου. Η κατανομή αυτή φαίνεται να καθορίζει τους κανόνες του παιχνιδιού και άρα την συνύπαρξη. Τέλος η διδακτορική διατριβή ανέδειξε σημαντικά διλλήματα για περισσότερη έρευνα στο μέλλον: α) πρώτα ο άνθρωπος ή όχι; β) συνύπαρξη ή διαχωρισμός κυκλοφοριακών ροών (και επομένως κυκλοφοριακές ρυθμίσεις ή όχι) και γ) σχεδίαση συστημάτων ή δρόμων;

Πως όμως αλλάζουν όλα αυτά τις πρακτικές σχεδιασμού της βιώσιμης κινητικότητας; Κατά πρώτον, ένας επιτυχημένος δρόμος συνύπαρξης είναι κάτι περισσότερο από την εγκαθίδρυση ενός μειωμένου ορίου ταχύτητας, π.χ. 30 ή 15 χλμ. ανά ώρα. Χρειάζονται έξυπνες παρεμβάσεις που θα διαμορφώσουν τη συμπεριφορά των χρηστών προς μία βέλτιστη εξισορρόπηση των δυναμικών και του παιχνιδιού ευρύτερα. Άρα η αποτελεσματικότητα του σχεδιασμού θα πρέπει να αξιολογείται σε κάθε περίπτωση. Παράλληλα, η κοινωνική αποδοχή του δρόμου συνύπαρξης θα πρέπει να εξετάζεται τόσο σε βραχυπρόθεσμο όσο και σε μακροπρόθεσμο άξονα. Βέβαια, το κοινό δεν αντιλαμβάνεται τους περιορισμούς που καλείται ο μηχανικός να λάβει υπόψη του ώστε να καταλήξει σε μία βέλτιστη λύση. Πάντα, ο δρόμος συνύπαρξης θα πρέπει να προσεγγίζεται ως μία μέση λύση σχεδιασμού. Στην πράξη, η ιδέα δεν είναι τόσο ριζοσπαστική όσο μπορεί να ακούγεται, καθώς η πλήρη συνύπαρξη με την έννοια του διαμοιρασμού των μονοπατιών από όλους δεν έχει παρατηρηθεί. Παράλληλα αποτελεί μια λύση χαμηλού κόστους (υπό προϋποθέσεις) ενδεδειγμένη για πυκνές πόλεις. Στον σχεδιασμό δικτύων, οι δρόμοι συνύπαρξης συμπληρώνουν σημαντικά ένα ποδηλατικό δίκτυο. Ουσιαστικά καλύπτουν τις ασυνέχειες ασφάλειας, που κάνουν μετακινούμενους χωρίς εμπειρία στην χρήση ποδηλάτου να διστάζουν να το χρησιμοποιήσουν. Με το συνδυασμό ποδηλατοδρόμων και δρόμων συνύπαρξης το σύστημα μεταφορών γίνεται περισσότερο βιώσιμο και κοινωνικά δίκαιο. Αυτό μπορεί να οδηγήσει σε μία νέα στρατηγική ιεράρχηση των οδικών δικτύων συνυπολογίζοντας τις ανάγκες της ενεργής κινητικότητας. Επιπλέον, αντί οι μελετητές να διαμορφώνουν δρόμους ώστε να λειτουργήσουν τα αυτόνομα οχήματα, ο συγκοινωνιακός και ο πολεοδομικός σχεδιασμός θα πρέπει να θέσει τις απαιτήσεις, βάσει των οποίων τα οχήματα αυτά θα σχεδιαστούν. Ο δρόμος συνύπαρξης μπορεί να είναι μια από αυτές τις απαιτήσεις καταλήγοντας σε ένα λιγότερο δυστοπικό περιβάλλον. Σε αυτό, η παρουσία του ανθρώπου θα κυριαρχεί, ενώ τα οχήματα θα εξυπηρετούν τις πραγματικές ανάγκες του.

Research outputs

In general, this PhD dissertation is based on the findings which were firstly presented in the following published journal and conference papers:

Chapter 1: Introduction

Conference proceedings

Tzouras, P. G., Karolemeas, C., Bakogiannis, E., Kepaptsoglou, K., 2021. A Concept Agent-Based Simulation Model to Evaluate the Impacts of a Shared Space Network. Procedia Computer Science, 184(C), 680–685. https://doi.org/10.1016/j.procs.2021.03.085

Conference presentations

ABMTRANS 2021: 10th International Workshop on Agent-based Mobility, Traffic and Transportation Models, Methodologies and Applications, 23-26 March 2021, Warsaw, Poland (virtual), Presentation: "A Concept Agent-Based Simulation Model to Evaluate the Impacts of a Shared Space Network".

Chapter 2: The future urban road concept

Journal papers

Tzamourani, E., Tzouras, P. G., Tsigdinos, S., Kepaptsoglou, K., 2023. Exploring the social acceptance of transforming urban arterials to multimodal corridors. The case of Panepistimiou Avenue in Athens. International Journal of Sustainable Transportation, 17(4), 333–347. https://doi.org/10.1080/15568318.2022.2037793

Tsigdinos, S., Tzouras, P. G., Bakogiannis, E., Kepaptsoglou, K., Nikitas, A., 2022. The future urban road: A systematic literature review-enhanced Q-method study with experts. Transportation Research Part D, 102, 103158. https://doi.org/10.1016/j.trd.2021.103158

Conference presentations

Changing Cities V: Spatial Design, Landscape, Heritage and Socio-Economic Dimensions, 20-25 June 2022, Corfu, Greece. Presentation: "Looking into the urban road of the future: Identification of transforming concepts".

Webinar

Future Mobility Lab, University of Huddersfield, Webinar Series, Thursday 23rd of February 2023, Virtually, Presentation: The Future Urban Road: Concepts and Perspectives.

Chapter 3: Analysis of Traffic Behavior

Journal papers

Tzouras, P. G., Kepaptsoglou, K., Vlahogianni, E. I., 2023. Empirical investigation of shared space traffic: a comparison to conventional urban road environment. International Journal of Transportation Science and Technology. https://doi.org/10.1016/j.ijtst.2023.08.001

Tzouras, P. G., Batista, M., Kepaptsoglou, K., Vlahogianni, E. I., Friedrich, B. 2023. Can we all coexist? An empirical analysis of drivers' and pedestrians' behavior in four different shared space road environments. Cities, 141. https://doi.org/10.1016/j.cities.2023.104477

TRB annual meeting papers

Tzouras, P. G., Karolemeas, C., Kepaptsoglou, K., Vlahogianni, E. I., 2022. Towards the Estimation of Macroscopic Traffic Parameters in Shared Space Network Links: An Empirical Study. 101st Annual Meeting of the Transportation Research Board (TRB), Washington D.C., USA https://trid.trb.org/view/1909535

Datasets

Tzouras, P. G., Kepaptsoglou, K., Vlahogianni, E. I., 2023. Traffic measurements in Amalias Street. Conventional Road vs Shared Space. Mendeley Data, V2. https://doi.org/10.17632/n3wzjd54pj.2

Chapter 4: Examination of safety perceptions

Journal papers

Tzouras, P.G., Pastia, V., Kaparias, I., Kepaptsoglou, K. XXXX. The effect of perceived safety in first/last mile mode/route choices. Transportation **(UNDER REVIEW)**.

Open-Source Tools/Models

The "Perceived Safety Choices" repository includes the empirical data analysis of safety perceptions. Moreover, it contains the Scenario Athens, where the final mental simulations were performed: https://github.com/lotentua/Perceived_safety_choices

Preprints

Pastia, V., Tzouras, P. G., Kaparias, I., & Kepaptsoglou, K., 2022. Modeling the impact of the urban road environment on the perceived safety of different road users in Greece. SSRN Electronic Journal, November 16, 2022. http://doi.org/10.2139/ssrn.4278512

Chapter 5: Development of network simulation tools

Journal papers

Zargiannaki, E., Tzouras, P. G., Antoniou, E., Karolemeas, C. and Kepaptsoglou K., XXXX. Assessing the impacts of traffic calming at network level. A multimodal agent-based simulation. Journal of Traffic and Transportation Engineering **(ACCEPTED FOR PUBLICATION)**.

TRB annual meeting papers

Tzouras, P.G., Tsigdinos, S. and Kepaptsoglou K., 2024. To share or segregate? An agent-based simulation experiment to evaluate the accessibility and transport equity of road space allocation scenarios. 103rd Annual Meeting of the Transportation Research Board (TRB), Washington D.C., USA **(ACCEPTED FOR LECTERN PRESENTATION)**.

Sarri, P., Tzouras, P. G., Tsigdinos, S., Kaparias, I., & Kepaptsoglou, K., 2022. Exploring the land use and transport interaction effects of city-wide active travel schemes. 101st Annual Meeting of the Transportation Research Board (TRB), Washington D.C., USA https://eprints.soton.ac.uk/454362

Conference presentations

MUM 2022: MATSim User Meeting 2022, 31 May 2022, Leuven Belgium, Presentation: Simulation of e-bike and e-scooter trips using MATSim.

RSS 2022: 8th Road Safety and Simulation International Conference, 8-10 June 2022, Athens, Greece, Presentation: Assessing the impacts of traffic calming at network level. A multimodal agent-based simulation.

Contents

List of Figures

List of Tables

1 Introduction

Shared space as a road design concept was originally introduced in 1965 by Prof. De Boer (Joseph, 1995). It was a piece of a general concept called Woonerf which was based more on the principles of Urban Planning than of Transportation Planning Science. An appropriate definition of this concept is provided by the review study of Karndacharuk et al. (2014a), shared space refers to that part of urban road space that all road users including pedestrians, cyclists, vehicles, and disabled people are encouraged to legally occupy with little physical or visual separation. Hamilton-Baillie (2008a, 2008b) underlined the significance of this concept in increasing daily social and physical activities in urban areas, improving pedestrians' comfort while reducing motorized traffic flows. This is a subject of controversy. Methorst et al. (2007) criticize this basic hypothesis since it seems to be completely based on the "law of the jungle". To enhance traffic safety and mitigate serious conflicts, various policies and strategies around the world have supported the full segregation of traffic, and the construction of specialized infrastructure per transport mode while reducing speed limits (SWOV, 2013). The safe coexistence of various road users in the same road environment is still debatable. Previous studies approached the problem of coexistence presenting contradicting findings and conclusions.

1.1 Problem description

In the UK, the Department for Transport (2011) published a report about shared space roads; in this report, five primary objectives were established. The first objective is the place making; it is related to the improvement of the attractiveness of the urban environment. The second one illustrates that the shared space should focus on the free movements of vulnerable road users (VRUs), such as pedestrians, cyclists, and disabled people who are prone to injury in any vehicular collision (Yannis et al., 2020). Furthermore, shared space should be designed in such a way as to reduce the speeds of motorized traffic. The reduction of traffic volumes through the reduction of speeds is also an important objective. The fifth objective refers to the establishment of roads, where pedestrians can move freely, which should contribute to the economic development of surrounding local businesses. The improvement of traffic safety is the last and most important objective of this concept. Yet, these guidelines were withdrawn in August 2018 demanding more research on how to better address the needs of road users with disabilities.

A primary issue that consequently arises is related to the consideration of shared space as the core design concept that will change urban roads in the future. Imrie (2012) thinks that shared space will enlarge inequalities and socio-spatial divisions, especially for visually impaired people, as their movements in road space are guided based on some formal rules and standards provided by the existence of proper road infrastructure. These design standards less evident in shared space (Karndacharuk et al., 2014a; Uttley et al., 2020). Yet, shared space is accompanied by lower speed limits (i.e., ≤ 30 km/h), which shall create a safety net around vulnerable road users (Johansson, 2009; Webster DC, 1996; Yannis et al., 2014). Indeed, the severity of a crash and its consequences are strongly reduced when the cruising speed of the vehicle is low. Hammond and Musselwhite (2013) consider the risk homeostasis theory to provide answers to the coexistence problem. According to this theory, humans shift the balance of risk according to their surrounding environment. However, not all people have fully developed the ability to adapt their behavior based on traffic interactions. Vitale Brovarone et al. (2021a) believe that future autonomous vehicles will resolve this since an autonomous vehicle will be able to cope with all complex interactions appearing in shared space providing an additional safety guard to these road users. Uttley et al. (2020) also think that shared space is the right road environment to introduce autonomous vehicles with greater capabilities than human drivers.

In the past, some research studies attempted to examine the validity of the main concept assumptions by exploiting empirical evidence. Most of them conducted a before-after analysis to point out major changes in traffic behavior that appeared after the implementation of shared space. Kaparias et al. (2014) collected empirical data on Exhibition Road located in London, UK; they observed a general drop in traffic conflicts, even though pedestrian movements increased significantly. They found that the number of serious traffic conflicts was reduced in all cases examined. In a follow-up study, Kaparias et al (2016) modeled pedestrian gap acceptance behavior. The output of this analysis suggests that even pedestrians moving with children or elderly people tend to accept shorter gaps. Later, Kaparias and Wang (2020a) concluded that shared space streets improve the pedestrian experience by higher Level of Service (LoS) ratings and without causing noticeable delays to motorized traffic. In three shared space cases in New Zealand, Karndacharuk et al. (2014b) found that a shared space environment attracts pedestrians to stay longer. Some pedestrians felt more comfortable to cross or walk in the space that was more dedicated to vehicles' movements. In virtual reality, Woodman et al. (2019) examined how pedestrians interact with a platoon of autonomous pods in mixed-traffic road environments, like shared space. Based on their findings, pedestrians are more willing to accept smaller temporal gaps between two consecutive pods. On the other hand, in the analysis of Moody and Melia (2014), general claims that a reduction in demarcation leads to a decrease in vehicle speeds and encourages pedestrians to "move more freely" are not supported by findings. Indeed, pedestrians preferred to cross the study area using an informal courtesy crossing and they avoided a very complex area (in terms of interactions) located in the center. Indeed, Anvari et al (2016) plotted pedestrians' and vehicles' trajectories in Exhibition Str. showed that the segregation of traffic flows still exists in informal terms; pedestrians remained on the sides of shared space whereas motorized traffic tends to follow assumed traffic lanes and traditional traffic regulations. Ruiz-Apilánez et al. (2017) who conducted systematic on-street observations in shared space roads, noticed that pedestrians behave more freely and make broader use of space in shared space road environments. Nevertheless, when a vehicle approaches, they avoid the carriageway and prefer to use a different part of the urban road. This is confirmed by the recent study of Batista and Friedrich (2022) who also noticed that the paths of pedestrians and vehicles tend to significantly differ.

Safety perceptions of road users seem to be a critical factor that may determine the assumed rules and standards of coexistence. Perceived safety is a very subjective notion. It differs not only per road user but per individual, while it determines travel behavior (Pastia et al., 2022). Therefore, perceived safety is strongly related to the potential of shared space in inviting people to walk or cycle more. Kaparias et al (2012) performed two web-based stated preferences surveys to analyze safety perception in Exhibition Street in London. They found that the presence/absence of children and pedestrian density influences drivers' perception, while pedestrians' perceived safety seems to be significantly affected by the provision of safe zones, lighting level, age, gender, and less vehicle traffic. Gkekas et al. (2020) dealt with high-volume non-motorized shared space; their research proved that cyclists tend to avoid pedestrian-dominated areas, but this tendency is constrained by travel time to perform safe detours. This is confirmed by the study of Kaparias and Li (2021), which revealed that the willingness of two-wheelers to share the space is decreased in mixed-traffic road environments with high pedestrian flows and static obstacles. This reality seems quite chaotic in terms of users' perceptions. However, the study by Akgün-Tanbay et al. (2022) showed that experienced users do not find shared space as chaotic as it was expected. To reach this conclusion, they conducted face-to-face surveys. In general, shared space can be approached as a (mental) game between pedestrians and vehicles regarding who will "dominate" the shared space (Tzouras et al., 2021). This space problem has scarcely been investigated.

The performance of shared space environments has been investigated through the development of microscopic simulation tools. Considering empirical observations, these tools model users' interaction by applying classical modeling techniques like the Social Force Model (SFM). Schönauer et al. (2017; 2012a) simulated traffic operations in shared space by subdividing it for the first time into 3 main sections: a traffic zone (vehicle dominant), a safe zone (pedestrian and cyclist exclusive), and a shared zone. This infrastructure model is used to model road users' behavior at strategic, tactical, and operational levels (Rudloff et al., 2014). Pascucci et al. (2015) limited the degree of freedom of vehicles in shared space. According to their modeling approach, drivers stay out of severe conflicts with pedestrians by reducing their speed while avoiding sudden steering movements. Pedestrians' trajectories are based on the shortest path principles considering the Dijkstra algorithm. This means that they have a large degree of freedom which allows them to make sudden changes of direction to avoid motorized traffic. The collision-avoidance mechanisms were implemented in the SFM that is commonly used in the existing commercial simulation tools showing a modified version of it. The study of Rinke et al. (2017) extended the previous simulation framework by developing tools to simulate pedestrian groups and cyclists' conflicts with pedestrians. Anvari et al. (2016, 2015) developed a three-layer simulation framework; the first layer refers to the planning of road users' trajectories to reach their final destination, the second one to SFM where short-range traffic interactions are modeled, and the last one to rule-based constraints which include long-range collision avoidance mechanisms. All these studies that were above referenced acknowledge that there is still space for future improvements regarding the development of a well-calibrated and validated micro-simulation model specialized for shared space areas. They are quite complex which is reasonable as they aim to represent an already complicated reality. Also, some studies extended commercial simulation models of walking to describe traffic operations in shared space (Frosch et al., 2019a; Gibb, 2015). Following a very simplified approach, cars are represented as a group of pedestrians relying on the existing SFM to resolve the interactions. Lastly, the approach of Knoop and Daganzo (2018a) is equally significant. Their mathematical simulation did not particularly focus on shared space but on a "crosswalk anywhere" scenario. They found that in this scenario, the road capacity is not reduced, since the pedestrian crossing flows are distributed at many points. Indeed, in mid-block sections, the capacity is mainly determined by the bottleneck with the lowest capacity, i.e., the crosswalk with the highest pedestrian crossing flow. This is a major consideration that previous specialized simulation tools did not consider. Yet, this requires considering shared space as a crosswalk anywhere road environment and not as a road environment of full coexistence.

Opponents of lower speed limits and shared space also argue that the implementation of these schemes to a large extent will downgrade transport system efficiency leading to an economic downturn. However, an alternative hypothesis suggests that there is no real trade-off between efficiency and safety in practice, as many transport planners assume. Lower traffic speeds result in lower accessibility of private cars as a transport mode and therefore lower travel demand and congestion points. This hypothesis has been formulated in the study of Tzouras et al. (2021). The examination of the validity of this hypothesis requires the utilization of simulation tools, as the implementation of large, shared space networks (i.e., living labs) is infeasible in the real world. While the previously mentioned microscopic simulation tools are useful to model traffic operations at the link or intersection level (Azimian et al., 2021; Khondaker and Kattan, 2015; Kladeftiras and Antoniou, 2013), they cannot be used for large city or metropolitan networks. The reason is their high level of detail which leads to a tremendous increase in computation time (Charypar et al., 2009). Existing mesoscopic or macroscopic frameworks (e.g., MATSim) should be extended so that the direct and indirect impacts of shared space networks can be predicted and assessed. Of course, this process requires the consideration of multiple perspectives on the shared space problem. This comprises the main topic of this PhD research.

1.2 Research scope and objectives

Shared space can potentially be a major design that will solve the road space allocation problem that many cities around the world face. Cities in Greece are surely among these. In dense city centers, flow segregation is not an option. Indeed, the narrow streets limit the available space to construct specialized infrastructure for each road user. In theory, shared space seems a low-cost and suitable alternative to address future transport challenges, make our cities more livable, and prioritize the active modes. Yet, before promoting ideas, strategies, and plans based on this controversial concept, the impacts of the establishment of shared space roads should be analyzed, assessed, and discussed appropriately.

In the literature, no assessment study attempted to explore the direct and indirect impacts of shared space in the entire transport system considering multiple perspectives of the problem. In this dissertation, the shared space problem is often mentioned as a coexistence problem, since the presence of one road user affects the behavior and perceptions of the others. The main research objective of this study is to develop integrated methodologies to evaluate shared space as a design concept for the future. The perspectives considered in this comprehensive approach are a) concept potential and acceptability, b) road users' traffic behavior, c) road users' safety perceptions, and d) transport system efficiency. The major (and more general) question that is going to be answered in this research is:

MRQ: *Is the future urban road of shared space character?*

Before answering the main research questions, eight intriguing sub-questions should be researched. The first two questions are related to the first perspective mentioned above. They also refer to the theoretical background of the shared space concept aspiring to further extend the discussion among experts and the public around this concept. Indeed, contradicting opinions should be reported before running a quantitative analysis of the impacts of shared space.

SRQ1: *What are the leading views among experts about road users' coexistence and shared space?*

SRQ2*: Is shared space a socially acceptable concept?*

In the next steps, the problem of coexistence ought to be examined at the link level considering traffic behaviors in the physical yet real world. A basic hypothesis formulated by the findings of previous relevant empirical studies is that pedestrians and vehicles compete with each other on who will "dominate" shared space affecting traffic operations. Nevertheless, this is already an issue that appears in many conventional streets around the world, and the validity of this hypothesis is still under investigation. Therefore, this research aspires to underline the main differential points that distinguish shared space from conventional street design. Furthermore, the feasibility of coexistence has to be further explored considering different compositions of traffic flows. Additionally, the design of this mixed traffic environment is an additional parameter that may influence traffic behaviors more than expected. The next two research questions are:

SRQ3: *What are the differences in traffic behavior between a shared space link and a conventional road link?*

SRQ4: *Can all road users coexist in the same road space? If yes, under which circumstances, can this coexistence be achieved?*

Many concerns around shared space have been raised regarding safety and how road users perceive it. Indeed, if pedestrians/cyclists feel unsafe in shared space areas, then they will avoid walking/cycling. This directly means a serious degradation of VRU accessibility; then, shared space turns out to be a non-friendly environment for pedestrians, as it promises. That is why perceived safety is a catalytic factor in assessing this controversial concept. Perceived safety is hypothesized to be correlated with social acceptability. Yet, perceived safety can affect travel behavior (i.e., mode/route choices) compared to social acceptability which has a serious impact on the policy-making process. Looking at the other side of the coexistence problem, a reduction in car drivers' perceived safety can lead to less use of private cars to access through shared space network. Therefore, based on this factor, the potential of this concept to create more human-oriented than car-dominated urban roads can be assessed quantitatively. Therefore, the next two questions refer to the mental world, i.e., the world of road users' perceptions and choices.

SRQ5: *Will pedestrians or cyclists feel safer walk or cycle in shared space compared to conventional road environments?*

SRQ6: *How will safety perceptions in shared space affect the accessibility of each transport mode?*

By answering all the previously mentioned questions, models that can simulate a shared space network can be developed. The proposed modeling approach should not increase the complexity of existing tools leading to higher computation times, while its outputs should be valid and useful in order to answer important research questions like the ones presented. It searches for a universal yet simple approach based on which the direct and indirect impact of lowering speed limits and creating more human-oriented urban road environments can be forecasted. Specifically, the developed model should provide some meaningful answers regarding the efficiency, sustainability, accessibility, and equity of shared space.

SRQ7: *Can a shared space road network improve the efficiency of the overall urban transport system?*

SRQ8: *Can a shared space road network contribute to sustainable mobility, accessibility, and transport equity?*

All the sub-questions reflect the different perspectives of the coexistence problem. This study combines various methodologies per perspective to answer the research questions. In the next paragraph, a methodological roadmap is presented.

1.3 Approach

To answer the previously presented research questions, an interdisciplinary approach consisting of four main processes is followed. All processes combine various qualitative and quantitative methodologies that aim to provide meaningful input information to discuss different aspects of the shared space concept. Therefore, the first process aims to evaluate the potential of shared space to transform the future urban road, the second one focuses on assessing the feasibility of road users' coexistence in the same road environment, while the third one investigates road users' safety perceptions to describe travel behavior changes due to the implementation of shared space networks. The final process refers to the development of simulation tools to evaluate the efficiency, sustainability, and equity of shared space concept. **Figure 1** provides the overall methodological flow diagram of this PhD dissertation.

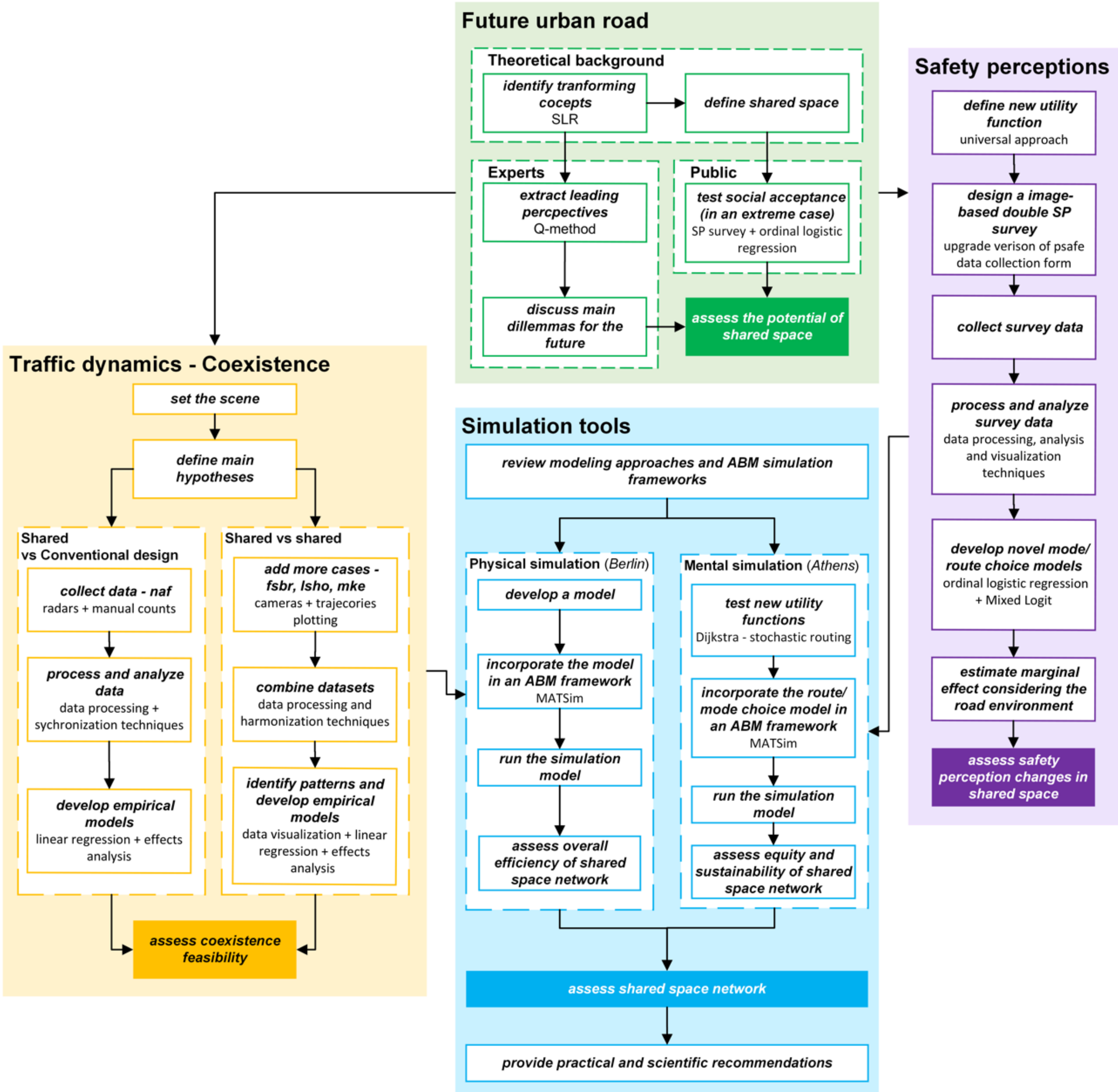

Figure 1: Dissertation methodological flow diagram

Starting with the first process (green box in **Figure 1**), the theoretical background is further explored. Specifically, by conducting a Systematic Literature Review (SLR), concepts that aim to transform the future urban road will be identified. Then, at this point, the shared space concept and its differences from other relevant concepts will be defined and further discussed. The outputs from this review process will be utilized to assess the potential of shared space as a design concept of the future. This will be performed by considering views from experts and the public. Q-method is usually applied to collect leading perspectives appearing around a particular topic among experts (Kougias et al., 2020a; Milakis et al., 2018; Wolbertus et al., 2020a). This research aims to determine the main dilemmas planners should answer in the future to redesign urban road environments. As has been mentioned, shared space is a controversial concept that creates contradicting views among urban and transport planners. Hence, these contradictions will be further discussed at this step. Simultaneously, a survey regarding the social acceptance of various road space re-allocation schemes will be conducted; ordinal logistic regression models will be developed to reveal determinant factors of social acceptance. The relationship of the identified factors with shared space will be particularly investigated so that SRQ2 can be answered appropriately.

In the second process (yellow box in **Figure 1**), the traffic behavior of road users in shared space schemes will be examined by analyzing empirical data while considering findings from the literature. The data collection techniques combine camera video recordings, radar traffic measurements, and manual counts. A shared space case from Nafplio, Greece will be utilized to identify differences in traffic behavior between a conventional road and a shared space road environment. This will require a proper data collection plan based on which hypotheses set in the previous steps can be either confirmed or rejected. The data analysis includes advanced data visualization methods, multiple linear regression with mathematical transformations of the dependent variable, and analysis of identified effects so that valid conclusions can be exported from this case. Next, the empirical analysis will be further extended to consider more than one shared space case. The open dataset[1] of trajectories provided by the research team of TU Braunschweig will be utilized to explore how different shared space configurations affect the traffic behavior of road users and therefore coexistence (Batista and Friedrich, 2022). This analysis also considers various traffic flow compositions to answer the research questions about coexistence feasibility. Data harmonization techniques are applied to combine the different datasets, while new useful empirical models will be computed. These will be utilized later in the development of physical simulation tools for shared space.

The examination of safety perceptions in shared space is performed in the third process (purple box in **Figure 1**) of the overall approach of this dissertation. The methodology of this process is inspired by a previous image-based double Stated Preferences (SP) experiment performed by the author to examine the perceived safety and driving stress of tram drivers in mixed-traffic road environments (Tzouras et al., 2020). This new survey will explore the way perceived safety influences mode and route choices in urban road networks. Therefore, the SP survey form will consist of two parts: in the first part, road users will be asked to rate the perceived safety of different scenarios presented with images, while in the second part, road users will be asked to choose between plans considering safety evaluations. Perceived safety is a subjective notion; therefore, high heterogeneity among individuals is expected to appear. This heterogeneity can be described appropriately by using random beta parameters in the utility functions. The main objective is to develop novel mode/route choice utility functions that indirectly take into account the road environment while modeling travel behavior of various first/last mile modes, such as car, e-bike, e-scooter, and walking. Based on the calculated beta parameters, the marginal effect can be estimated. These will describe the contribution of shared space schemes to increasing/decreasing the utility of one transport mode. Higher utility corresponds to a higher willingness of a first/last mile traveler to use one transport mode to access shared space. The integration of mixed logit models in

[1] Link for the open dataset of TU Braunschweig: https://doi.org/10.24355/dbbs.084-202210281217-0

Agent-Based Model (ABM) frameworks is another challenge that will be tackled in this research. In the past, the studies of Livingston et al. (2018) and Ziemke et al. (2019, 2017) followed a similar approach to examine the influence of the route environment on cyclists' route choices.

The final evaluation of shared space networks will be performed based on two pilot scenarios that have been developed for Berlin, Germany, and Athens, Greece. Hence, two simulation experiments using an updated Agent-Based Model (ABM) will be conducted in this dissertation, namely physical simulation and mental simulation experiment. In all cases, a toy population will be utilized to describe the demand. The physical simulation experiment will test the efficiency of an extensive shared space network. Considering a metropolitan area, the speed limits and other traffic parameters will be modified; this will cause a significant change in the supply of the transport network. The mental simulation experiment will consider the perceived safety factor in a last-mile shared space network. The aim is to evaluate the impact of this parameter and consider all interactions and behavioral changes happening in this area. Additionally, the results of an ABM are not only travel times, but other important indicators, such as vehicle kilometers or average traffic speeds in the network, that are related to sustainable mobility and transport equity. These quantitative indicators can be translated into appropriate criteria so that the performance of the shared space network can be explored in the three dimensions of sustainability, namely: environment, economy, and society.

1.4 Structure of the Dissertation

The structure of the dissertation completely follows the methodological flow diagram that was previously presented. Each chapter comprises one process of this diagram presented with different colors. Introduction and discussion chapters have been added at the start and the end of this dissertation. Therefore, the general structure of this study can be summarized as follows:

The second chapter introduces the concept of the future urban road. Based on interdisciplinary research, answers to SRQ1 and SRQ2 are searched in this chapter.

The third chapter deals with the traffic behavior of road users in shared space and more specifically with the notion of coexistence. Based on the findings from the empirical data analysis, SRQ3 and SRQ4 are addressed.

The fourth chapter focuses on safety perceptions in shared spaces. Based on an image-based double SP survey, valid conclusions are exported to answer SRQ5 and SRQ6.

The fifth chapter presents two simulation experiments to evaluate the direct and indirect impacts of shared space. The conclusions refer to the efficiency and the sustainability of these concepts. Thus, answers for SRQ7 and SRQ8 are provided.

The sixth chapter discusses all findings from all the previously described methodological steps. By considering the answers to sub-questions, the MRQ is finally addressed. It is the final assessment of the shared space concept. Additionally, practical recommendations are given based on the research conclusions, while study limitations are reviewed to provide some important scientific recommendations. Finally, a list of related publications is provided at the end of the text.

2 The future urban road concept

In an era of rapid technological advances and the need for climate change action, urban roads, which are evidently the backbone of urban public space, should be transformed (von Schönfeld and Bertolini, 2017). Shared space can be considered as one of these transforming concepts aiming to resolve problems related to the safety, accessibility, and liveability of urban spaces. However, there are various driving forces that tend to reshape roads in a completely different direction (Loorbach and Shiroyama, 2016). What is an ideal scenario for an urban road design? Still, there is no consensus among experts about this ideal scenario resulting in various leading perspectives and dilemmas for the future. In this PhD research, these dilemmas and their relationship with shared space are revealed. Simultaneously, in this wide discussion, the strongest driving force, i.e., mobility culture and citizens' needs that influenced the form and characteristics of urban roads is seriously considered (Nikitas et al., 2017). That is why, in this chapter, the public acceptance of various road space distributions is p investigated. As it has been mentioned in the Introduction, the main objective of this chapter is to assess the potential of shared as a design concept that will form the future urban road.

2.1 Transforming concepts

A Systematic Literature Review (SLR) is conducted in order to identify the 28 transforming concepts, which are presented in this subchapter. Of course, one of them is shared space which is better defined considering similarities and differences with other transforming concepts.

2.1.1 Systematic Literature Review

SLR is a powerful technique that synthesizes research findings considering a particular topic or topic area (Davis et al., 2014; Rowley and Slack, 2004). On a meta-level, SLR contributes to contextualizing the catalytic concepts for the future urban road and building a discrete theoretical background to assess shared space (Snyder, 2019). It is a more systematic methodology that is proposed by this PhD research for controversial concepts and concepts difficult to define and explain like shared space. The main difference with a traditional or narrative literature review is found in the strict inclusion and exclusion rules that appear in SLR. Indeed, SLR objects to limiting possible biases that may occur by selecting a sample of studies (Booth et al., 2016; Dekker and Bekkers, 2015). Additionally, the qualitative outputs of SLR have less subjectivity in comparison to a narrative literature review which specifically focuses on an idea or perspective.

The SLR is based on a three-stage procedure. This procedure was clearly defined by Bask and Rajahonka (2017), Yigitcanlar et al. (2020), and Oliveira et al. (2017). These stages are:

- Planning stage: selection of objectives, review protocol, and sources for literature review searching.
- Review stage: definition of inclusion/exclusion criteria, records screening, and eligibility assessment.
- Synthesis stage: identification and presentation of concepts and approaches.

Starting with the first step, the objective of this study is to identify transforming concepts for the future urban road hypothesizing that shared space is one among them. Hence based on this consideration, a variety of keywords can be assembled. These keywords should be combined with the term "urban road" to enclose the research scope in the search process. Of course, the terms "street" and "road" are frequently utilized interchangeably by studies that deal with urban space issues (Brown and Tarko, 1999; Ershova and Smirnov, 2017; McAndrews and Marshall, 2018). However, to enhance consistency and avoid confusion or results misinterpretation, the term "road" is only utilized in the search process. Therefore, this process objects to identify studies that contain both keywords ("urban road" AND keyword i). These additional keywords used in this study are:

"traffic management", "urban road network", "autonomous vehicles", "electric vehicles", "smart cities" "smart mobility", "urban planning", "public health", "quality of life", "sustainability" and "urban environment", "traffic safety", "mixed traffic", "drivers' behavior", "road design", "traffic calming", "vulnerable road users", "public transport", "transport geography", "parking", "accessibility", "sustainable mobility", "public space", "social welfare", "social interactions", "social equity", "shared mobility" and "network hierarchy"

The source that is used in this research is the SCOPUS database excluding as many as possible studies that did not pass from peer-review process. Also, to minimize the number of "Grey Literature" records, conference proceedings, books, and technical reports are not included in this SLR. Hence, it focused on journal articles that deal with the urban road.

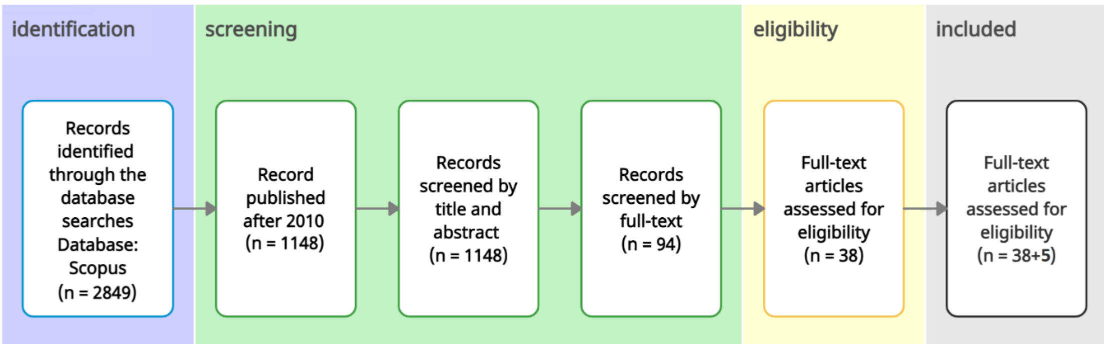

Figure 2: PRISMA workflow diagram and number of collected papers in each step.

The second stage contains sub-steps which are given in **Figure 2** which presents the PRISMA diagram, an important component of an SLR process. Based on the previously mentioned keywords, a total of 2849 journal articles written in the English language were found in SCOPUS in January 2021. Journal papers before 2010 were excluded from the SLR to ensure as much as possible the novelty of the identified concepts and approaches. Hence, 1148 papers passed through the screening process, where the relevance of the records was evaluated based on the title and abstract. Irrelevant papers were also excluded; so, 94 papers remained. The eligibility of these papers was assessed by studying the full text of the papers. Ineligible papers were excluded. In the end, a review pool of 38 journal articles was utilized in this study. The remained articles were reviewed, categorized, and further analyzed to identify the transforming concepts.

In stage 3, the work focused on synthesizing the literature findings based on the research objective mentioned above. As supporting literature, 5 additional publications on the same topic were integrated in this last step to elaborate better the qualitative outputs of SLR. Therefore, the total number of reviewed papers was 43. In the next section, the identified transforming concepts are presented. Simultaneously, similarities and contradictions among concepts are discussed. This contributes to synthesizing the future urban road based on already developed ideas while defining the role of shared space.

2.1.2 Concepts' presentation

A catalog of identified concepts is presented below. At the end of this section, more similar concepts to shared space are presented; this will contribute to the proper distinction of shared space as a design idea for the future urban road.

Road pricing should be considered an effective measure to reduce demand therefore traffic congestion in critical urban areas; yet, it has an extremely high political cost. This is because road users are pushed to pay an additional cost to use a part of the entire urban road network and particularly to access dense urban areas (Nikitas et al., 2011; Rentziou et al., 2011; Zheng et al., 2012).

Dynamic Road Space Allocation is an alternative approach that aims to optimize the transport system efficiency by applying various spatiotemporal decisions that tune the transport supply. These refer to opening bus lanes during peak hours and closing them during off-peak so that the available road space cannot be wasted (Zhang et al., 2018; Zheng and Geroliminis, 2013).

(a) (b)

Figure 3: (a) Reallocation of space based in the city center of Leuven, Belgium, and (b) Bus Lane in Piccadilly Square in London, UK

The Bus Priority Lanes can be mixed traffic, semi-exclusive, exclusive, and grade-separated (Hadas and Nahum, 2016). Therefore, it is a broader concept that encloses various traffic management solutions to minimize traffic-related delays by prioritizing buses over cars (Gitelman et al., 2020; Novotný et al., 2016).

The existence of different road users in the road environment creates side friction which disturbs traffic flow. To eliminate them, some studies introduced the concept of Divided Arterials which refers to the construction of specialized infrastructure for pedestrians, cyclists, two-wheelers, etc. so that the interactions with motorized traffic will be significantly minimized (Biswas et al., 2020; Salini and Ashalatha, 2020). Parking facilities, bus bays instead of curbside stops, and pick-up/drop-off points are some of the designs that are enclosed in this concept.

The Multimodal Corridors as a concept have been defined in the study of Tsigdinos et al. (2020). *"Multimodal Corridors are major transport facilities which accommodate automobile, bus, bicycle and pedestrian travel".* This concept does not only focus on the optimization of transport system efficiency but also aims to provide an appropriate accessibility level for all road users reinforcing transport equity.

The speed compliance of drivers to the respective speed limits is a critical factor in assessing the effectiveness of a design; that is why, Gargoum et al. (2016a) introduced the concept of Credible Speed Limits. According to their considerations, low compliance rates mainly appear in wide collectors with median or physical segregation, as these design elements encourage speeding behavior.

This concept is close to the one of what transportation engineers call Design Consistency. This concept aims to add in the road environment operational and geometric features which support the functionality of each road. Mono-functional urban roads are necessary to create consistent designs that homogenize traffic speeds and drivers' behavior (Colonna et al., 2019; Demasi et al., 2018).

This will result in Self-Explaining Roads. This design focuses on drivers' expectations and perceptions in order to propose safe designs (Charlton et al., 2010).

In the urban road environment with complicated interactions and heavy volumes of various road users, human errors are meant to happen. That is why transportation engineers should design Forgiving Roads. to *"designs that are resilient with respect to human errors"* (O'Hern et al., 2019). As a concept, it objects to eliminating the probability of a fatal accident (Oxley et al., 2010).

Cycling Infrastructure mostly refers to cycle lanes or cycle tracks, while Walking Infrastructure encloses sidewalks, pedestrianized zones, and infrastructure destined for facilitating disabled people's movement (e.g., curb ramps, tactile paving, intersection repairs) (Macmillan et al., 2014; Oxley et al., 2010).

(a) (b)

Figure 4: (a) Grade-separated cycling infrastructure in Nafplio, Greece - full segregation of traffic flows and (b) 30 km/h zone with pedestrian crosswalks in Paris, France

Urban roads are not only travel corridors; they can be Cultural Assets and Social Places, as McAndrews & Marshall (2018) have mentioned. Open streets or play streets can bring together people coming from various social groups in the same urban space, where they can socialize and express themselves (Karndacharuk et al., 2014b, 2014a). These soft pull measures are enclosed in the concept of Urban Roads as Public Spaces. Indeed, urban roads are vital organs of the city; they are the means to observe and understand the city (Aral and Demirbaş, 2015; Tsigdinos and Vlastos, 2020; Vitale Brovarone et al., 2021b).

Roadside Vegetation aims to make the road environment more liveable by shaping conditions that are favorable to vulnerable road users, especially pedestrians or cyclists (Li, 2012). According to Samuel et al. (2016), *"all types of cultivated or wild-grown plant assemblages growing in road verges, medians, swales, tree pits or paving joints"*.

Extending the concept of a liveable urban road, two additional dimensions should be mentioned, namely: Vitality and Diversity. Vitality refers *"generally to the extent to which a place feels alive or lively and can be gauged by measuring pedestrian flows and movements"* (Aral and Demirbaş, 2015). Diversity can be described as the variety of different activities occurring in an urban road environment (McAndrews and Marshall, 2018).

Electric Vehicles (EVs) demand the establishment of Electric Vehicles Charging Stations in the urban road environment. By creating these stations in the city centers, EVs are invited increasing their penetration rate (Karolemeas et al., 2021). It is considered by policymakers as an alternative policy to develop zero-emission traffic zones in the city centers. Of course, this is related to the source of electric energy comes from in each country. Even though planners criticize the idea of establishing charging stations in the city centers, this will extremely increase demand and traffic congestion in these critical areas (van Wee, 2012). This is a major contradiction that may form the future urban roads. The installation of equipment that will support Dynamic Wireless Charging of electric vehicles or the creation of Photovoltaic Roads are alternative concepts that should be taken into account (García-Vázquez et al., 2017; Liu et al., 2019).

Figure 5: Urban Road as a public and liveable space. A paradigm from New York, US.
Source: "The Roles of Streets" (www.nacto.org/publication/urban-street-stormwater-guide/streets-are-ecosystems/the-role-of-streets/ - Link accessed in June 2023)

Another change that is expected to come is the installation of Vehicle-to-Infrastructure (V2I) communication systems which will potentially be future transport policy tools; some of them are smart traffic lights and signs, speed detectors and controls, 5G band, etc. (Vitale Brovarone et al., 2021b).

Additionally, Vehicle-to-Vehicle (V2V) systems will be capable of ensuring safe interactions among users of the urban road. Autonomous Vehicles (AVs) will communicate in the future adjusting their behavior based on the static and moving objects of the road environment (Szele and Kisgyorgy, 2018). These new capabilities may fully transform urban roads, since conventional rules and signs appearing in intersections may not be necessary.

Shared Autonomous Vehicles (SAVs) will contribute to the transformation of urban roads, as Stead et al. (2019) argue. The increased use of shared mobility services will lead to a considerable reduction in the land consumption for parking spaces, according to their thoughts. This will resolve the problem of space that many dense cities around the world face.

In a very different scenario, the construction of Fully Segregated AV Corridors will fully segregate AV traffic flows from other road users providing a new specialized road environment (Parkin et al., 2018). These corridors will have all the required systems so that an intelligent vehicle can operate while moving at higher speeds.

Traffic Calming Measures attempt to reduce severe accidents with serious injuries or even fatalities in urban areas (Yannis et al., 2014). Such measures are roundabouts, raised intersections or intersection repairs, chicanes, parklets, curb extensions, speed humps, and so on (Colonna et al., 2019). This requires considerably lower speed limits, e.g., 30 km/h or even 15 km/h.

The Superblock concept "*can be perceived as a new model of mobility that restructures the existing urban road network; they are made up of a grid of main roads forming a polygon, with both interior and exterior components*" (López et al., 2020). Superblocks discourage cut-through motorized traffic, i.e., car trips whose origins and destinations are both located outside the neighborhood. This means that the inner road network functions only for access purposes (Soret et al., 2011). Of course, these restrictions do not apply to pedestrians and cyclists who can use the inner networks to form safe (and as short as possible) paths to reach their destination. Therefore, Superblock has the potential to increase the accessibility of vulnerable road users.

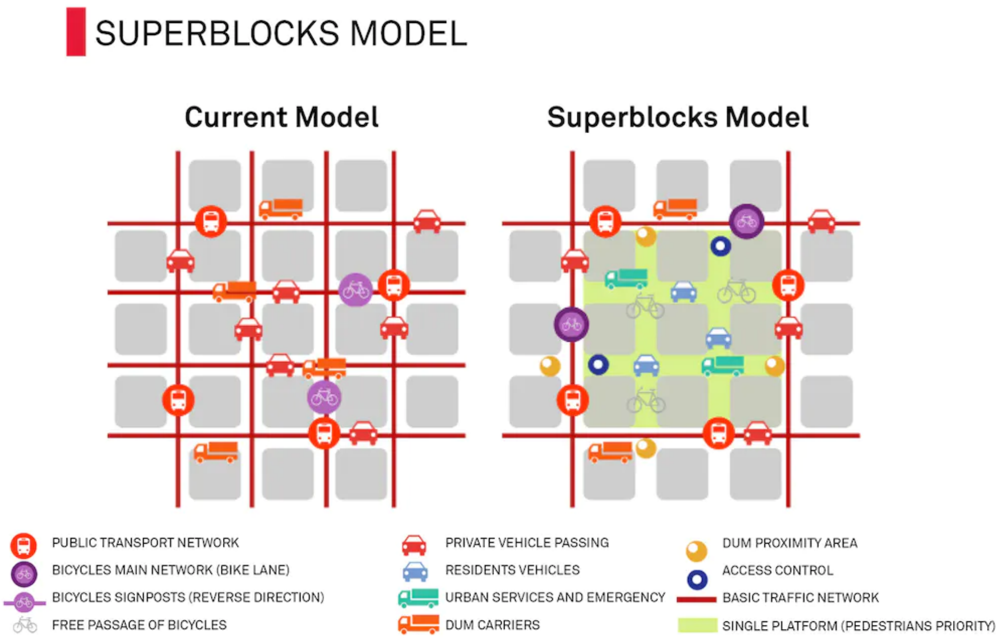

Figure 6: The Superblock Model - The Barcelona practice
Source: "Superblocks are transforming Barcelona. They might work in Australian cities too." (www.theconversation.com/superblocks-are-transforming-barcelona-they-might-work-in-australian-cities-too-123354 - Link accessed in June 2023)

Place Making requires better use of the public space by constructing liveable road environments that attract road users to spend more time reflecting on a wider range of street activities (Karndacharuk et al., 2014c). There are two complementary concepts of Place Making, namely: Home Zones and Traffic Calming. According to Curl et al., (2015) home zones aim to transform an urban road in order to balance the needs of residents and vehicular traffic.

Human-Oriented Road Environments pay substantial attention to Vulnerable Road Users (VRUs) to construct an appropriate infrastructure to sustain their needs (Villegas Flores et al., 2021). VRUs can be pedestrians, cyclists, people with disabilities, elders, and minors.

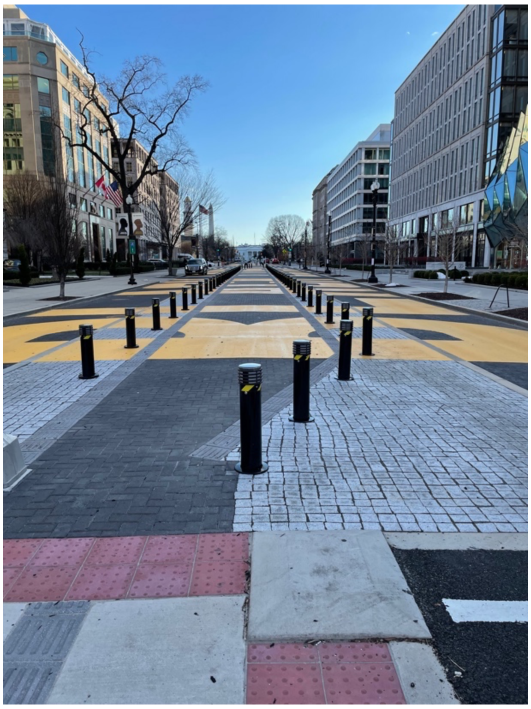

Figure 7: Place making in a central road in Washington D.C., US

2.1.3 Defining shared space

As it has been mentioned, **Shared space** aspires to create safer road environments by adding more danger; this hypothesis seems to be based on the risk homeostasis theory. There are studies that consider shared space as a Traffic Calming Measure (Clarke, 2006; Frosch, 2017; Karndacharuk et al., 2014a). Nevertheless, According to Kaparias et al (2014), *"shared space is an umbrella term that relates to a range of streetscape interventions aiming at creating a more pedestrian-friendly environment by removing the physical separations of traffic flow"*. As it will be noticed in the next chapter that considers various concept realizations, shared space is not a homogenous design. There are differences in how the informal (or abstract) segregation is achieved or how space is finally configured. Traffic calming measures aim to decrease traffic speeds and flow to create a less car-dominated road environment. Shared space aims to develop a human-oriented road environment that will be respected by car drivers so that they will change their driving behavior, i.e., lower speeds. Of course, shared space can be combined with superblock schemes, as the study of Stead et al. (2019) envisions.

Another relationship that should be discussed is between shared space and a Crosswalk Anywhere scenario. Besides, there are studies which already made this assumption in order to develop some simulation tools using commercial software (Frosch et al., 2019; Schmid, 2018). Crosswalk anywhere scenario refers to a traffic situation, where any part of the road could be considered as a courtesy crossing (Knoop and Daganzo, 2018b). Based on this definition, it can potentially be a traffic state or a road design without specific crossing spots, i.e., courtesy (or zebra) crossing. According to Knoop and Daganzo (2018a), this state can theoretically be beneficial both for pedestrians and cars in terms of travel delays, as the road section capacity is not affected by the total amount of pedestrian crossings, but by the flow of pedestrians per crosswalk which create a bottleneck. The crosswalk anywhere scenario distributes the crossing flow over the entire space creating bottlenecks with higher capacity. Therefore, based on this consideration, it potentially increases the efficiency of an urban road network.

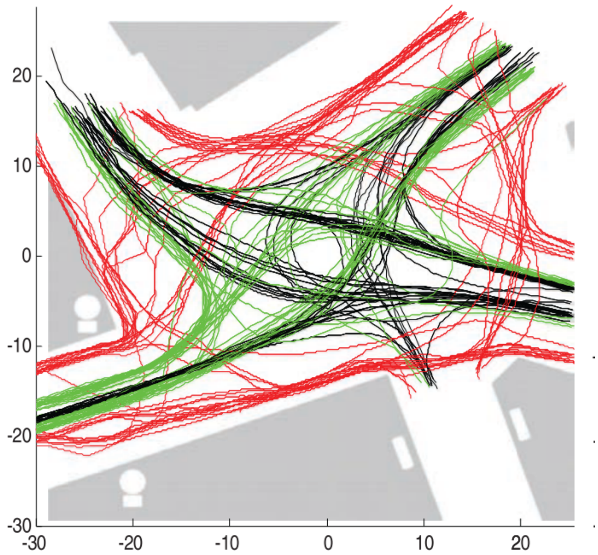

Figure 8: Trajectories in Sonnenfelsplatz in Graz, Austria, pedestrians with red, bicycles with green, and vehicles with black. Source: (Rudloff et al., 2014)

At this point, it is crucial to investigate trajectories from shared space cases, as they were reported in the literature, in order to define shared space. **Figure 8** and **Figure 9** show trajectories from, Austria and Exhibition Road in London, UK. As can be seen, flows of road users are segregated in practice although the frequency of pedestrian crossings increased (Anvari et al., 2016; Rudloff et al., 2014). Shared space tends to replicate segregated patterns with pedestrians moving to the sides of the street (Anvari et al., 2016; Batista and Friedrich, 2022; Moody and Melia, 2014). As noted by Peters (2019), motor vehicles still represent the feelings and perceptions that cyclists or pedestrians associate with standard traffic space. According to the findings of Akgün-Tanbay et al. (2022), in practice, the shared space in Maqueda Street in Palermo, Italy is considered less chaotic by road users than expected. Another important observation is that cyclists tend to follow similar paths and speeds with motorized traffic (Batista and Friedrich, 2022). In shared space, pedestrians tend to shorten their paths according to previous empirical studies (Kaparias and Wang, 2020b; Ruiz-Apilánez et al., 2017; Schönauer et al., 2012a). Therefore, shared space has more similarities than differences with the crosswalk anywhere scenario.

Figure 9: Trajectories in Exhibition Road, London, UK, pedestrians with white and vehicles with red.
Source: (Anvari et al., 2016)

The main difference lies in the fact that shared space aims to attract people not only to coexist with other transport modes but also to socialize, according to Karndacharuk et al. (2014a, 2014b). Hence, shared space should not only be considered as a road design idea but a place-making concept. This is in line with the initial thoughts of Hamilton-Baillie (2008a, 2008b) underlined the significance of this concept in increasing daily social and physical activities and making modern cities more livable. Therefore, a shared space road should consist of three main zones: circulation, safety, and activity zone. These zones should be informally segregated; segregation measures can be tactile paving, bollards, color variations, trees, etc. In the circulation zone, motorized traffic is predominant; yet, it can be crossed by pedestrians at any point. In a safe zone, pedestrian trajectories are concentrated. They comprise channels based on which pedestrians can reach their destination without detouring much from the shortest path. An activity zone is a space where people can dwell and socialize. The widths of the zones can be considered significant descriptors of the shared space design. They define the shared space configuration which may impact the behavior of road users. **Figure 10** shows four different shared space configurations.

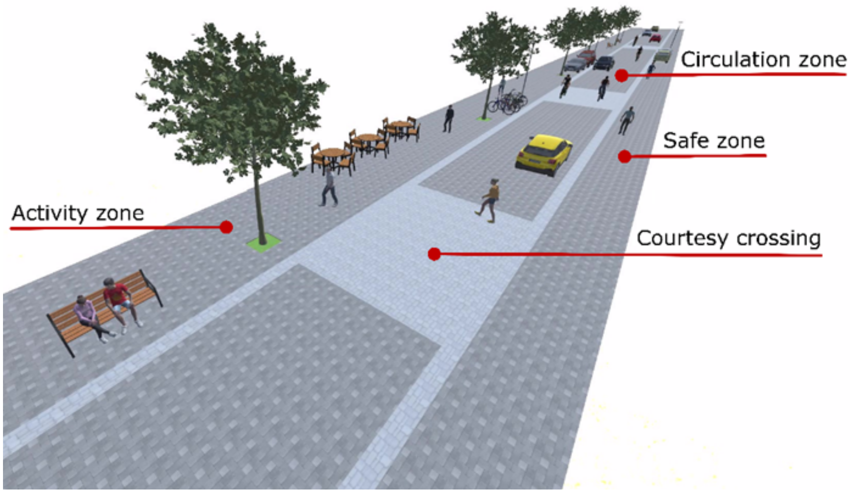

Figure 10: Shared space configuration:

2.2 Leading perspectives and main dilemmas

The identification of leading dilemmas and leading perspectives for the Future Urban Road is achieved by applying the Q-method, qualitative analysis to assess subjective opinions that exist around a topic. As it will be interpreted, there are noticeable contradictions among experts' leading perspectives that create major dilemmas to be answered in the future. In the end, the role and the potential of shared space to transform urban roads are reveled and discussed.

2.2.1 Q-method

Q-method can contribute to mapping and understanding the plethora of subjective views regarding a specific subject which requires further research (Milakis et al., 2018). It is not a tool based on which consensus can be reached; yet it stimulates the extraction of heterogeneity that appears among experts' opinions (Watts and Stenner, 2005). Q-method forces respondent to rank or/and prioritize pre-specified statements based on their level of agreement or disagreement, as Wolbertus et al. (2020b) mentioned. According to Kougias et al. (2020a), due to this, Q-method can effectively mitigate responses' biases; yet the flexibility in expressing your own thoughts is very limited using this framework. In other words, experts' perspectives are puzzled based on predefined thoughts. Compared to other survey techniques, the Q-method requires a small yet diverse sample of experts.

Q-method follows four pre-set steps defined by the study of Davies and Hodge (2006). The first step refers to the development of statements that describe a particular topic. They can be positive, negative, or quite controversial so that the various views can be mapped. The developed statements comprise the Q-set. In the second step, the P-set is defined. It refers to the pre-selected participants of the survey. Researchers aim to maximize diversity while inviting people with high expertise in the selected topic. The development of the survey form is included in the third step. The form is based on an inverted symmetrical pyramid based on which the statements can be ranked. Lastly, the survey is distributed, and the data are collected.

2.2.2 Data collection process

The objective of the data collection form is to reveal the image of the Future Urban Road and the role of shared space taking into consideration various experts' leading perspectives. The creation of the Q-set, i.e., a set of statements, is based on the SLR and the transforming concepts identified from it. Q-method assumes that participants will agree and disagree with a group of statements, yet this depends on the design of the Q-set structure. The main aim is to keep the right balance between very positive and negative statements while integrating some contradictions noticed from the literature review process. In total, 40 statements were formulated. Each one relates to at least one of the 28 identified concepts. The 40 statements are presented below:

1. To enhance their reliability, public transport modes should not operate in mixed traffic urban environments with complex interactions (<u>Divided Arterials</u>, <u>Bus Priority Lanes</u>).

2. Roads within a superblock should not be exclusively destined to active modes and micro-mobility (Superblocks, Place Making, Home Zones).
3. Lane numbers should be designed not only based on traffic flow but also based on noise pollution considerations (Home Zones, Vitality and Diversity).
4. Future urban road design cannot possibly consider all the different travel needs of road users (i.e., older car drivers, people with special needs, etc.) (Place Making, Human Oriented Road, Forgiving Roads, **Shared Space**).
5. Road signs and traffic lights will be replaced by Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) technologies that will guide Autonomous Vehicles (AVs) (V2I and V2V Communication Systems).
6. Shared Autonomous Vehicles (SAVs) should not be designed to operate in complex road environments including those providing shared space (Shared Autonomous Vehicles, **Shared Space**).
7. On-street parking should be radically restricted in future urban roads (Divided Arterials).
8. Cities should fully focus on the aesthetics of the urban road environment since urban roads are means to observe and understand the city (Roadside Vegetation, Urban Road as Public Space, Vitality and Diversity).
9. Medians should exist in unidirectional urban roads as they eliminate dangerous overtaking maneuvers and boost pedestrian safety (Forgiving Roads, Design Consistency).
10. Shared space roads cannot increase daily social and physical activities in urban areas (Social Places, Shared Space).
11. The deployment of Electric Vehicle (EV) charging points should be preferred in off-street parking facilities (Electric Vehicles' Charging Stations).
12. Enhancement of multimodality in urban arterials and collectors will decisively contribute to the improvement of transport system efficiency (Multimodal Corridors).
13. Future interventions in (physical) road infrastructure will not be necessary, since connected AVs will solve traffic congestion and safety problems (V2I and V2V Communication Systems, Shared Autonomous Vehicles).
14. Shared space can critically undermine traffic safety by creating more mixed traffic interactions and thus increased collision danger (**Shared Space**).
15. Cities should implement tram systems as a tool for urban regeneration projects (Urban Road as Public Space).
16. Arterials should also be redesigned to enhance pedestrian and cycling presence (Human Oriented Road Environment, Walking/Cycling Infrastructure).
17. Speed limits of 30 km/h can now be established in all residential streets without any design intervention (Speed Limits Credibility, Traffic Calming Measures).
18. Improper road user behavior (e.g., illegal pedestrian crossing movements) and traffic blocking activities (e.g., parking maneuvering) should be banned in urban streets as they cause speed reductions (Divided Arterials, Crosswalk Anywhere, **Shared Space**)
19. High flow arterials should still prioritize automobile traffic over other transport modes (Road Space Allocation, Divided Arterials).
20. Urban roads can be neighborhood cultural assets in addition to their travel corridor role (Streets as Cultural Assets).
21. Urban roads can promote sustainable energy policies through the establishment of photovoltaic equipment (e.g., on the roof of public transport stops or on the smart road surface) (Photovoltaic roads, Dynamic Wireless Charging).

22. Future urban roads should dedicate space to mobility hubs offering shared mobility and public transport services (Road Space Allocation, Multimodal Corridors).
23. A superblock is the most complete measure for diverting traffic volumes away city centers (Superblocks).
24. Public transport should not use pedestrianized streets in central city areas (Bus Priority Lanes).
25. Road pricing could result in accessibility inequalities in European cities (Road Pricing).
26. It will be necessary to fully restrict the use of AVs in some areas as their dominance will result in a dystopic environment (Human Oriented Road Environment, **Shared Space**).
27. It is necessary to plan exclusive AV corridors accompanied with V2I sensors in European Cities (Fully Segregated AV Road).
28. Permanent bus lanes in urban arterials downgrade the efficiency of the transport system (Bus Priority Lanes).
29. Speed limits are not necessary in urban roads as interactions among road users using automated means of mobility (e.g., AVs and automated buses) can self-regulate traffic speeds (Speed Limits Credibility, Crosswalk Anywhere, **Shared Space**).
30. Roadside vegetation is the only counter measure to maintain the urban environment quality, which will be caused by an intense use of private AVs (Roadside Vegetation).
31. SAVs will have a decisive role in urban roads as they will free up parking spaces in city centers (Shared Autonomous Vehicles).
32. It is essential to eliminate traffic conflicts in junctions by constructing roundabouts in cities (Forgiving Roads, Design Consistency).
33. It is impossible to adequately accommodate all transport modes in European Cities due to space limitations (Road space allocation, **Shared Space**).
34. Cities ought to increase the use of EVs in city centers through deploying EV charging points in central streets (Electric Vehicles' Charging Stations).
35. Accessibility of vulnerable road users will be downgraded by implementing shared space (**Shared Space**, Human Oriented Road Environment).
36. Congestion problems in cities can be effectively mitigated through road pricing schemes (Road Pricing).
37. Exclusive cycling infrastructure (i.e., bike lanes and bike sharing schemes) is the only proper way to promote cycling trips (Walking/Cycling Infrastructure).
38. It is not so significant to create urban road environments that attract users to spend more time for socializing (Social Places, **Shared Space**).
39. Traffic calming measures should be preferred over pedestrianized streets or car-free areas as they do not restrict any transport mode (Traffic Calming Measures, **Shared Space**).
40. Urban road design should inspire correct expectations and better driving behavior (Self-Explaining Roads).

The P-set was built based on a diverse pool of experts in subjects related to urban, transportation planning, environmental policy, urban geography, computer science and sociology. Instead of snowball sampling, a non-randomized sampling technique was finally used. The list of experts was formed simultaneously with the development of the Q-set. The final pool of potential respondents included 95 specialists. Yet, the acceptance rate was equal to 52.6% at the end. This means that 50 stakeholders participated in filling in the data collection form. The final sample consists of experts from 36 different organizations and 12 European Countries. Around 28 experts are coming from academia, while 15 work in local or regional governance and regulatory authorities. The rest respondents are consultants, entrepreneurs, and project managers. The P-Set is presented in the **Table 1** in section **2.2.3**.

In the survey form, respondents ranked the previously presented statements respecting a fixed quasi–normal distribution which ranges from prohibitive (-3) to imperative (+3). This inverted symmetrical pyramid is given in **Figure 11**. As can be seen, in each level of agreement, a specific number of cells has been assigned. The maximum number of cells (i.e., 12 cells) is given to neutral, while the minimum ones (i.e., 2 cells) are provided to prohibitive and imperative levels. This survey form was built in a .xlsx file. The distribution method was fully based on personal e-mails, where further instructions were provided to the respondents. Internet links with the definitions of the concepts were also given.

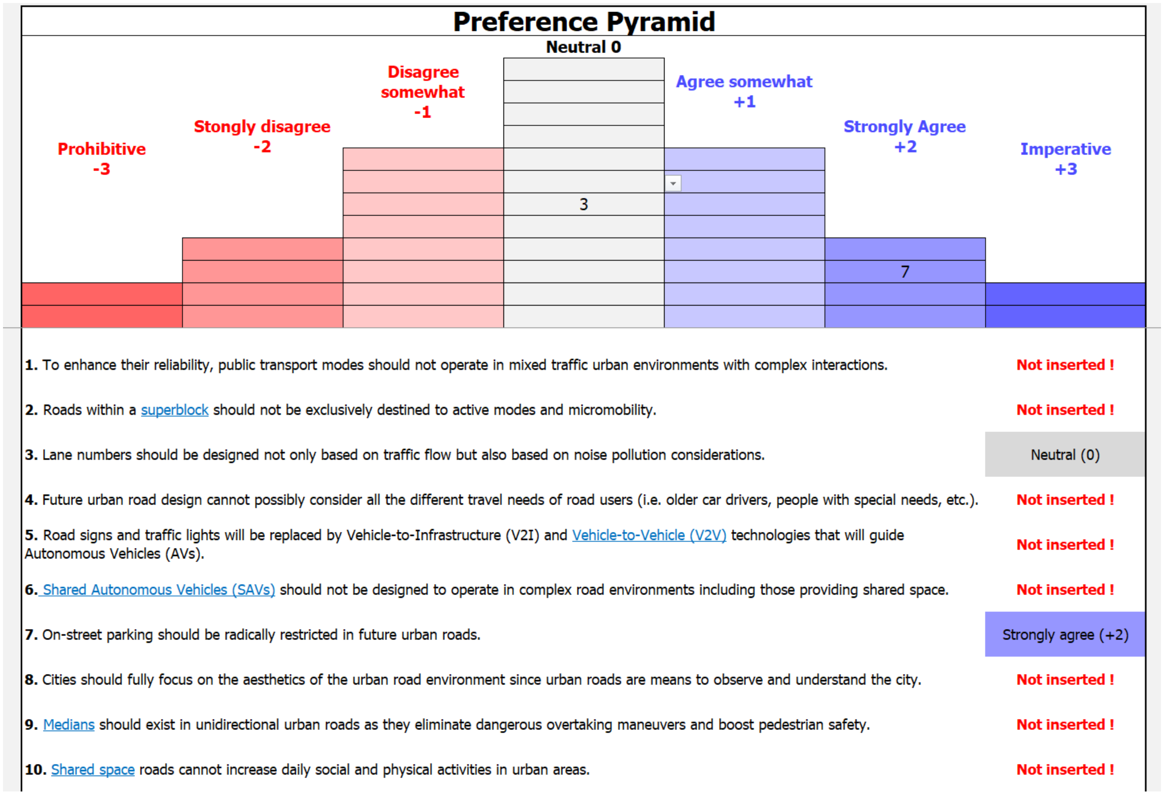

Figure 11: Q-method, data collection form

2.2.3 Factors' identification

The Principal Component Analysis (PCA) was utilized to identify the main factors that form the leading perspectives for the future urban road. It is based on the computation of a correlation matrix, in which Q-sorts with high intercorrelation create one factor (Kougias et al., 2020b; Zabala and Pascual, 2016). This analysis called Q-pattern analysis was performed in R using the "qmethod" package developed by Zabala (2014). In this method, the total number of factors is defined by the user beforehand. Two rules of thumb were followed: (a) the eigenvalue of each factor should be greater than 1 and (b) at least two Q-sort should significantly load upon each factor (Curry et al., 2013; Kougias et al., 2020a). In the end, four factors or perspectives were extracted from the Q-pattern analysis. **Table 1** presents the division of experts into factors, which are analytically presented in the next paragraphs.

Table 1: Sample (P-Set) Composition and identified factors

Expert	Country	Sector	Discipline	Factor
1	Greece	Academic	Transportation planning	3: Unconventionalists
2	Greece	Academic	Urban planning	0: Unclassified
3	Greece	Academic	Transport or environmental policy	4: Infrastructurists
4	Greece	Academic	Transportation planning	4: Infrastructurists
5	United Kingdom	Academic	Transport or environmental policy	1:People-first Techno-centrists
6	United Kingdom	Consultant	Transportation planning	1:People-first Techno-centrists
7	Norway	Academic	Transport or environmental policy	0: Unclassified
8	Greece	Policy maker	Transport or environmental policy	2: Autonomous Vehicle Sceptics
9	the Netherlands	Consultant	Traffic safety	3: Unconventionalists
10	Finland	Academic	Urban planning	3: Unconventionalists
11	United Kingdom	Academic	Traffic safety	1:People-first Techno-centrists
12	Belgium	Academic	Computer science	0: Unclassified
13	Switzerland	Academic	Transportation planning	4: Infrastructurists
14	Czech Republic	Academic	Transport or environmental policy	1:People-first Techno-centrists
15	Greece	Academic	Traffic safety	4: Infrastructurists
16	Greece	Consultant	Urban geography and sociology	3: Unconventionalists
17	the Netherlands	Consultant	Transport or environmental policy	2: Autonomous Vehicle Sceptics
18	Greece	Academic	Transportation planning	1:People-first Techno-centrists
19	United Kingdom	Academic	Transportation planning	2: Autonomous Vehicle Sceptics
20	United Kingdom	Academic	Transportation planning	1:People-first Techno-centrists
21	Greece	Academic	Transportation planning	4: Infrastructurists
22	the Netherlands	Academic	Traffic safety	3: Unconventionalists
23	Greece	Consultant	Traffic safety	1:People-first Techno-centrists
24	Belgium	Policy maker	Transport or environmental policy	0: Unclassified
25	United Kingdom	Academic	Urban planning	4: Infrastructurists
26	United Kingdom	Academic	Traffic safety	1:People-first Techno-centrists
27	the Netherlands	Consultant	Traffic safety	0: Unclassified
28	Malta	Academic	Transport or environmental policy	2: Autonomous Vehicle Sceptics
29	Greece	Consultant	Urban geography and sociology	0: Unclassified
30	Greece	Consultant	Transportation planning	2: Autonomous Vehicle Sceptics
31	United Kingdom	Academic	Transport or environmental policy	0: Unclassified
32	United Kingdom	Consultant	Urban planning	4: Infrastructurists
33	the Netherlands	Policy maker	Transport or environmental policy	3: Unconventionalists
34	Greece	Consultant	Transportation planning	1:People-first Techno-centrists
35	Greece	Consultant	Urban geography and sociology	1:People-first Techno-centrists
36	United Kingdom	Policy maker	Transport or environmental policy	1:People-first Techno-centrists
37	Greece	Academic	Urban Geography	1:People-first Techno-centrists
38	the Netherlands	Consultant	Urban planning	3: Unconventionalists
39	the Netherlands	Academic	Transportation planning	2: Autonomous Vehicle Sceptics
40	Greece	Consultant	Computer science	1:People-first Techno-centrists
41	the Netherlands	Academic	Traffic safety	0: Unclassified
42	Italy	Academic	Urban planning	3: Unconventionalists
43	Portugal	Academic	Urban geography and sociology	2: Autonomous Vehicle Sceptics
44	Ireland	Consultant	Transportation planning	2: Autonomous Vehicle Sceptics
45	Belgium	Policy maker	Transport or environmental policy	1:People-first Techno-centrists
46	Greece	Academic	Traffic safety	1:People-first Techno-centrists
47	United Kingdom	Policy maker	Transport or environmental policy	2: Autonomous Vehicle Sceptics
48	United Kingdom	Academic	Urban planning	2: Autonomous Vehicle Sceptics
49	United Kingdom	Consultant	Transport or environmental policy	2: Autonomous Vehicle Sceptics
50	the Netherlands	Academic	Transportation planning	1:People-first Techno-centrists

The first factor includes experts who are defined as People-First Techno-Centrists. The total number of experts who belong to this group is 16 out of 50. Based on their beliefs, important technological advancements like SAVs will decrease vehicle ownership freeing up road space. This space can be used to accommodate all transport modes including VRUs like pedestrians and cyclists.

These experts are opposed to any restriction applied in transport modes that are technologically advanced.

An opposite perspective is expressed by 11 experts which are defined as Autonomous Vehicles Sceptics. While both groups agree that emerging technologies will transform urban roads, these respondents think that autonomous vehicles will never solve complicated safety issues that appear in the urban road environment. The coexistence of pedestrians with AVs is definitely not a feasible scenario, according to their beliefs. That is why, planners and engineers should continue to design safe road environments, which prioritize the slowest modes. Superblocks and traffic calming measures are some of the concepts they are in favor of.

The Unconventionalists support the mix of road users in the same road environment. Indeed, 8 experts propose a scheme without conventional traffic regulations. Interactions and mutual understanding among road users should be the driving forces in this transformation process. That is why, shared space seems to be the key concept to solve the problem of space which appears in many dense cities around the world. Indeed, based on their beliefs, there is not enough space to accommodate all transport modes in urban areas.

Infrastucturists have significantly different perspectives than experts who belong to the previously presented factor. 7 out of 50 have been grouped into this factor. Based on their viewpoints, engineers are fully responsible for designing roads that are self-explained while forgiving human errors. The road environment should consist of exclusive or semi-exclusive corridors, one of each transport mode; the main aim is to decrease complicated interactions among road users while reinforcing the efficiency of the transportation system. This can be achieved by traffic regulation and road pricing schemes that will mitigate traffic congestion. The last group is in favor of a fair distribution of road space across all transport modes.

Table 2 gives the distinguishing statements based on which the previously described leading perspectives were defined. **Figure 12** concentrates on statements that refer to shared space; it aims to highlight the differences in the level of agreement among factors.

Table 2: Q-set and distinguishing statements; with bold and italics statements that refer to shared space.

Statement	**Result**
1. To enhance their reliability, public transport modes should not operate in mixed traffic urban environments with complex interactions.	Distinguishes all
2. Roads within a superblock should not be exclusively destined to active modes and micro-mobility.	Distinguishes f2 Distinguishes f4
3. Lane numbers should be designed not only based on traffic flow but also based on noise pollution considerations.	Distinguishes f4 only
4. Future urban road design cannot possibly consider all the different travel needs of road users (i.e. older car drivers, people with special needs, etc.).	Distinguishes f3
5. Road signs and traffic lights will be replaced by Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) technologies that will guide Autonomous Vehicles (AVs).	
6. Shared Autonomous Vehicles (SAVs) should not be designed to operate in complex road environments including those providing shared space.	Distinguishes f2 Distinguishes f4

7. On-street parking should be radically restricted in future urban roads.	Distinguishes f1 Distinguishes f4
8. Cities should fully focus on the aesthetics of the urban road environment since urban roads are means to observe and understand the city.	Consensus
9. Medians should exist in unidirectional urban roads as they eliminate dangerous overtaking maneuvers and boost pedestrian safety.	
10. Shared space roads cannot increase daily social and physical activities in urban areas.	Distinguishes f4 only
11. The deployment of Electric Vehicle (EV) charging points should be preferred in off-street parking facilities.	
12. Enhancement of multimodality in urban arterials and collectors will decisively contribute to the improvement of transport system efficiency.	Distinguishes f4
13. Future interventions in (physical) road infrastructure will not be necessary, since connected AVs will solve traffic congestion and safety problems.	Distinguishes f1 only
14. Shared space can critically undermine traffic safety by creating more mixed traffic interactions and thus increased collision danger.	Distinguishes f3 only
15. Cities should implement tram systems as a tool for urban regeneration projects.	
16. Arterials should also be redesigned to enhance pedestrian and cycling presence.	Distinguishes f2 Distinguishes f4
17. Speed limits of 30 km/h can now be established in all residential streets without any design intervention.	
18. Improper road user behavior (e.g. illegal pedestrian crossing movements) and traffic blocking activities (e.g. parking maneuvering) should be banned in urban streets as they cause speed reductions.	Distinguishes f3 Distinguishes f4
19. High flow arterials should still prioritize automobile traffic over other transport modes.	Distinguishes f1 Distinguishes f3
20. Urban roads can be neighborhood cultural assets in addition to their travel corridor role.	
21. Urban roads can promote sustainable energy policies through the establishment of photovoltaic equipment (e.g. on the roof of public transport stops or on the smart road surface per se).	Distinguishes f4
22. Future urban roads should dedicate space to mobility hubs offering shared mobility and public transport services.	Distinguishes f3 only
23. A superblock is the most complete measure for diverting traffic volumes away city centers.	Distinguishes f2 Distinguishes f4
24. Public transport should not use pedestrianized streets in central city areas.	Distinguishes f3
25. Road pricing could result in accessibility inequalities in European cities.	Distinguishes f3 only
26. It will be necessary to fully restrict the use of AVs in some areas as their dominance will result in a dystopic environment.	Distinguishes f1 Distinguishes f3
27. It is necessary to plan exclusive AV corridors accompanied with V2I sensors in European Cities.	Distinguishes f1 Distinguishes f3
28. Permanent bus lanes in urban arterials downgrade the efficiency of the transport system.	Distinguishes f4
29. Speed limits are not necessary in urban roads as interactions among road users using automated means of mobility (e.g. AVs and automated buses) can self-regulate traffic speeds.	Distinguishes f2 Distinguishes f3
30. Roadside vegetation is the only counter measure to maintain the urban environment quality, which will be caused by an intense use of private AVs.	Distinguishes f4 only
31. SAVs will have a decisive role in urban roads as they will free up parking spaces in city centers.	Distinguishes f2
32. It is essential to eliminate traffic conflicts in junctions by constructing roundabouts in cities.	
33. It is impossible to adequately accommodate all transport modes in European Cities due to space limitations.	Distinguishes f1 Distinguishes f3

34. Cities ought to increase the use of EVs in city centers through deploying EV charging points in central streets.	Distinguishes f1 Distinguishes f4
35. Accessibility of vulnerable road users will be downgraded by implementing shared space.	Consensus
36. Congestion problems in cities can be effectively mitigated through road pricing schemes.	Distinguishes f3
37. Exclusive cycling infrastructure (i.e. bike lanes and bike sharing schemes) is the only proper way to promote cycling trips.	Distinguishes f4
38. It is not so significant to create urban road environments that attract users to spend more time for socializing.	Distinguishes f1 Distinguishes f4
39. Traffic calming measures should be preferred over pedestrianized streets or car-free areas as they do not restrict any transport mode.	
40. Urban road design should inspire correct expectations and better driving behavior.	Distinguishes f4 only

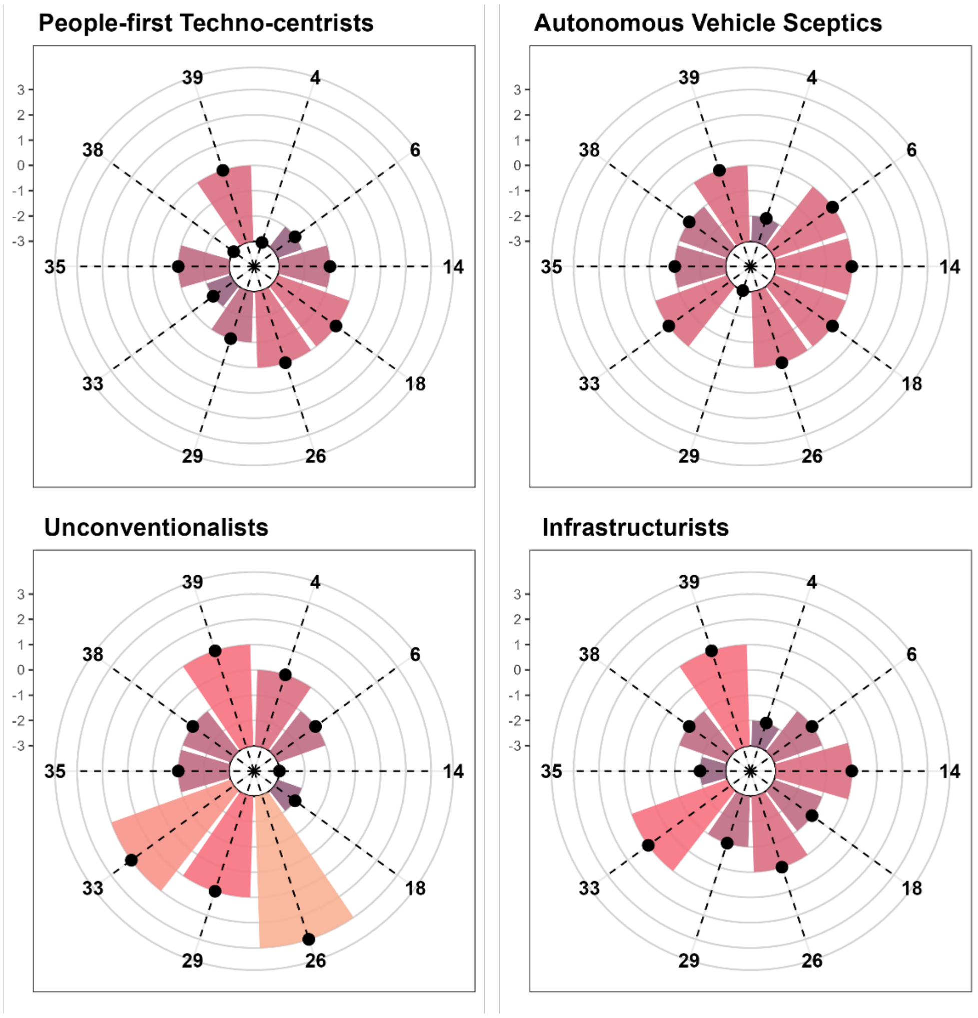

Figure 12: Score of statements that refer to shared space per factor.

2.2.4 Contradicting views

The contradicting views which appear among the previously determined leading perspectives formulate three main dilemmas that ought to be answered in the future. All these dilemmas are related to the shared space concept, as it was defined in this chapter. This signifies the potential of this concept to transform the future urban road environment.

The first dilemma is: *will the future urban road prioritize human movement, or will car dependency and dominance prevail?* This refers to a pivotal issue that puzzles researchers of urban and transportation science, i.e., the space allocation priority. Unconventionalists see shared space as an innovative solution; it reflects a balanced situation where all transport modes can coexist in the same road space. Infrastructurists are in favor of this balanced situation but with segregation of traffic flows to ensure safety and efficiency. The other two groups prioritize humans over vehicles. They see shared space more as a promising measure to create human-oriented road environments than solving the road space allocation problem in a balanced way.

The second contradiction can be summarized by the following question: *should we design systems or roads?* People-First Techno-Centrists believe that AVs will facilitate the creation of shared space urban roads in many cities around the world. Their better capabilities will act as a safety net for resolving complicated safety issues appearing in mixed-traffic road environments today. AV skeptics and Infrastructurists fully oppose this opinion. The first group is in favor of shared space but without vehicles that move autonomously. According to their beliefs, the potential of the shared space concept will be determined by the tendency of car drivers to respect VRUs adopting a safer behavior. Unconventionalists think that unregulated road environments like shared space should be first created so that the development of automation will be forced to meet these new challenges. In other words, shared space is seen as a way to guide technological advancements.

The last dilemma is related to the research question of this dissertation: *to share or to segregate?* To answer it, Infrastructurists argue the necessity of traffic regulations to ensure safety. Therefore, this dilemma can be translated into: *to regulate or not?* The establishment of new or updated traffic regulations should be always considered as push measures since it forces road users to follow particular behaviors in order to coexist harmonically on urban roads. Shared space invites people to coexist. In the next section, the public acceptance of various road space allocation schemes in an urban arterial is investigated aspiring to give more answers to the last dilemma posed by experts.

2.3 Social acceptance

The social acceptance of transport policies refers to the assessment of the anticipated individual and collected outcomes, e.g., travel time reduction, accessibility improvement, environmental benefits, etc. (Falzanaro, 2009a; Odioso and Smith, 2009). Measures that arise from the transport planning process can be characterized as either "push" or "pull", according to Vlek (1997). Push measures refer to restrictions or regulations that aspire to solve a problem appearing in the transportation system, e.g., road pricing, speed limit reduction, parking restriction, etc. Pull measures refer to interventions in the transportation system, which can be either the construction of a new infrastructure or the introduction of a new service. According to De Groot and Schuitema (2012), push measures should be presented in a correct way, so that they can be accepted by the public. To raise the effectiveness of sustainable mobility policies, Xia et al. (2017) argued that push measures (e.g., more expensive petrol) should be accompanied by pull measures (e.g., cheaper public transport). Such a case is shared space, as it reduces the speed limit while increasing the space where VRUs can coexist and move. Simultaneously, multimodal corridors and bus priority lanes decrease the traffic lanes, so that new exclusive or semi-exclusive corridors can be established. Which of these two policies will be preferred by the public? This research yet practical question is investigated in Panepistimiou Avenue, Athens, Greece by developing ordinal models that measure social acceptance.

2.3.1 Study Context

In this section, the public acceptance of various road space allocation scenarios is investigated in a major Greek arterial, namely: Panepistimiou Avenue, Greece. The length of this corridor is approximately 1 km, while it connects two significant squares of the city: Omonoia and Syntagma. The width of this signalized avenue is approximately 30 m. In 2019, it had 5 traffic lanes and one bus lane. On both sides, the width of the sidewalks is approximately 7 meters wide and there is no cycle lane. The daily traffic flow is estimated to be 100.000 vehicles along with over 50 buses. Two recent projects aspired to transform this avenue, i.e., the Rethink Athens project in 2012 and the Great Walk project in 2020.

The Rethink Athens project proposed the transformation of this corridor into a pedestrianized zone with a semi-exclusive tram line in the middle of the street (see **Figure 13**). It focused on the creation of a human-oriented road environment with green spaces by blocking heavy through traffic flow that passes from central areas in Athens today. The main objective was the creation of a more resilient, accessible, and vibrant city center. Tram line would comprise the major connector of the Athens city center. This would reinforce the role of this mode in the transportation system of Athens. This plan raised many concerns in the Athenian community regarding its capacity to mitigate instead of increasing traffic congestion in the city center. In 2014, the Rethink Athens project was finally canceled due to a lack of funding.

The Great Walk project followed a more conservative approach. It aspired to transform this arterial into a multimodal corridor by integrating a pop-up cycle lane while reducing the traffic lanes from 5 to 2. The cross-section design included a bus lane. Great Walk was implemented after the first lockdown of the COVID-19 pandemic in May 2020. Pop-up walking and cycling infrastructure was a trend in Europe during that period (Nikitas et al., 2021). One month later, due to extreme traffic congestion problems that appeared, one traffic lane was restored. In 2022, the implementation of permanent interventions was started in this arterial. Yet, the final plan did not include a cycle lane but only the extension of sidewalks with the addition of more roadside vegetation.

As it can be interpreted, over the years, the objectives of plans and the resulting designs have changed a lot creating confusion, while middle-ground instead of radical solution seem to be preferred each time at the end. **Table 3** gives the various designs which have been established (or proposed) in this avenue. At this point, it should be mentioned that Panepistimiou Avenue is an interesting, extreme case to investigate the public acceptance of various hypothetical road space allocation schemes.

Figure 13: Panepistimiou Avenue: (a) Rethink Athens design, (b) status quo in 2019, and (c) Great Walk in 2020
Source: www.kathimerini.gr; www.tanea.gr; www.archdaily.com (Accessed in March 2023); own elaboration, 2023

2.3.2 Experimental design

The public acceptance of a push or pull measure is definitely a subjective notion. Stated Preferences (SP) experiment accompanied by a Likert Scale has been utilized as a method to quantify subjective variables like perceived safety, comfort, accessibility, driving stress, etc. (Cheng and Chen, 2015; Fitch et al., 2022a; Pastia et al., 2022; Tzouras et al., 2020). SP experiments are based on a set of hypothetical scenarios that are pre-designed by the researcher (Kroes and Sheldon, 1988); in this case, these hypothetical scenarios refer to different cross-section designs of Panepistimiou Avenue. The steps to construct such an experiment are 1) selection of variables, 2) identification of measurement unit, 3) determination of variable levels, 4) survey design, 5) translation of designed scenarios into a set of questions, 6) selection of appropriate estimation procedure and 7) model estimation (Tzouras et al., 2020).

The dependent variable is of course the public (or social) acceptance which is rated on a Likert Scale from 1 to 5, where 1 corresponds to fully unacceptable and 5 to fully acceptable. In the survey form, the respondents answered the following question: *rate from 1 to 5 how acceptable is this design for you?* The independent variables refer to the existence or not of a particular transport infrastructure, namely: a bus lane, tram line, and a uni-directional cycle lane. Therefore, dummy variables are imported into the developed social acceptance model that is presented in **Equation 1**. For the pedestrian space, a dummy variable is also used in this experiment; it refers to the increase or not of the width of the present sidewalks (i.e., as it was before the pop-up interventions of the Great Walk). Yet, the installation of new semi-exclusive corridors for other transport modes requires the reduction of traffic lanes as the available space is not unlimited. Therefore, there are dependencies among the explanatory variables. To reduce the chance of multicollinearity appearance, the travel delay is introduced as a function of traffic speed and capacity. The capacity of a cross-section is related to the number of traffic lanes. Three levels are used in this experiment, namely: (a) more than or equal to 6 minutes, (b) 6 to 2 minutes, and (c) less than 2 minutes. These levels correspond to the additional travel time due to the reduction of traffic lanes. A fixed traffic flow of 4200 pcu/h and a typical BPR function modified accordingly is considered to estimate the remaining traffic lanes and the speed limit (Kepaptsoglou et al., 2015). In the experiment, the mean public transport waiting time is taken into account. The variable levels are given in **Table 3**. It should be mentioned that the mean waiting time at bus stops is approximately 8 minutes on Panepistimiou Avenue today.

The gender and the age group are the only socio-demographic variables that are considered in this experiment. It is hypothesized that the present travel behavior of the respondent directly influences social acceptance. Three groups are created: car users, public transport users, and VRUs. The last one corresponds to respondents who mostly travel to work (or other daily activities) either by walking or cycling. The present travel behavior interacts with other explanatory variables, as it is assumed. For example, a daily public transport user tends to prefer a bus lane over a cycle lane, while a car commuter will be highly concerned about reducing traffic lanes. Therefore, interaction effects enclose the high contradictions that also appear among road users.

Table 3: Explanatory variables and variable levels

Explanatory variables	Number of levels	Rethink Athens (2012)	Status quo (2019)	Great Walk (2020)	Selected levels presented in survey forms		
Gender	2				0: male	1: female	
Age group	6				1: 20 or younger	2: 21-30 years	3: 31-40 years
					4: 41-50 years	5: 51-65 years	6: 65 or older
Road user type	5				0: VRU	1: pt user	2: car user
Traffic delay	3	no traffic lanes	4-5 traffic lanes, 3 to 9 minutes at peak hours	3 traffic lanes, 3 to 9 minutes at peak hours	1: more than or equal to 6 minutes	2: 6 to 2 minutes	3: less than 2 minutes
Mean PT waiting time	3	depends on the frequency of the new tram line	mean value approx. 8 minutes (all hours)	mean value approx. 8 minutes (all hours)	1: less than or equal to 4 minutes	2: 4 to 12 minutes	3: more than 12 minutes
Bus lane	2	without bus priority lane	with bus lane, both directions (no priority at intersections – green wave)	with bus lane, one direction (no priority at intersections – green wave)	0: without bus priority lane	1: with bus priority lane	
Tram line	2	with tram line (semi-exclusive infrastructure)	without tram line	without tram line	0: without tram line	1: with tram line (3.5 m wide semi-exclusive infrastructure OR 3.5 m wide one-way PT corridor)	
Cycle lane	2	without a unidirectional cycle lane	without a unidirectional cycle lane	with unidirectional cycle infrastructure (pop–up intervention)	0: without a unidirectional cycle lane	1: with unidirectional cycle infrastructure	
Pedestrian space	2	pedestrianized zone – green route	right and left Sidewalk ≈ 7	increase of right sidewalk width by 3.25 m	0: no increase in pedestrian space	1: increase in pedestrian space	

$$\begin{aligned} acc_{i,j}^{*} &= \mathrm{us_j} \times \left(\beta_{delay} \times \mathrm{dt_i} + \beta_{wait} \times \mathrm{tw_i} + \beta_{bus} \times bus_i + \beta_{tram} \times tram_i + \beta_{cycle} \times cycle_i + \beta_{ped} \times ped_i \right. \\ &\qquad \left. + \varepsilon_{i,j}\right) \\ &= us_j \times \left[\beta_{delay} \times \left(\frac{L}{uf_i} \times \left[1 + a \times \left(\frac{v}{n_i \times c}\right)^{\beta}\right] - t_{present}\right) + \beta_{wait} \times \mathrm{tw_i} + \beta_{bus} \times bus_i + \beta_{tram} \times tram_i \right. \\ &\qquad \left. + \beta_{cycle} \times cycle_i + \beta_{ped} \times ped_i + \varepsilon_{i,j}\right] \quad \mathbf{(1)} \end{aligned}$$

<u>where</u>:

$acc_{i,j}^{*}$: acceptance of scenario i from individual j (latent variable),

$\beta_{delay}, \beta_{wait}, \ldots, \beta_{ped}$: beta parameters (or line slope),

dt_i: traffic delay in minutes of scenario i,
tw_i: mean waiting time at public transport stops in minutes of scenario i,
bus_i: 1, if there is a bus lane in the scenario i,
us_j: road user type; it can be '1: car user', '2: public transport user' and '3 vulnerable road user',
$tram_i$: 1, if there are tram line operations in scenario i,
$cycle_i$: 1, if there is a unidirectional cycle lane in scenario i,
ped_i: 1, if there is an increase of pedestrian space in scenario i,
L_i: link length in km; a fixed value equal to 1.15 km, which is the length of Panepistimiou Avenue,
uf_i: free-flow speed in km/h for scenario i; it is equal to the selected speed limit in each case,
v_i: arterial volume in pcu/h per case; in scenario design, it remains constant,
c: capacity per lane; fixed value equal to 1200 pcu/h,
n_i: number of traffic lanes in scenario i,
α, β: function calibration parameters; for Athenian arterials, $\alpha = 0.15$ and $\beta = 4$.

$$acc_{i,j} = \begin{cases} 1, & -\infty < acc^*_{i,j} \leq k_1 \quad fully\ unacceptable \\ 2, & k_1 < acc^*_{i,j} \leq k_2 \\ 3, & k_2 < acc^*_{i,j} \leq k_3 \\ 4, & k_3 < acc^*_{i,j} \leq k_4 \\ 5, & k_4 < acc^*_{i,j} < +\infty \quad fully\ acceptable \end{cases} \qquad (2)$$

where:
$acc_{i,j}$: acceptance of scenario i from individual j measured in a Likert Scale from 1 to 5,
k_1, k_2, k_3, k_4: social acceptance kappa thresholds.

The socio-demographic characteristics and travel behavior attributes are not considered in the survey design process, as their values can be controlled a priori. The total number of combinations is equal to 3 * 3 * 2 * 2 * 2 = 144. Surely, rating 144 cases would be a tedious process for every respondent. Therefore, a fractional factorial design is preferred to decrease the number of scenarios from 144 to 36. Fractional factorial designs are based on an orthogonal table which ensures zero correlation among the selected independent variables. At this point, it should be mentioned that stated preference rating experiments cannot be constructed based on an efficient, which eliminates scenarios in which a choice (or rate) presents a high probability to be selected. It is important to include a scenario that will be rated with the maximum or minimum to "train" the model computation process. Additionally, the scenarios are divided into 3 blocks, so that each respondent will rate at most 12 scenarios. Still, among the blocks, the sample in terms of socio-demographic characteristics should not differ. Therefore, the survey was distributed based on a block randomization algorithm.

The translation of scenarios into cross-section designs was achieved by using the StreetMix[2] tool and applying a general strategy that is explained in the forthcoming lines of this paragraph. First, changes in the public transport, cycling, and walking infrastructure were performed in the present cross-section. Afterward, the travel delay was estimated by using the BRT function and importing the remaining lanes.

[2] Link of the StreetMix tool: www.streetmix.net

If the estimated travel delay does not correspond to the determined level, then the speed limit was updated. The available speed limits were 30, 50, and 70 km/h. Additionally, in the scenarios that presented lower space requirements, extra buffer zone with roadside vegetation were implemented instead. The result of this process was 36 hypothetical yet realistic design proposals for Panepistimiou Avenue. To give the scenario in detail, a table was added below the cross-section image (see **Figure 14**). It shows the present situation and the changes that will be made based on the proposed design. The survey was uploaded on Google Forms[3]. It was distributed using social media in January – March 2021.

Scenario 10

Proposed design

Considering it, we know that:

	Present situation	Proposed design
Number of lanes	6	2
Speed limit	50	30
Travel time with car in minutes	3	10
Total travel time with public transport in minutes	14	18
Waiting time in public transport stop in minutes	8	12
Bus lane	no	no
Tram line	no	yes
Cycle lane	no	no
Pedestrian space width in each side in meters	7	8

Rate from 1 to 5 how acceptable is this design for you? *

	1	2	3	4	5	
Fully unacceptable	○	○	○	○	○	Fully acceptable

Figure 14: Sample page from the survey form about social acceptance (in English)

[3] Link of the Google Forms: www.google.com/forms

2.3.3 Social acceptance models

Each of the 131 respondents rated acceptance at most 12 times. The total number of observations was equal to 1572; 45.0% of respondents were male and 54.2% were female. 65 out of 131 respondents belong to the age group 21-30 years old; the next group i.e., 31 – 40 years old reports a percentage that is equal to 36.6%. In total, only 3 persons were above 65 years old, while the remaining groups comprise 11.5% of the sample population. Higher variance is reported in the variable that refers to road user types. Indeed, 51 and 52 out of 131 respondents are daily public transport and car users. The remaining individuals commute either by motorcycle, bicycle, or walking. In general, respondents tended to avoid extreme values, namely: unacceptable (1) and fully acceptable (5). Yet, there were some noticeable differences in the rates provided by each road user group. That is why, in the modeling process, interaction effects were considered. Interaction effects contribute to exploring the systematic variation of tastes, while with the use of random beta variables, the unobserved variation of tastes is examined too. As was reported in the data, the addition of a tram line and the installation of a cycle lane seem to be two controversial parameters with significant interaction effects. Two thousand Halton random draws were used to estimate the social acceptance model. The model outputs are presented in **Table 4**. In **Equation 3** the general model formulas are provided.

$$acc_{i,j}^{*}=\begin{cases}-0.228*\left(\frac{L}{uf_i}\times\left[1+0.15\times\left(\frac{v}{n_i\ \times 1200}\right)^4\right]-\ t_{present}\right)-0.089\times \mathrm{tw_i}+\ 0.582\times bus_i+\ 0.659\times tram_i \\ \quad +1.158\times cycle_i-0.248\times ped_i, \qquad for\ vulnerable\ road\ users \\ -0.228\times\left(\frac{L}{uf_i}\times\left[1+0.15\times\left(\frac{v}{n_i\ \times\ 1200}\right)^4\right]-\ t_{present}\right)-0.089\times \mathrm{tw_i}+0.582\times bus_i+\ 0.201\times tram_i \\ \quad +0.718\times cycle_i-0.248\times ped_i, \qquad for\ public\ trasnport\ users \\ -0.228\times\left(\frac{L}{uf_i}*\left[1+0.15\times\left(\frac{v}{n_i\ *\ 1200}\right)^4\right]-\ t_{present}\right)-0.089\times \mathrm{tw_i}+0.582\times bus_i+\ 0.332\times tram_i \\ \quad +0.710\times cycle_i-0.248\times ped_i, \qquad for\ car\ users\end{cases}$$

$$with\ \beta_{delay}\sim N(-0.228,0.191)\ and\ \beta_{ped}\sim N(-0.248,0.410) \qquad (\mathbf{3})$$

As can be seen, the installation of a bus lane and mean waiting time at bus stops are statistically significant variables with no difference among user groups for a confidence interval higher than 95%. The last variable reports an inverse relationship with the dependent (latent) variable; this was not something unexpected. Furthermore, all road users seem to agree with the installation of a uni-directional cycle lane in this arterial, since this parameter is positive in all cases. Nevertheless, VRUs seem to have a stronger preference over the construction of cycling infrastructure on Panepistimiou Avenue. The introduction of a tram line does not lead to noticeably higher social acceptance both of public transport and car users, in comparison to VRUs. This is proved by the negative interaction effects, where their values are almost similar. For a confidence interval higher than 99%, traffic delay is a statistically significant variable. It was surprising that the parameter referring to sidewalks' extension has a negative sign as well. The standard deviations of the previously mentioned beta parameters are statistically significant. This proves the existence of heterogeneity in the opinions of individuals.

Table 4: Social acceptance ordinal models
Source: (Tzamourani et al., 2022); own elaboration, 2023

	Estimate	Std. error	z-value	P (>|z|)
Beta values of non-random variables				
With bus lane (yes = 1)	0.582	0.096	6.023	< 0.001
With tram line (yes = 1)	0.659	0.181	3.652	< 0.001
With uni-directional cycle lane (yes = 1)	1.158	0.187	6.197	< 0.001
Mean PT waiting time in minutes	-0.089	0.015	-5.757	< 0.001
Interaction effects of non-random variables				
With tram line (yes = 1) * Car users (yes = 1)	-0.337	0.220	-1.533	0.125
With tram line (yes = 1) * PT users (yes = 1)	-0.458	0.220	-2.081	0.037
With cycle lane (yes = 1) * Car users (yes = 1)	-0.448	0.222	-2.021	0.043
With cycle lane (yes = 1) * PT users (yes = 1)	-0.440	0.222	-1.981	0.047
Mean beta values of random variables				
Traffic delay in minutes	-0.228	0.024	-9.390	< 0.001
Increase of pedestrian area (yes = 1)	-0.248	0.102	-2.435	0.015
Standard deviation of random variables				
Traffic delay in minutes	0.191	0.018	10.432	< 0.001
Increase of pedestrian area (yes = 1)	0.410	0.161	2.551	0.011
Thresholds				
kappa 1	-2.905	0.177	-16.392	< 0.001
kappa 2	-1.240	0.121	-10.247	< 0.001
kappa 3	0.079	0.007	11.286	< 0.001
kappa 4	1.777	0.092	19.261	< 0.001
Number of observations	1572			
Number of individuals	131			
Null Loglikelihood (with zero coefficients)	-2815			
Loglikelihood at convergence	-2247			

To test the social acceptance of the shared space, some extreme scenarios for Panepistimiou Avenue are prepared. All of them refer to the reduction of traffic lanes from 6 to 2. So, in the first scenario, all transport modes coexist in a corridor of two traffic lanes. The pedestrian space is extended and no dedicated infrastructure both for bicycles and public transport is provided. As a result, the pedestrian safe space is extended. To ensure safe coexistence among road users, the speed limit is reduced to 30 km/h. In all cases, it is assumed that car drivers fully respect the established speed limit. In scenario 2, a cycle lane is installed, while the speed limit is set to be equal to 50 km/h. In scenario 3, the road space of Panepistimiou Avenue is utilized in order to construct exclusive (or semi-exclusive) corridors for each transport mode. Therefore, a tram line is installed, while the speed limit is increased to 70 km/h. In all the cases, the probability that a design will be rated with a score higher than or equal to 3 is estimated. In an ordinal logit model, this probability can be calculated by the following equation:

$$P\left(acc^*_{i,j} > -1.240\right) = \frac{\exp\left(acc^*_{i,j} - (-1.240)\right)}{1 + \exp\left(acc^*_{i,j} - (-1.240)\right)} \qquad \textbf{(4)}$$

The acceptability of each design is evaluated by considering various demand scenarios that are simulated. More specifically, a range of motorized traffic volume from 0 to 7200 pcu/h, which is approximately the capacity of a 6-lane arterial is utilized. The outputs of this process are presented in **Figure 15**. As can be seen, daily VRUs tend to demand road designs that segregate traffic flows and reduce the number of unsafe (according to their perceptions) interactions. If the traffic volume is below 2000 pcu/h, car, and public transport users are willing to accept designs of Panepistimiou Avenue with two traffic lanes and a uni-directional cycle lane by a percentage higher than 75%. Yet, as the traffic volume increases and the delays rise as well, the social of 2-lane designs drop significantly. Shared space in an arterial with 7 m wide sidewalks reports low social acceptance (i.e., not higher than 50%) considering all traffic volume levels. There is a general agreement on this among road users.

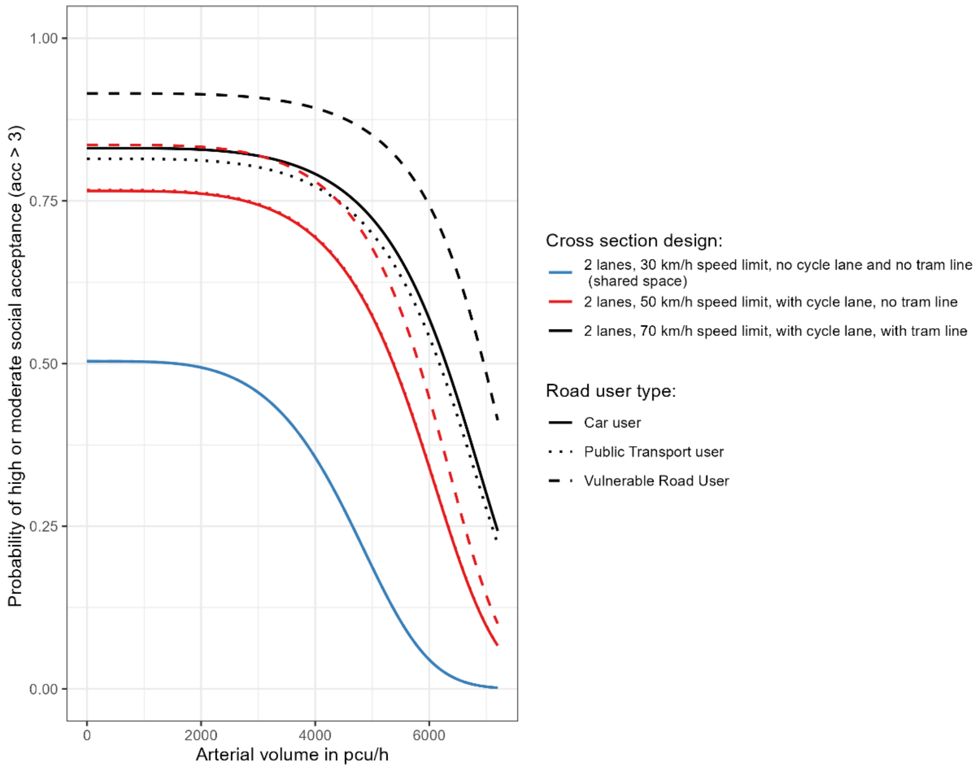

Figure 15: Social acceptance model prediction outputs; assessment of three alternative designs in Panepistimiou Ave.

2.4 Discussion

In this chapter, an SLR, a Q-method experiment with experts, and a Stated Preferences Experiment with the public were conducted in order to better define shared space and assess its potential. This chapter dealt with the Future Urban Road showing that shared space is a major transforming concept that creates significant contradictions and theoretical discussion regarding its social acceptance.

The Systematic Literature Review identified 28 transforming concepts; their objectives seem to significantly differ. This signifies that the Future Urban Road has a multitude of diverse elements.

Shared space presents some noticeable contradictions with concepts that object to segregating traffic flows like multimodal corridors or bus priority lanes, while it presents similarities with concepts that support mixed traffic road environments with lower traffic speeds, i.e., 30 km/h speed limit. Compared to traffic calming measures that aim to decrease traffic speeds and flows, shared space invites road users to safely coexist in the same road environment. According to this concept, mutual understanding and interactions will be the major driving forces, so that traffic speeds will be decreased in home zones and other public spaces too. Shared space can be considered as a Crosswalk Anywhere scenario, as in reality, the various traffic flows seem to informally follow different channels. A noticeable difference between shared space with this scenario is the existence of activity zones where people can also socialize and spend time. Therefore, shared space as a concept aspires to create road environments that are less car-dominated and more human-oriented.

Among European experts, one group defined as Unconventionalists seems to fully support this concept and its assumptions. According to their views, shared space is a way to create less dystopic road environments in the future, when autonomous vehicles will have fully replaced conventional private cars. It is also a way to guide technology developments towards systems that will be able to cope with complex interactions occurring in shared space. People-First Techno-Centrists think that new technologies will decisively contribute to the creation of human-oriented environments compared to road design concepts. Autonomous Vehicles Sceptics strongly disagree with the last view, while Infrastructurists are in favor of concepts that fully segregate traffic flows. Based on this discussion, three dilemmas arise, namely: a) prioritization of modes? Human first or not? b) Share or segregate and therefore regulate or not and c) design systems or roads? All of them are related to the shared space concept. This conclusion underlines the potential of shared space to fully transform urban in either a negative or positive way.

This discussion was extended in the third part of this chapter considering the public. Particularly, the second dilemma which refers to a fair road space allocation was examined in an extreme case, i.e., Panepistimiou Avenue, by measuring the social acceptance of various road designs. A promising outcome is that respondents coming from various user groups highly ranked designs that contained the installation of a unidirectional cycle lane in Panepistimiou Avenue. In arterials with heavy traffic, the results also show that any increase in a pedestrian area that is already sufficiently wide influences social acceptance. The decrease in traffic lanes and the establishment of lower speed limits will result in higher delays if the demand remains constant (i.e., quite probable case in the short term). Instead of increasing pedestrian space and creating a human-oriented road environment, people are willing to accept designs that propose the construction of new infrastructure in the form of exclusive or semi-exclusive corridors that can reinforce both the safety and efficiency of the transport system. This scenario is feasible in wide traffic corridors with high space availability.

3 Analysis of traffic dynamics – Coexistence

The third chapter is fully based on the concept of Coexistence. More specifically, it empirically investigates whether the coexistence of various road users in the same road environment is feasible. Additionally, it aspires to predict the impacts of coexistence in traffic behavior. In this analysis, vehicles and pedestrians are the main players of the game. Therefore, coexistence is given by two relative indicators: a) the pedestrian crossing rate and b) the speed compliance. The first variable quantitively describes the freedom pedestrians may feel to cross more, while the second one is related to the effectiveness of this controversial design to trigger compliant driving behavior and calm traffic speeds. To answer all these intriguing research questions, findings from previous cases and data from four (new) different cases are considered and discussed at the end of this chapter.

3.1 Previous cases

Various intriguing cases can be used to test some of the primary assumptions of shared space. A comparative before-after analysis is a typical approach to identify differences in road users' behavior and traffic conditions in general. All cases are presented in summary in **Table 5**.

The Laweiplein Roundabout[4], Drachten in the Netherlands is a major intersection channeling about 22.000 vehicles per day. After many years of discussion, it was redesigned in 2002 as a shared space (Gerlach and Methorst, 2009; Methorst et al., 2007). Empirical data show that the speed levels of cyclists and vehicles were much steadier, approximately 15 to 25 km/h, after the redesign. Mean travel delays were decreased, although the traffic demand increased. Additionally, the implementation of shared space in this roundabout resulted in a general reduction in waiting time for pedestrians to cross the circulation zone.

Another interesting case is the Skvallertorget Intersection[5], Norrköping in Sweden. It is a shared space intersection constructed back in 2004 (Cheng et al., 2021; Jaredson, 2002). By studying the collected trajectories of road users, it was observed that pedestrians tend to use more direct paths in shared space to reach their destinations. Priority is still negotiable; that is why, traffic speeds were reduced to 16-20 km/h. This is a positive effect of this concept acknowledged by most empirical studies.

Indeed, the implementation of shared space in Exhibition Road[6], London in the UK between 2008 and 2011 led to a lively urban environment surrounded by museums, academic institutions, and other venues. The studies of Kaparias et al. (2016, 2014; 2021; 2020a) underlined the general drop in traffic speeds and flow on this street which resulted in a higher level of service both for vehicles and pedestrians. According to Ruiz-Apilanez et al. (2017), pedestrians in shared space tend to behave more freely and make broader use of the space. The studies of Kaparias et al. (2016) and Woodman et al. (2019) also concluded that pedestrians seem to accept smaller temporal gaps to cross in shared space

[4] Laweiplein Roundabout location on OpenStreetMap: https://www.openstreetmap.org/#map=19/53.10315/6.09851
[5] Skvallertorget Intersection location on OpenStreetMap: https://www.openstreetmap.org/#map=19/58.59030/16.17866
[6] Exhibition Road location on OpenStreetMap: https://www.openstreetmap.org/#map=17/51.49776/-0.17492

compared to a conventional street. This implies pedestrians who belong to vulnerable groups, e.g., elderly people, pedestrians with children, etc. Later, the collected trajectories from Exhibition Road have been utilized for the development of micro-simulation tools (Anvari et al., 2016, 2015).

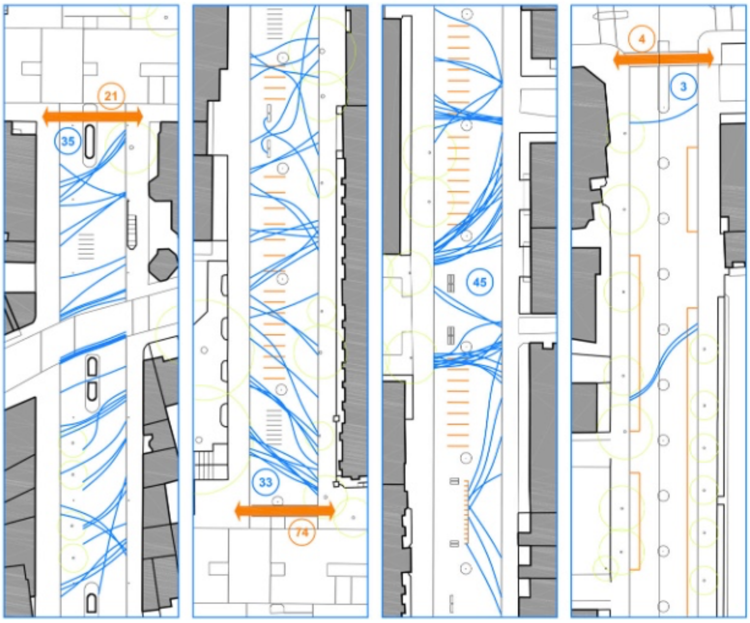

Figure 16: Pedestrians' crossing behavior in four sections of Exhibition Road in London, UK.
Source: (Ruiz-Apilánez et al., 2017)

Elwick Square[7] is a shared space scheme with no street furniture. It is located in Ashford, UK. Moody and Melia (2014) showed that pedestrians tend to walk in the periphery of the square instead of moving freely in it. This is due to the high motorized traffic that dominates this road environment. As a result, pedestrians use specific points to cross the street. This is a contracting finding compared to the previously mentioned cases.

In the shared space of Sonnenfelsplatz Square[8] in Graz, Schönauer et al. (2012b) were fewer stop-and-go situations and steady traffic speeds after the redesign. Crossing movements of pedestrians were comparably shorter and more diverse. This means that VRUs use a variety of locations to cross the square. This confirms the hypothesis that shared space looks more like a crosswalk anywhere scenario.

[7] Elwick Square location on OpenStreetMap: https://www.openstreetmap.org/#map=19/51.14686/0.86957
[8] Sonnenfelsplatz Square location on OpenStreetMap: https://www.openstreetmap.org/#map=19/47.07615/15.45011

Table 5: Summary of previous empirical analyses in shared space streets

Study area	Design features	Traffic conditions	Key findings	Reference(s)
Laweiplein Roundabout, Drachten, Netherlands	Shared space roundabout, continuous surface, courtesy crossings, and road markings	- 22,000 veh/day	Steadier traffic speeds - between 15 to 25 km/h; traffic flow increased but delays reduced; Pedestrians mostly use courtesy crossings.	Methorst et al. (2007) Gerlach and Methorst (2009)
Skvallertorgen Intersection, Norrköping, Sweden	Shared space intersection with no level segregation but with little visual separation, bollards, and benches in some parts.	- 13,000 veh/day	Reduction in traffic speed to 16-20 km/h; Pedestrians use the more direct central path to cross the space.	Jaredson (Jaredson, 2002) Hamilton-Baillie (2008b) Cheng et al. (Cheng et al., 2021)
Exhibition Road, London, UK	One-way street segment with no level segregation; Provision of a safe zone, benches, trees, and bollards in some parts.	- 472 veh/hour in the main section; - 334 ped/hour crossing in the main section.	Mean traffic speed decreased from 40 to 29 km/h in the main section; Traffic flow decreased; Increase in pedestrian crossing points; Slightly longer crossing time and lower crossing speed;	Kaparias et al. (2016, 2014); Anvari et al. (2016); Ruiz-Apilánez et al. (2017); Woodman et al. (2019); Kaparias and Wang (2020a);
Elwick Square, Ashford, UK	Intersection with no level segregation; Provision of courtesy crossings and bollards in some locations.	- 11,000 veh/day; up to 850 veh/hour; - 281 pedestrians during peak traffic	Pedestrians to the sides and crossing mainly using the courtesy crossing (avoiding the circulation area).	Moody and Melia (2014)
Sonnenfelsplatz, Graz, Austria	Intersection with a central round traffic island; No level segregation; Bollards, benches, and trees at the sides.	At midday: - 58 veh/h; - 38 ped/h; - 50 cyclists/h.	More constant low traffic speed (10 km/h); Shorter and more direct road users' paths; Pedestrian crossing at a steady speed.	Schönauer et al. (2012a) Rudloff et al. (2014)
Elliott Street, Auckland, New Zealand	One-way street segment with no level segregation; Provision of a safe zone, benches, trees, and temporary dining tables along one side.	- 1,139 veh/day; - 0.028 ped/m² during peak hours.	Mean traffic speed decreased from 19 to 16 km/h; Traffic flow was reduced by 40%; Strong negative correlation between pedestrian density and mean traffic speed; Pedestrians walked more freely.	Karndacharuk, et al. (2014b)
Lorne Street, Auckland, New Zealand	One-way street segment with no level segregation; Provision of the safe zone and informal outdoor seating on steps.	- 397 veh/day; - 0.027 ped/m² during peak hours.	Mean traffic speed decreased from 31 to 21 km/h; Traffic flow was reduced by 60%; Pedestrian density and occupancy increased; More spread pedestrian movement.	Karndacharuk, et al. (2014b)
Jean Batten Place, Auckland, New Zealand	One-way street segment with no level segregation; Provision of a safe zone, benches, and greenery along one side.	- 2,031 veh/day; - 0.033 ped/m² during peak hours.	Mean traffic speed decreased from 21 to 17 km/h; Traffic flow was reduced by 35%; Pedestrians walked more freely; More diverse stationary pedestrian activity.	Karndacharuk, et al. (2014b)

Karndacharuk et al. (2014b) conducted a before-after analysis on three shared space streets, namely: Elliot Street[9], Lorne Street [10], and Jean Batten Place. The cases are in Auckland, New Zealand. The empirical findings show a negative association between pedestrian density (in p/m²) and mean traffic speed (in km/h). Activities that exist in each street directly influence the crossing behavior of pedestrians and therefore traffic operations. In general, after the redesign, pedestrians felt more comfortable staying and walking along and across the space.

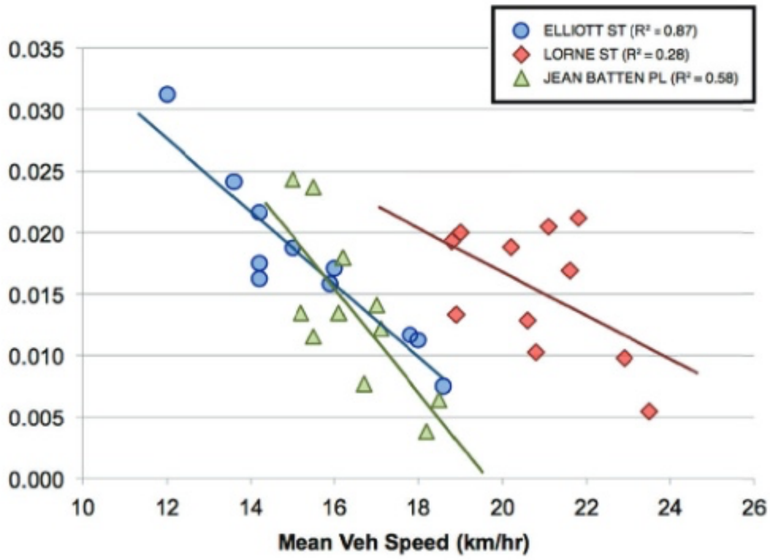

Figure 17: Associations between pedestrian density and mean vehicle speed in New Zealand Cases
Source: (Karndacharuk et al., 2014b)

3.2 Study hypotheses

Respecting the research objective and SRQ3 and SRQ4, the empirical analysis included in this chapter focuses on the problem of coexistence. This problem refers to how the presence of one road user affects the behavior of others. Therefore, it follows a more game theoretic approach to predict the impacts of coexistence at the macro-level (or network level). It utilizes empirical data from four different shared space cases, namely: a) Frankfurter Str. in Bad Rothenfelde [11], b) Lange Str. in Hessisch Oldendorf [12], c) Marktplatz in Königslutter am Elm[13] , and d) Amalias Street in Nafplio[14]. This data is analyzed to investigate six study hypotheses which are:

H1: Pedestrians modify their behavior by crossing more the circulation zone compared to a conventional street design.

H2: Vehicles and pedestrians follow similar paths in shared space.

[9] Elliot Street location on OpenStreetMap: https://www.openstreetmap.org/#map=18/-36.84977/174.76375
[10] Jean Batten Place location on OpenStreetMap: https://www.openstreetmap.org/#map=19/-36.84627/174.76679
[11] Frankfurter Street location on OpenStreetMap: https://www.openstreetmap.org/#map=18/52.10746/8.16162
[12] Lange Street. location on OpenStreetMap: https://www.openstreetmap.org/#map=18/52.16817/9.24980
[13] Markplatz location on OpenStreetMap: https://www.openstreetmap.org/#map=18/52.25022/10.81891
[14] Amalias Street location on OpenStreetMap: https://www.openstreetmap.org/#map=19/37.56608/22.79967

H3: Compared to a conventional road environment, pedestrian crossings in shared space strongly reduce vehicle speeds.

H4: When the vehicle flow approaches to capacity in shared space, there is no difference with a conventional road environment.

H5: As shared space is more an umbrella term, the coexistence of road users is still influenced by the (informal) design of the road.

H6: Coexistence is a feasible scenario. Shared space can create road environments that are less car-dominated and more human-oriented.

To investigate the above hypotheses, the following datasets are required per study cases: pedestrians' flow (H1), pedestrians' crossing flow (H1, H3, H5, H6) and trajectories (H2), vehicle flows (H4, H5) and trajectories (H2), and vehicle speeds (H3, H5, H6). Design characteristics are also necessary to test the fifth hypothesis.

3.3 Study Cases

As it has been mentioned, four different shared space cases are considered in this analysis. Their design characteristics are presented below:

Frankfurter Street is in Bad Rothenfelde, Germany, and was designed as an "encounter zone". The design includes a continuous surface with different paving designating pedestrian zones along both sides of the street. The road is two-way with a circulation zone of 6.0 m. In the target area, the width of the activity zone does not exceed 3.5 m; in the mid-block section, this space is also used as a safe zone for pedestrians' movements.

Table 6: Design characteristics of study cases (zone widths refer only to the target areas)

	Full name	**Speed limit**	**Informal zones**			**Informal segregation**	**Design Elements**
			Circulation	Safe	Activity		
fsbr	Frankfurter Street, Bad Rothenfeld, Germany	20 km/h	6 m. wide (two-way) $s_{circ_j} = 46.2\%$	0 – 3.5 m. wide (both sides) $s_{saf_j} = 0.00\%$	0 – 3.5 m. wide (both sides) $s_{act_j} = 53.8\%$	visual	benches, trees, bollards, parking spaces, courtesy crossings
lsho	Lange Street, Hessisch Oldensorf, Germany	10 km/h	5 m. wide (one-way) $s_{circ_j} = 45.5\%$	1.5 – 3.0 m. wide (both sides) $s_{saf_j} = 27.2\%$	0.0 – 1.5 m. wide (both sides) $s_{act_j} = 27.2\%$	visual	trees and parking spaces
mke	Marktplatz, Königslutter am Elm, Germany	20 km/h	6 m. wide (two-way) $s_{circ_j} = 25.5\%$	3.5 m. wide (one side) $s_{saf_j} = 14.8\%$	square 14 m. wide (one side) $s_{act_j} = 59.5\%$	visual and level	benches, bollards, parking spaces
naf	Amalias Street, Nafplio, Greece	30 km/h	4.5 m. wide (one-way) $s_{circ_j} = 26.4\%$	3.0 m. wide (both sides) $s_{saf_j} = 35.2\%$	3.25 m. wide (both sides) $s_{act_j} = 38.2\%$	level	trees, bollards, parking spaces

Lange Street is located in Hessisch Oldendorf, Germany, and was designed as a "traffic calming zone". The design includes a continuous surface with different paving designating pedestrian zones along both sides of the street. This case refers to a one-way street with a circulation zone of only 3.0 m. Focusing on the target zone where measurements are collected, the pedestrian space (i.e., activity and circulation zone) on each side is 3.0 meters.

Markplatz is located in Königslutter am Elm, Germany, and was designed as a "20 km/h zone. Different paving visually segregates the walking and driving zones and a slight level of segregation is presented in the pedestrian zone. The target area of Marktplatz includes a square of 14 m. wide; this is considered an activity zone. On the other side, the safe zone is approximately 3.5 m. The road is two-way with a circulation zone of 6 m.

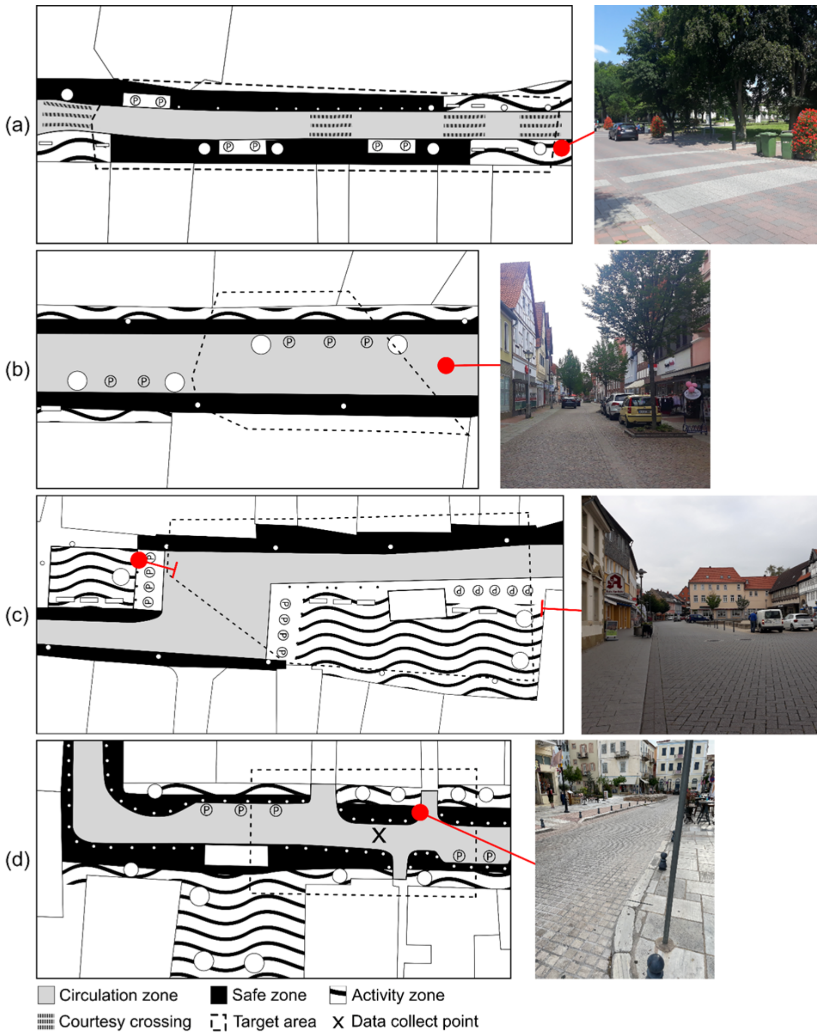

Figure 18: Presentation of study cases: (a) Frankfurter Str., Bad Rothenfeld, Germany, (b) Lange Str., Hessisch Oldensorf, Germany, (c) Marktplatz, Königslutter am Elm, Germany and (d) Amalias Str., Nafplio, Greece.

Amalias Street is located in Nafplio, Greece, and serves as an access street for vehicles to the pedestrianized (historical) city center. It contains two main sections, one with a conventional road design and the other with a shared space design. In the shared space section, the width of the circulation decreases from 7 m to 4.25 m, while the sum of activity and safe zone increases from 3.5 m to 6.25 m. **Table 6** and **Figure 18** summarize the information presented in the previous paragraphs.

3.4 Empirical data collection and analysis

The empirical data analysis utilizes data from two different sources, i.e., (a) camera video recordings from Frankfurter Street, Lange Street, and Markplatz and (b) vehicle detections and classification using traffic radars and manual count by observers in Amalias Street. The overall methodological flow diagram is provided in **Figure 20**. It should be mentioned that in Amalias Street, the data collection process was fully organized by the author of this PhD dissertation, while in the German cases the data were collected by the research of the TU Braunschweig. Both datasets are open and available on the internet by clicking on the following links:

Tzouras, P., Kepaptsoglou, K., Vlahogianni, E. I. (2023). Traffic measurements in Amalias Street. Conventional Road vs Shared Space. Mendeley Data, V2: https://doi.org/10.17632/n3wzjd54pj.2

Batista, M., Trifunović, A., Friedrich, B., (2022). Road users' trajectories in different shared space schemes: https://doi.org/10.24355/dbbs.084-202210281217-0

(a) (b)

Figure 19: (a) Section A: conventional road section and (b) Section B: shared space road section (the black tape line on the curb shows the examined cross-section)

The SDR traffic classifier provided by DataCollect[15] was used in Amalias Street to measure headways between two succesive vehicles and vehicle speeds. Traffic radars can classify vehicles based on their length; the SDR considers four main categories: namely: motorcycle, car, truck, and long

[15] SDR radar traffic classifier: https://datacollect.com/sdr.html

vehicle. The accuracy of speed measurement does not exceed ±1 km/h. In the experiment of Amalias Str., the research team used two traffic classifiers, i.e., one per section of this street (see **Figure 20**). Simultaneously, two observers were manually counting the flow of pedestrians. A black tap line was added to determine the cross-section where measurements are collected. The pedestrian crossing movements were manually counted as well. In this analysis, <u>one pedestrian crossing is considered when a pedestrian leaves the safe (or activity) zone to "touch" the circulation zone</u>. **Figure 18** presents the safe, activity, and circulation zone, as they were determined for each study case. Manual observers reported traffic measurements every two minutes. This fixed time interval was utilized to provide some time for observers to save the data on the database while collecting as many as possible manual observations. This experiment lasted 3.5 hours; thus, the dataset contained 105 manual observations (2-minute time intervals). The data were collected in June 2021, a period right after the national lockdowns of the COVID-19 pandemic. The selected periods were: 11:30-14:00 and 18:00-20:30; these periods are related to the working hours of shops, restaurants, and cafes in the surrounding areas. Besides, one of the main objectives of this data collection process was to observe traffic conditions when the load of pedestrians highly fluctuates.

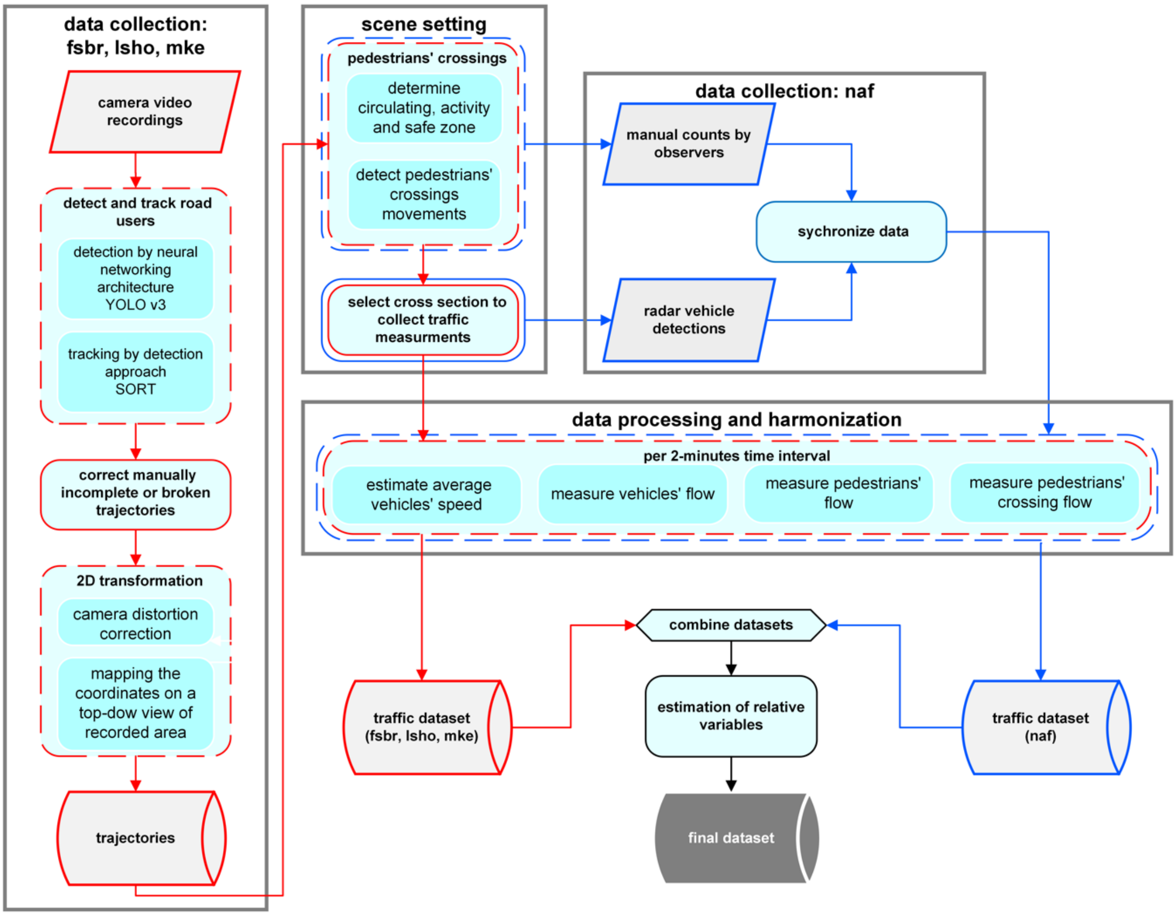

Figure 20: Methodological flow diagram of empirical data collection

In Frankfurter Street, Lange Street, and Marktplatz, a mounted camera on a 5 m. tripod tied to a light pole was used to collect vehicles' and pedestrians' trajectories. This alternatively means the collection of thirty images (or frames) per second which show the position of road users in the entire road environment. For each case, the target area is illustrated in **Figure 19** using a black dashed line. The video recordings were in the morning in the time 09:00 – 11:00 when local shops were open. To extract the trajectories, this study applied a methodology that is particularly described in the study of Trifunović et al. (2021); it combines computer vision tools to automatically map the location of road users. More specifically, the detection of moving objects in the road environment is achieved using YOLO (You-Only-Look-Once) algorithm. Machine learning algorithms that use (Bayesian) neural networks are utilized to classify the detected objects. Additionally, the SORT tracking software is used to track the moving object and therefore collect the trajectories. A manual correction process was done by the research team of the TU Braunschweig to delete incorrect or broken trajectories. The last step refers to the conversion of the image coordinates into real word coordinates. Camera distortion was considered as well. This conversion is achieved through a distortion matrix. The result of this process is the trajectories of road users in a top-down view of the target area.

The virtual space of Frankfurter Street, Lange Street, and Marktplatz was divided into zones to collect flow and speed measurements by developing tools in Python. The speed of one moving object can be accurately estimated by the location of its difference from one frame to another. To measure flows, a cross-section should be virtually defined. The zone division allowed the detection of crossing movements based on the principles applied in the experiment on Amalias Street. To synchronize all the data sources, a fixed time interval of 2 minutes was used as a "global" time step. Therefore, one observation in this analysis refers to the traffic conditions that occurred in these 2 minutes. Traffic conditions are described by four main variables, namely: average vehicle speed in km/h, and flow of vehicles.

The data analysis consists of four main stages, namely: 1) estimation of descriptive statistics, 2) data visualization and identification of potential correlations, 3) development of multiple linear regression models, and 4) utilization of model outputs and simulation. The quality of the dataset is evaluated in the first step by calculating the mean, standard deviation, median, min, and max value of each observed variable. Simultaneously, a Shapiro–Wilk test is conducted to evaluate the normality of each continuous variable. A non-parametric Wilcoxon rank-sum test for the non-normally distributed variables and an (unpaired) t-student test for the normally distributed ones is conducted to assess the significance of traffic parameter differences (Xia, 2020). Advanced data visualization techniques that combine various plots are used in this chapter to interpret some of the major trends appearing in the dataset. A Kendal rank correlation test is used to test the significance of these relationships considering a 95% confidence interval. Yet, the multicollinearities are checked in all the developed models based on the Variance Inflation Factor. This factor quantifies the severity of the multicollinearity problem by indicating how many times the predictor is larger compared to the case that the predictor had zero correlations with others. Nevertheless, the multiple linear regression method is used to investigate the hypothesis of the form: "the more X, the more or less Y" (Best and Wolf, 2015). This method uses the Ordinary Least Square (OLS) method to create linear empirical models based on which predictions can be made. Yet, the OLS method is based on a set of six assumptions that should be met. One of them is the absence of multicollinearities. The other five assumptions are: a) the relationships between the y-variable and x-variable are not linear (global stat), b) the distribution of residuals is skewed either positively or negatively (skewness), c) the distribution of residuals is leptokurtic or platykurtic (kurtosis), d) the dependent variable is categorical (link function), e) and the residuals are heteroscedastic (heteroskedasticity) (Peña and Slate, 2006). Mathematical transformation based on a Box–Cox statistical test should be applied to the dependent variable. The main criterion lies in the λ parameter. If this parameter tends to 1, then no mathematical transformation is necessary. Otherwise, a value equal to 0 indicates that the natural log transformation should be preferred.

3.5 Analysis of empirical data and assessment

Two separate empirical analyses are performed in this section. The objective of the first one is to evaluate the performance of a shared space design in comparison to a conventional road design. The second empirical analysis evaluates various shared space configurations both in Greece and Germany.

3.5.1 Shared space vs conventional road design

The quantitative comparison between a shared space section and a conventional road section is performed in Amalias Street based on 98 and 100 forms which were manually collected per section, respectively. As has been mentioned, Amalias Street contains both designs, i.e., Section A: Conventional Road Section. **Table 7** presents the descriptive statistics of the observed variables per section. Overall, a higher mean pedestrian flow by +3.61 peds/2 minutes was observed in the shared space section of this street. In Section B, the maximum value reached 53 peds/2 minutes. By performing a Wilcoxon signed-rank test (non-normally distributed variables), the previously mentioned difference is proved significant for a confidence interval of 95%. Consequently, an increased number of pedestrians' crossings by 2.13 cross/2 minutes was observed in the shared space section. This difference is statistically significant too. **Figure 21**: Visualization of statistical relationship between pedestrian volume, crossings, and car speeds in conventional road section and shared space section**Figure 21** visualizes the relationships between pedestrian flow (y-axis) and crossings (x-axis) per section. There is a positive association between these two factors with a similar R-squared, i.e., 0.46.

Regarding the data collected by the radar detectors, the headway between vehicles seems to be longer in the shared space section. The median measured value is higher by almost 4 seconds in Section B in comparison to Section A. The observed headways were not normally distributed, as was expected. Yet, the difference between the two sections is statically significant for a 99% confidence interval. In Section A, car drivers followed higher speeds; the mean values differ by +4.24 km/h. Simultaneously, the standard deviation and the range of the recorded speeds are lower in the shared space section compared to the conventional road section. In **Figure 21**, the relationship between vehicle speeds and pedestrian crossings is presented too; a statistically negative correlation (with R-squared equal to -0.22) is detected in Section B. The analysis does not consider other vehicle types, e.g., moto, truck, and long since this assumption would influence the validity of the previously mentioned observations.

Based on the previously mentioned observations, two models per section are developed. The first one estimates the number of pedestrian crossings as a factor of pedestrians' flow (or volume) and measured vehicle headway. The second one predicts the average car speed per 2-minute interval using the number of pedestrian crossings and the average headway.

Table 7: Descriptive statistics - Amalias Street dataset

	Descriptive statistics						**Shapiro - Wilk test**		**Wilcoxon signed-rank test**	
	N	**mean**	**std. dev**	**median**	**min**	**max**	**W**	**p-value**	**w**	**p-value**
Pedestrian volume in peds/2 minutes IN shared space section	98	14.48	8.9	13	2	53	0.861	< 0.001		
Pedestrian volume in peds/2 minutes IN conventional road section	100	10.87	4.53	10	2	26	0.954	0.002		
Difference in pedestrian volumes (shared space - conventional road section)		3.61							3750.5	0.004
Pedestrian crossings in cross/2 minutes IN shared space section	98	4.17	2.38	4	1	14	0.906	< 0.001		
Pedestrian crossings in cross/2 minutes IN conventional road section	100	2.04	1.42	2	0	5	0.924	< 0.001		
Difference in pedestrian crossings (shared space - conventional road section)		2.13							7657.5	0.004
Vehicle headway in seconds IN shared space section	270	23.57	13.75	21	59	6	0.923	< 0.001		
Vehicle headway in seconds IN conventional road section	325	20.59	12.77	17	57	6	0.908	< 0.001		
Difference in vehicle headways (shared space - conventional road section)		2.98							49580	0.006
Car speed in km/h IN shared space section	270	24.29	6.45	24	6	40	0.991	0.133		
Car speed in km/h IN conventional road section	325	28.53	8.62	29	5	55	0.964	< 0.001		
Difference in car speeds (shared space - conventional road section)		-4.24							28101	< 0.001

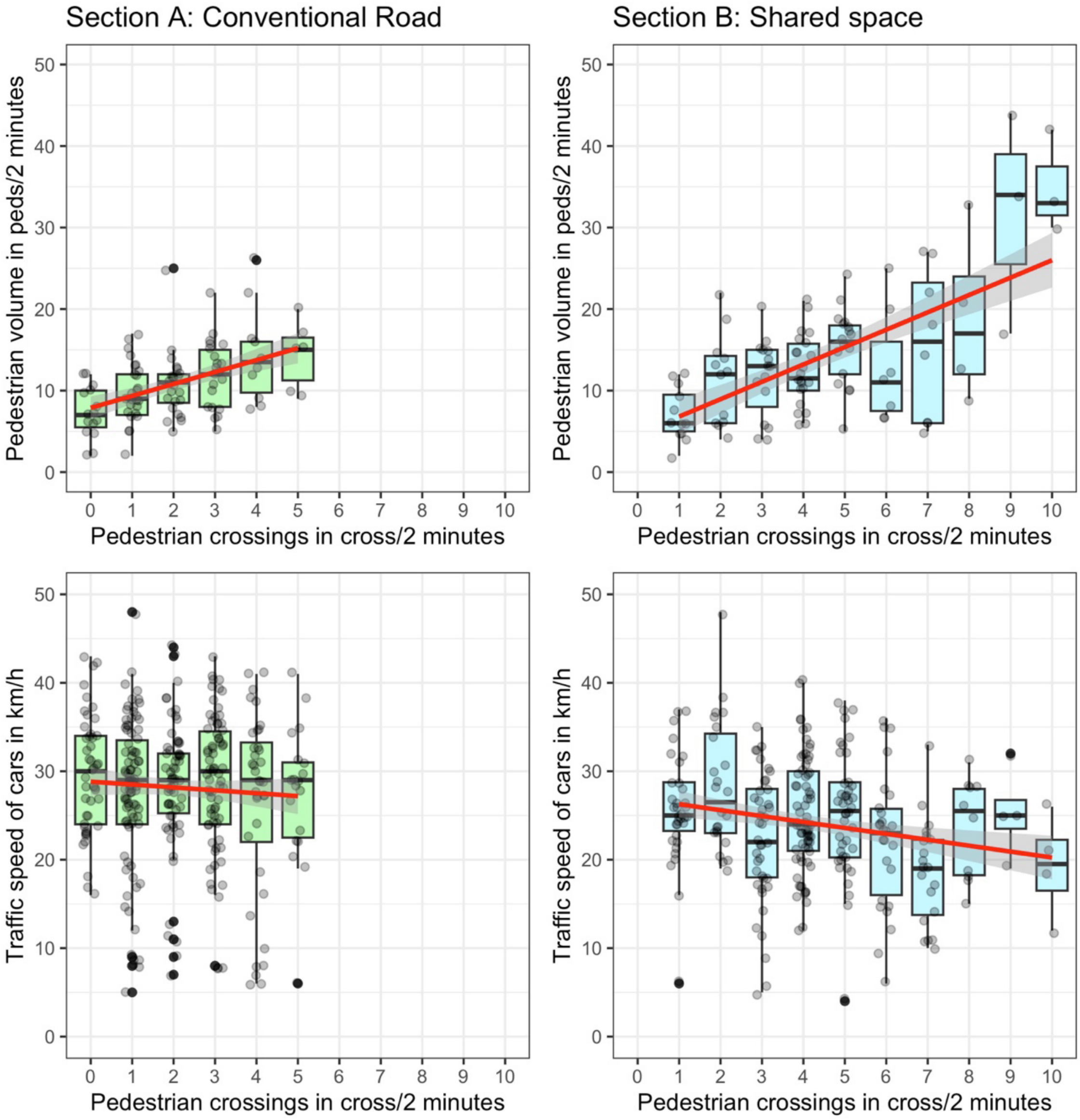

Figure 21: Visualization of statistical relationship between pedestrian volume, crossings, and car speeds in conventional road section and shared space section

The Box-Cox statistical test is applied to select the right mathematical transformation formula. The natural log transformation equation is proved to be the most suitable for pedestrian crossing observations ($\lambda = 0.22$). However, the dependent variable contains zero values, which means infinity by applying this transformation. This problem is overcome by adding a constant α that is equal to 1. In the pedestrian crossing model, the intercept was selected to be fixed to zero. This assumption seems to be reasonable, as a zero headway between vehicles does not provide any chance for pedestrians to cross. At the same time, if the flow of pedestrians is zero, then no crossings will be observed (see **Equation 5**).

$$\log(a + cr) = \log(1 + cr) = f\left(ped, \bar{h}\right), \quad where\ f\ linear\ regression\ model \quad \mathbf{(5)}$$

where:

cr: pedestrian crossing rate in cross/2 minutes,

ped: pedestrian volume in peds/2 minutes,
$\bar{h}$: mean vehicle headway in minutes.

The pedestrian volume is a statistically significant parameter with a positive sign in both sections, as was expected. The vehicle headway as a parameter seems to be more determinant when speaking about pedestrian crossings. Indeed, in shared space, 30 seconds longer headway between two consecutive vehicles leads to almost 1.8 more pedestrian crossings considering a 2-minute interval. In Section A, this ratio is equal to 0.436. Of course, in all cases, the vehicle headway is the statistically significant parameter with a positive sign. Both models report high goodness of fit, yet this is related to the absence of intercept parameters. According to the outputs from the glvma package, all linear regression assumptions were met. The absence of multicollinearities in both models is confirmed by the VIF values which are lower than 1.1. Below, the equation of the pedestrian crossing model is provided (see **equation 6**). The general model outputs are given in **Figure 22**.

$$\boldsymbol{cr} = \boldsymbol{f}(\boldsymbol{ped}, \boldsymbol{h}) = \begin{cases} \exp\left(0.059 \times ped + 0.789 \times \bar{h}\right) - 1, & if\ section\ A: conventional\ road \\ \exp\left(0.070 \times ped + 0.952 \times \bar{h}\right) - 1, & if\ section\ B: shared\ space \end{cases} \quad (\boldsymbol{6})$$

<u>where:</u>
cr: pedestrian crossing rate in cross/2 minutes,
$ped \in [2, 53]$: pedestrian volume in peds/2 minutes,
$\bar{h} \in [0, 1]$: mean vehicle headway in minutes.

In the second set of models, the mean vehicle headway per 2-minute intervals and not the measure one is utilized, because these models predict the average car speed in this interval. In other words, average numbers are used to "feed" the estimation process. No other mathematical transformation is performed in this case. In the conventional road section, all selected factors proved to be insignificant. An insignificant F-statistic model was also reported. This means that the estimated model is not significantly different than an intercept-only model. On the contrary, in shared space, both factors are significant considering a 95% confidence interval. Yet, the multiple and the adjusted R-squared are below 0.10; this indicates a considerably low goodness of fit. Considering a 2-minute interval, 10 more pedestrian crossings can result in a decrease of 6.50 km/h in average car speed. Additionally, every extra minute in mean headway leads to an approximately 4.2 km/h increase in average car speed. **Equation 7** gives the empirical model functions, while **Figure 22** the outputs of the multiple linear regression process are provided. Last, the VIF values are equal to 1; this indicates the absence of serious multicollinearities.

$$\boldsymbol{v} = \boldsymbol{f}(\boldsymbol{cr}, \boldsymbol{h}) = \begin{cases} 28.757, & if\ section\ A: conventional\ road \\ 25.437 - 0.650 \times cr + 4.159 \times h, & if\ section\ B: shared\ space \end{cases} \quad (7)$$

<u>where:</u>
v: average car speed in km/h (considering a 2-minute interval),

$cr \in [0, 14]$: pedestrian crossing rate in cross/2 minutes,

$h \in [0, 1]$: measured headway between two consecutive vehicles in minutes.

Table 8: Developed empirical models - conventional road vs shared space.

	Point A: Conventional Road section				**Point B: Shared space section**			
	Estimate	**St. Error**	**p-value**	**VIF**	**Estimate**	**St. Error**	**p-value**	**VIF**
A. Empirical model of pedestrian crossings								
<u>Coefficients</u>								
Intercept	0.000				0.000			
Pedestrian volume (peds/2 minutes)	0.059	0.006	< 0.001	1.000	0.070	0.004	< 0.001	1.043
Mean vehicle headway (minutes)	0.789	0.174	< 0.001	1.000	0.952	0.130	< 0.001	1.043
<u>Regression statistics</u>								
Degrees of freedom	86				91			
Residuals standard error	0.511				0.461			
Multiple R-squared	0.823				0.918			
Adjusted R-squared	0.819				0.916			
F-statistic	227.9		< 0.001		513.6		< 0.001	
<u>Assumptions</u>								
Global Stat (i.e., linearity)	3.267		0.514		6.162		0.187	
Skewness of residuals' distribution	0.372		0.542		3.002		0.083	
Kurtosis of residuals' distribution	1.836		0.175		2.150		0.142	
Link function	0.189		0.664		0.332		0.564	
Heteroscedasticity	0.870		0.351		0.677		0.410	
B. Empirical model of average car speed								
<u>Coefficients</u>								
Intercept	28.757	1.150	< 0.001		25.322	1.085	< 0.001	
Pedestrian crossing rate (cross/2 minutes)	-0.223	0.337	0.509	1.000	-0.650	0.174	< 0.001	1.000
Measured vehicle headway (minutes)	0.696	2.255	0.758	1.000	4.159	1.724	0.016	1.000
<u>Regression statistics</u>								
Degrees of freedom	322				271			
Residuals standard error	8.632				6.513			
Multiple R-squared	0.001				0.068			
Adjusted R-squared	-0.004				0.061			
F-statistic	0.267		0.7657		9.947		< 0.001	
<u>Assumptions</u>								
Global Stat (i.e. linearity)	0.204		< 0.001		3.629		0.458	
Skewness of residuals' distribution	6.611		0.010		0.003		0.958	
Kurtosis of residuals' distribution	0.117		< 0.001		0.010		0.920	
Link function	< 0.001		0.999		0.151		0.697	
Heteroscedasticity	2.711		0.099		3.465		0.062	

To extend the model outputs and highlight the difference in traffic behavior between the two sections, the following functions are plotted (see **Equations 8 and 9**). **Figure 22** gives the result of this in-depth analysis of Amalias Street. High volumes of pedestrians, i.e., 40 peds/2 minutes or 1200 peds/h, may potentially create significant decreases in average speed, i.e., approximately 96.2% to 177.3% lower average car speeds. As in Section A, average speeds are not affected by the flow of pedestrians, the proportional differences seem to be highly influenced by its contribution to traffic operation of shared space. Regarding the pedestrian crossing in shared space, headway is a determinant factor. Longer headways provide more space for pedestrians to cross. Even when the pedestrian volume is low (i.e., less than 15 peds/2 minutes), more crossings are likely to occur in the shared space compared to the conventional road section. Indeed, the crossing rate increases by 277.8% in Section B, when both vehicle and pedestrian traffic flow (i.e., the inverse of mean headway) reach the maximum values of the specified ranges.

$$dcr = exp\left(0.070 \times ped + 0.952 \times \bar{h}\right) - exp\,(0.059 \times ped + 0.789 \times \bar{h}) \quad (8)$$

$$dv = 25.324 - 0.650 \times \left[exp\left(0.070 \times ped + 0.952 \times \bar{h}\right) - 1\right] + 4.159 \times h - 28.757 \quad (9)$$

<u>where:</u>

dcr: difference in pedestrian crossing rate in cross/2 minutes,

dv: difference in mean car speed in km/h.

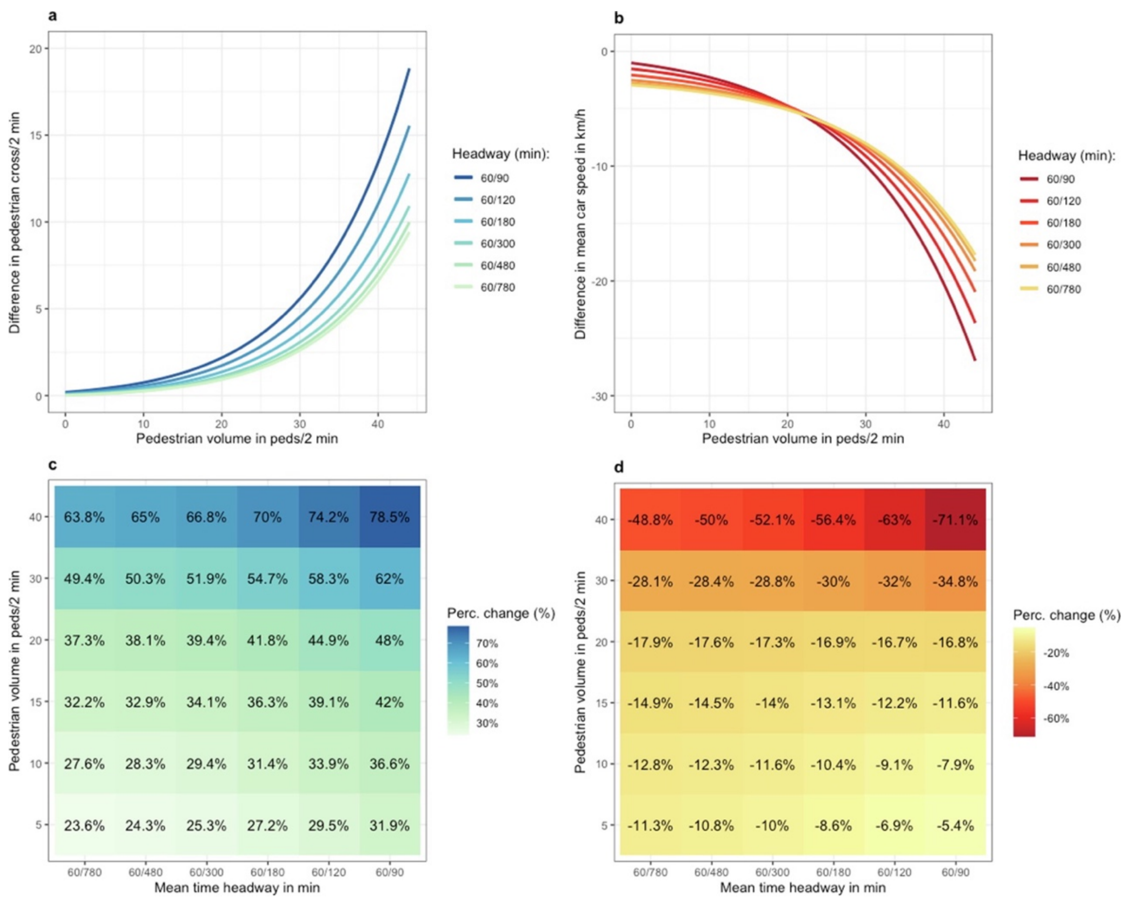

Figure 22: Shared space vs conventional street section
a) difference in pedestrian crossings, b) difference in average car speed, c) percentage change in pedestrian crossings, and d) percentage change in average car speed as a function of pedestrian volume and mean time headway.

3.5.2 Four shared space designs – comparison

The second empirical analysis is based on relative variables. These are used to minimize potential correlations among the explanatory variables. For instance, the flow of pedestrians per time interval relates to the overall demand, which is affected by the activities that appear in the surrounding urban area of each case (Batista et al., 2022; Karndacharuk et al., 2014b). Therefore, the deviations of vehicle and pedestrian flow from the average measure in each case study are estimated. These new variables are defined by **Equations 10 and 11**:

$$dq_{veh_i} = q_{veh_{i,j}} - \overline{q_{veh_j}} \quad (10), \quad dq_{ped_i} = q_{ped_{i,j}} - \overline{q_{ped_j}} \quad (11)$$

where:

dq_{veh_i}: deviation of vehicle traffic flow in the 2-minute time interval i in veh/2minutes or veh/h,

dq_{ped_i}: deviation of pedestrian traffic flow in the 2-minute time interval i in ped/2minutes or ped/h,

$q_{veh_{i,j}}$: vehicle traffic flow in 2-minute time interval i in study case j in veh/2minutes or veh/h,

$\overline{q_{veh_j}}$: mean vehicle flow of study case j in veh/2minutes or veh/h,

$q_{ped_{i,j}}$: pedestrian traffic flow in 2-minute time interval i in study case j in ped/2minutes or ped/h,

$\overline{q_{ped_j}}$: mean pedestrian flow of study case j in ped/2minutes or ped/h.

The pedestrian crossing rate reflects the number of crossings per pedestrian (see **Equation 12**). It gives the willingness of pedestrians to cross the circulation zone and therefore to minimize the distance between their origin and destination points. The ratio of measured speed over the speed limit and the ratio of measured speed over the established speed limit in each street is the speed compliance rate (see **Equation 13**). This ratio is mostly used to evaluate the effectiveness of traffic calming schemes (Domenichini et al., 2018; Gargoum et al., 2016b). Speed deviation is defined as the difference between the average speed per 2-minute time interval and the mean speed estimated in each case considering all time intervals (see **Equation 14**).

$$csr_i = \frac{q_{cs_{i,j}}}{q_{ped_{i,j}}} \quad (12), \qquad cmr_i = \frac{\overline{V_{veh_\iota}}}{V_{\mathrm{lm_j}}} \quad (13)$$

$$dV_{veh_i} = \overline{V_{veh_\iota}} - \overline{V_{veh_j}} \quad (14)$$

where:

csr_i: pedestrian crossing rate in 2-minute time interval i in crossings per pedestrian,

cmr_i: speed compliance rate in 2-minutes time interval i, $if\ cmr_i = 1 \leftrightarrow \overline{V_{veh_\iota}} = V_{lm_j}$,

dV_{veh_i}: deviation of vehicle speed in 2-minute time interval i in km/h,

$q_{cs_{i,j}}$: pedestrian crossing flow in 2-minute time interval i in study case j in cross/2minutes or cross/h,

$\overline{V_{veh_\iota}}$: mean vehicle speed in 2-minute time interval i in km/h,

V_{lm_j}: speed limit of study case j in km/h,

$\overline{V_{veh_j}}$: mean vehicle speed in study case j in km/h.

Table 9: Descriptive statistics – combined dataset

		fsbr	**lsho**	**mke**	**naf**
Mean vehicle speed in km/h (includes vehicle speed deviation values)	N	64	66	65	105
	Mean	16.28	8.94	13.21	25.5
	Std. Dev	2.70	2.04	5.82	5.99
	Min	-5.70	-8.94	-13.21	-14.05
	Max	5.64	5.39	4.55	24.45
Flow of pedestrians in peds/2 -minutes	Mean	9.22	6.20	17.08	14.42
	Std. Dev.	4.33	3.03	5.27	9.07
	Min	3.00	1.00	4.00	2.00
	Max	22.00	16.00	30.00	53.00
Flow of vehicles in veh/2-minutes	Mean	18.09	6.08	4.14	6.56
	Std. Dev.	4.90	2.59	2.28	4.72
	Min	6.00	1.00	0.00	2.00
	Max	28.00	12.00	10.00	25.00
Pedestrian crossing rate in cross/2-minutes	Mean	0.21	0.20	0.29	0.37
	Std. Dev.	0.17	0.19	0.14	0.24
	Min	0.00	0.00	0.00	0.08
	Max	0.80	0.75	0.62	1.40
Speed compliance rate	Mean	0.81	0.91	0.74	0.83
	Std. Dev.	0.13	0.17	0.23	0.20
	Min	0.53	0.45	0.15	0.37
	Max	1.10	1.43	1.30	1.65

The dataset of the second empirical analysis included 105 observations from Amalias Str. (naf), 64 observations from Frankfurter Str. (fsbr), 66 observations from Lange Str. (lsho), 65 observations from Marktplatz (mke). In Amalias Street, only the observations from the shared space section were considered. As it has been reported, the mean value of vehicle speeds in this section has been estimated approximately equal to 25.5 km/h, while the maximum value exceeds 50 km/h. In Lange Street, the mean speed of vehicles is below 10 km/h on average. In Frankfurter Street and Markplatz, higher speeds are reported in the descriptive statistics of the dataset. These are between 13 and 17 km/h. These last streets have similar designs. Yet, there is a high difference in pedestrian flows. Indeed, in Marktplatz, the highest mean and maximum values were measured, i.e., 17.08 and 30.00 peds/2-minutes, respectively. The mean pedestrian flow was equal to 9.22 peds/2 minutes on Frankfurter Street. Yet, the heaviest flow of vehicles of approximately: 6 – 28 veh/2 minutes was reported in this street. In Amalias Street, the pedestrian crossing rate reached its maximum value of 1.4 cross/ped; it has a heavy pedestrian crossing flow. The same was observed in Marktplatz. Regarding speed compliance, this ratio is close to 1 in Lange Street. In Marktplatz, the mean value drops to 0.74. Last, wider ranges of speed deviations are indicated in Amalias Street and Lange Street. The descriptive statistics of the dataset are shown in **Table 9**.

The correlations and their significance among the relative variables are estimated based on a Kendal non-parametric correlation test. In this analysis, space configuration parameters are taken into account. **Table 10** presents the outputs of this analysis. As can be observed, the share of the circulation zone is positively correlated with the speed compliance rate (+0.17) and negatively with the pedestrian crossing rate (-0.31). Speed compliance has a negative and significant covariance with the respective parameter of activity zone (-0.27). The pedestrian crossing rate is positively correlated with the pedestrian crossing rate (+0.23). Vehicle speed deviations do not report any significant correlation with space configuration parameters. Pedestrian and vehicle flow deviation variables have negative and significant correlations with the main dependent variables, namely: pedestrian crossing and speed compliance rate. As it was expected, vehicle speed deviations are significantly correlated with pedestrian flow deviation. The sign of the covariance value is negative.

Table 10: Results of the correlation analysis with Kendall non-parametric test (with * the correlations which are significant for a confidence interval of 95%)

	Share of circulation zone	Share of activity zone	Share of safe zone	Vehicle flow deviation	Pedestrian flow deviation	Vehicle speed deviation	Pedestrian crossing rate	Speed compliance rate
Share of circulation zone	1.00							
Share of activity zone (upper bound)	-0.25*	1.00						
Share of safe zone (lower bound)	-0.50*	-0.71*	1.00					
Vehicle flow deviation	0.00	0.00	0.00	1.00				
Pedestrian flow deviation	0.00	0.00	0.00	0.00	1.00			
Vehicle speed deviation	0.00	0.00	0.00	0.00	-0.11*	1.00		
Pedestrian crossing rate	-0.31*	0.01	0.23*	-0.06*	-0.21*	-0.12*	1.00	
Speed compliance rate	0.17*	-0.27*	0.02	-0.11*	-0.12*	0.75	-0.01	1.00

Some of these relationships are visualized in the next step. In **Figure 24**, there are time series plots and a boxplot that show the impact of pedestrian crossings on vehicle speeds. As can be seen, pedestrian crossing rates that are higher than 1 can cause serious deviations in vehicle speeds. The boxplot proves the increase of speed variance as the pedestrian crossing rate increases.

Figure 25 gives some associations between the relative variables, namely: pedestrian crossing rate vs pedestrian flow and vehicle flow deviations, and speed compliance rate vs pedestrian flow and vehicle flow deviations. The behavioral differences per study case are indicated by plotting a linear trending line. Yet, the relationships do not seem to be linear in all cases. It is noticeable that in Lange Street, as the pedestrian flow increases, the pedestrian crossings tend to raise too. The same occurs in Markplatz, yet in the other two cases, this line has a negative slope. Simultaneously, pedestrian flow increases by 300 ped/h in Lange Street can lead to a decrease of the speed compliance rate below 1. In Markplatz, vehicle flow deviation seems to be a more determinant factor in comparison to the deviation of pedestrian flow. In Frankfurter Street, flow deviations do not influence the behavior of road users, as no significant relationship among the relative variables is reported. Finally, Amalias Street has a high number of outliers. This is due to the high variance in all relative variables.

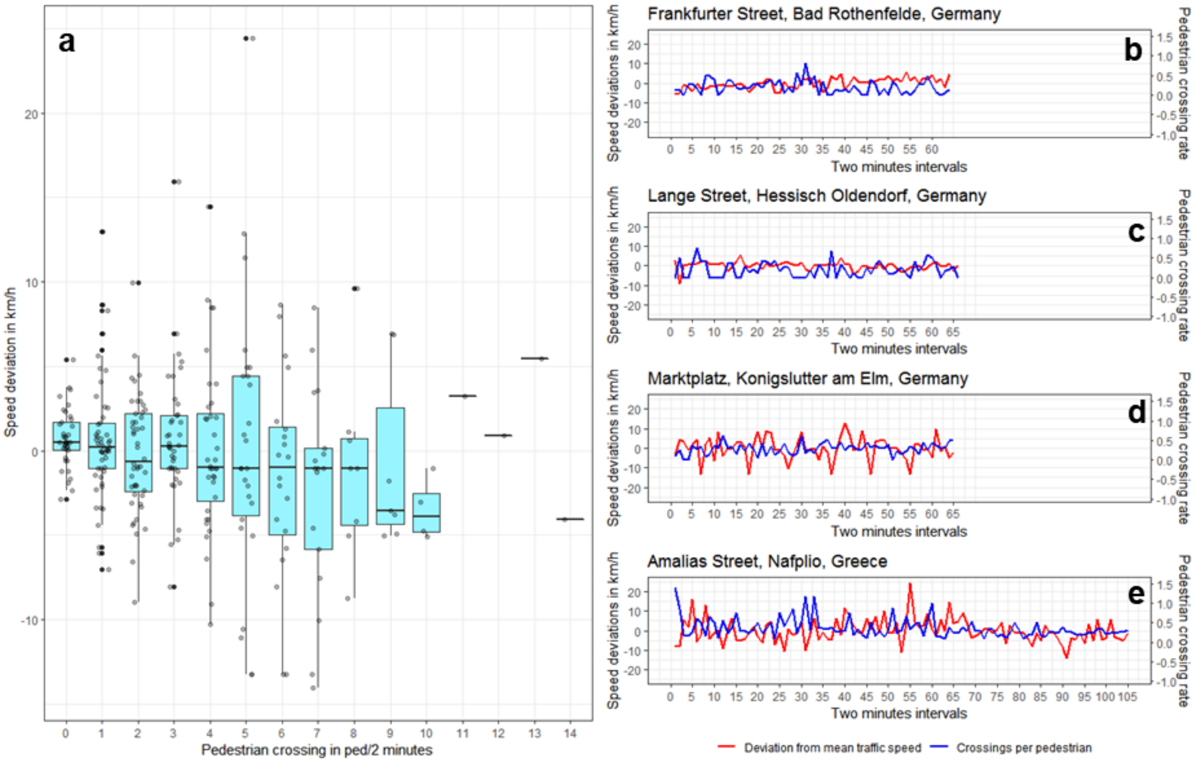

Figure 23: Pedestrian crossing flows vs Vehicle speed Deviations: (a) box-scatter plot considering all cases, time series plot of (b) Frankfurter Str., (c) Lange Str., (d) Marktplatz and (e) Amalias Str.

A mathematical transformation is applied to ensure a linear relationship between the pedestrian crossing rate and flow deviations. The dependent variable is defined as the negative value of the pedestrian crossing rate (see **Equation 15**). According to the multiple linear regression outputs which are shown in **Table 11**, pedestrian crossing rates are influenced by the pedestrian and vehicle traffic flow deviations for a confidence interval of 95%. As there is an inverse relationship between the explanatory variables and the "real" dependent variable, positive signs indicate a negative relationship with flow deviations. The share of the circulation zone is a statistically significant variable with a positive sign as well. Based on the model outputs, the provision of a large safe zone does not impact pedestrian crossing rates considering a confidence interval of 95%. The model reports a residual standard error that is equal to ± 0.1226. Multiple and adjusted R-square are 0.1709 and 0.1594, respectively. Additionally, the results from the F-statistic test prove that the estimated model is better than a zero-coefficient model. No significant multicollinearities were detected. Indeed, the values of VIFs are below 2 in all variables. Lastly, based on the outputs of the analysis using gvlma package, all linear regression assumptions were met excluding only 7 outliers from the estimation process.

$$\frac{1}{\exp(csr)} = f(Q, S), \qquad where\ f\ linear\ regression\ model \quad (15)$$

where:

csr: pedestrian crossing rate in cross/2 minutes

Q: the set of the flow parameters

S: the set of space configuration parameters

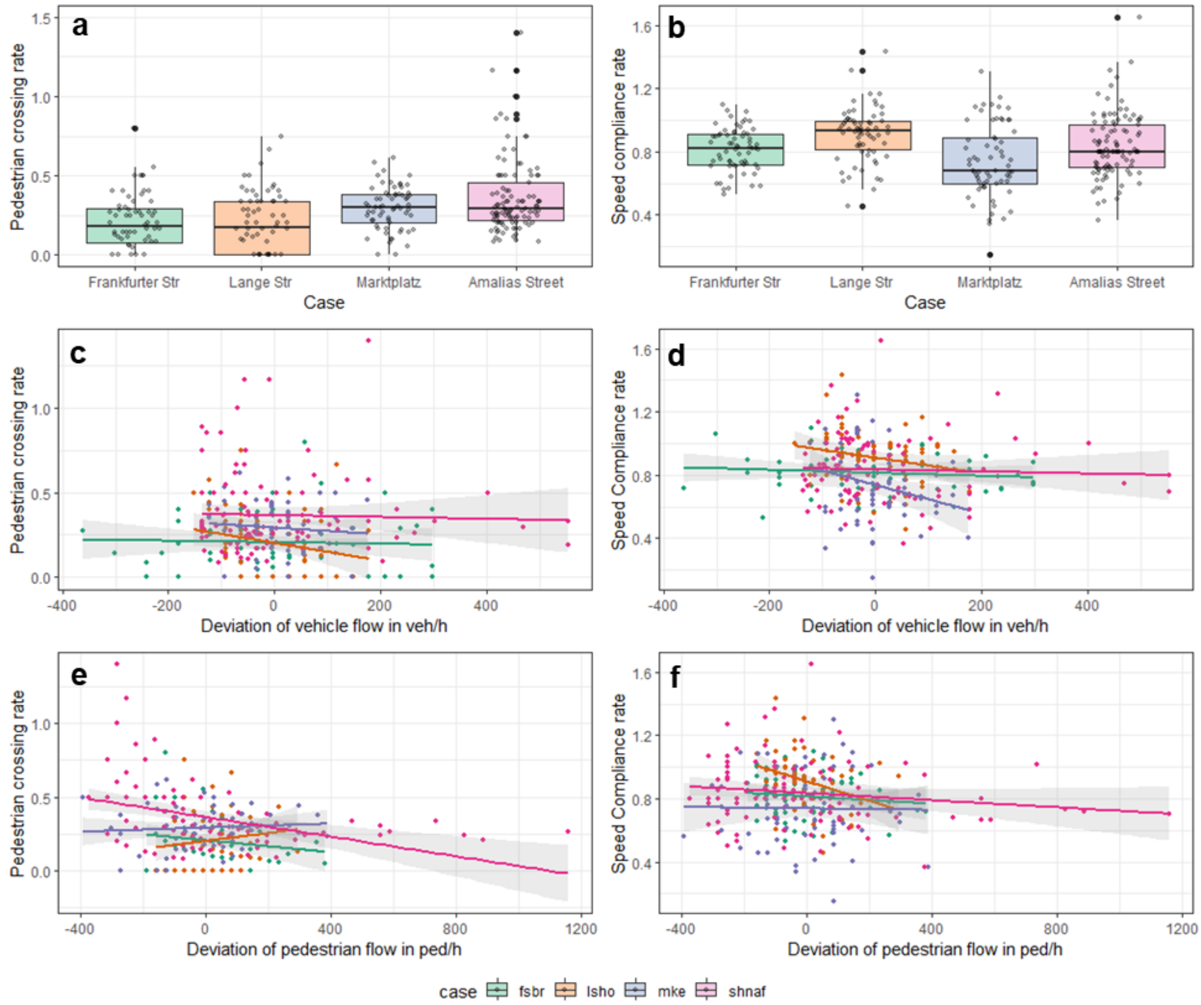

Figure 24: Box Plots of (a) pedestrian crossing rate and (b) speed compliance rate, combined with Scatter Plots of pedestrian crossing rate vs (c) vehicles flow deviation and (e) pedestrian flow deviation, speed compliance rate vs (d) vehicle flow deviation and (f) pedestrians flow deviation.

Table 11 also shows the results of the second regression analysis. Pedestrian and vehicle flow deviations have a negative yet significant contribution to the speed compliance rate. The provision of a larger circulation zone led to higher speed compliance rates. Nevertheless, an informal safe zone instead of an activity zone results in an increase in vehicle speed and consequently speed compliance rates. In this case, the parameter is statistically significant considering the same confidence interval. The prediction error of this model is ± 0.1781. The speed compliance rate model reports lower goodness of fit since multiple and adjusted R-squared are equal to 0.1224 and 0.1104, respectively. The F-statistic test proved that the developed model significantly differs from the zero-coefficient, while all linear regression assumptions were met without excluding observations. The models are presented in the next equations.

$$\frac{1}{\exp(csr_{i,j})} = 0.6331 + 0.0130 \times \frac{dq_{veh_{i,j}}}{100} + 0.0084 * \frac{dq_{ped_{i,j}}}{100} - 0.4677 \times s_{circ_j} - 0.0705 \times s_{saf_j} \leftrightarrow csr_j = -\ln\left(0.6331 + 0.0130 \times \frac{dq_{veh_{i,j}}}{100} + 0.0084 \times \frac{dq_{ped_{i,j}}}{100} - 0.4677 \times s_{circ_j} - 0.0705 * s_{saf_j}\right), \quad if\ s_{circ_j} = 0\ and\ s_{saf_j} = 0, then\ s_{act_j} = 1 \quad (16)$$

$$cmr_{i,j} = 0.5255 - 0.0176 \times \frac{dq_{veh_{i,j}}}{100} - 0.0127 \times \frac{dq_{ped_{i,j}}}{100} - 0.6195 \times s_{circ_j} - 0.3840 \times s_{saf_j}, \quad if\ s_{circ_j} = 0\ and\ s_{saf_j} = 0, then\ s_{act_j} = 1 \quad (17)$$

The notion of coexistence is further investigated in this section based on a simulation of traffic behavior. The developed empirical models are used to predict the behavior of both pedestrians and vehicle drivers in a 15-meter-wide shared space. The test scenarios are 5 and refer to different shared space configurations. For example, in the first one, the entire road space is a circulation zone prioritizing motorized traffic. With the absence of vulnerable road users, vehicle speeds are approximately 1.25 times higher than the selected speed limit. At the same, the pedestrian crossing rate is below 0.5 cross/ped. By defining a better balance in terms of space configuration (i.e., scenarios 2 and 4), speed compliance is approximately equal to 1 considering all variations of traffic flow. The third case is an extreme case in which pedestrians can use the entire road space to safely move. In this scenario, the pedestrian crossing rate reaches its maximum value. Scenario 5 refers to the situation where the entire road space is an activity zone, e.g., a square. Interestingly, there is a high reduction in vehicle speeds. The results of the simulation process are presented in **Figure 25**.

Table 11: Statistical modeling estimation outputs: (a) pedestrian crossing rate model and (b) speed compliance rate model

	Estimate	Std. Error	t-stat	P-value	VIF
A. Pedestrian crossing rate model					
Coefficients					
Intercept	0.6331	0.0380	16.6608	< 0.0001	
0.001 * vehicle traffic flow deviation (in veh/h)	0.0130	0.0062	2.1159	0.0352	1.0006
0.001 * pedestrian traffic flow (in ped/h)	0.0084	0.0062	1.3584	0.0267	1.0000
Share of circulation zone (in %)	0.4677	0.0840	5.5675	< 0.0001	1.3096
Share of safe zone (in %)	-0.0705	0.0612	-1.1530	0.2499	1.3101
Regression statistics					
Degrees of freedom	293				
Residuals standard error	0.1226				
Multiple R-squared	0.1709				
Adjusted R-squared	0.1594				
F-statistic	14.84			< 0.0001	
Assumptions					
Global Stat (i.e., linearity)	8.7812			0.0668	
Skewness of residuals' distribution	1.5151			0.2184	
Kurtosis of residuals' distribution	2.2323			0.1351	
Link function	1.8937			0.1689	
Heteroscedasticity	3.1412			0.0763	
B. Speed compliance rate model					
Coefficients					
Intercept	0.5255	0.0546	9.6220	< 0.0001	
0.001 * vehicle traffic flow deviation (in veh/h)	-0.0176	0.0086	-2.0364	0.0426	1.0001
0.001 * pedestrian traffic flow (in ped/h)	-0.0127	0.0053	-2.3837	0.0178	1.0001
Share of circulation zone (in %)	0.6195	0.1202	5.1528	< 0.0001	1.3346
Share of safe zone (in %)	0.3840	0.0869	4.4194	< 0.0001	1.3346
Regression statistics					
Degrees of freedom	294				
Residuals standard error	0.1781				
Multiple R-squared	0.1224				
Adjusted R-squared	0.1104				
F-statistic	10.18			< 0.0001	
Assumptions					
Global Stat (i.e., linearity)	4.4445			0.3492	
Skewness of residuals' distribution	1.1036			0.2934	
Kurtosis of residuals' distribution	0.2057			0.6501	
Link function	0.1065			0.7441	
Heteroscedasticity	3.0286			0.0818	

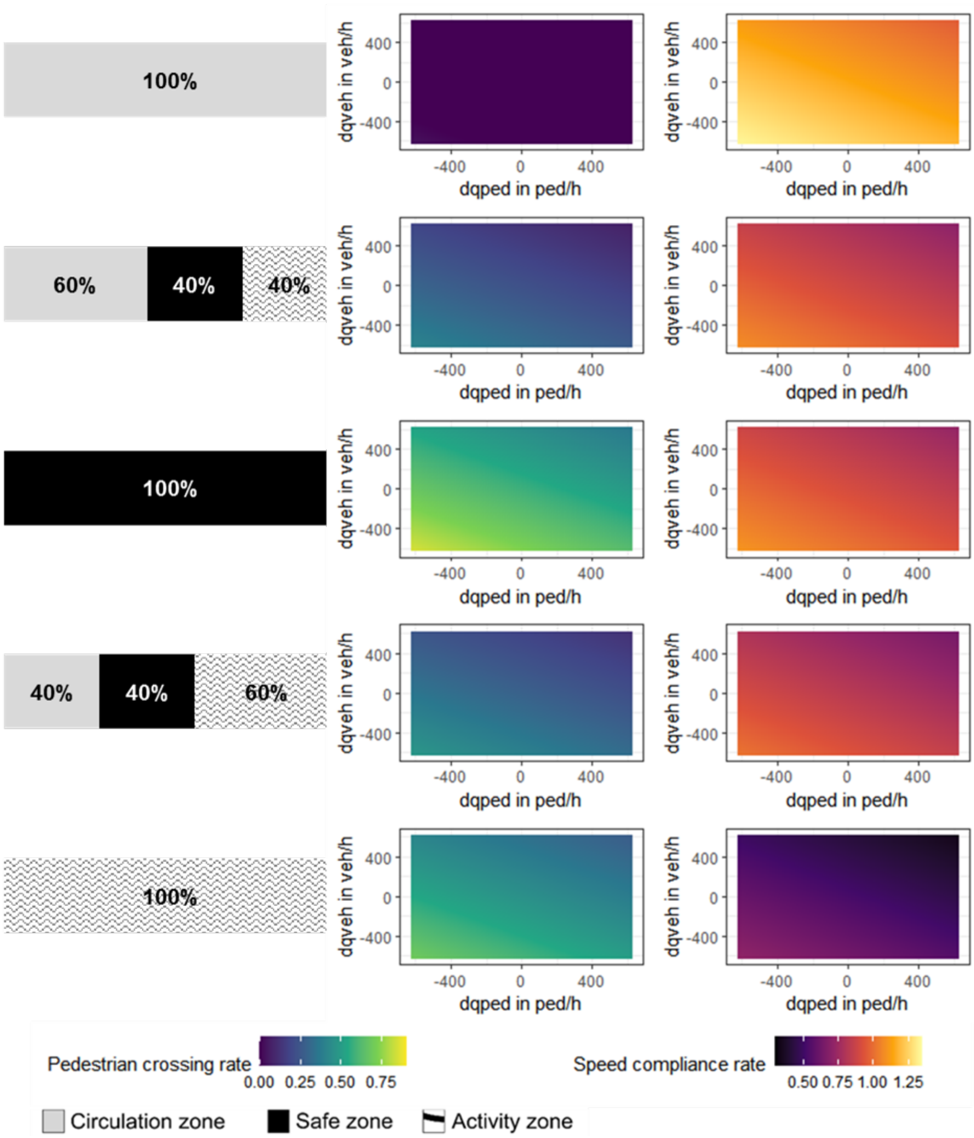

Figure 25: Visualization of models' outputs per shared space configuration; dqveh: deviation of vehicle flow in veh/h; dqped: deviation of pedestrian flow.

3.6 Discussion

In this section, the validity of the six main hypotheses is assessed, and valid conclusions are exported based on the empirical models.

H1: Pedestrians modify their behavior by crossing more the circulation zone compared to a conventional street design.

Shared space aspires to be a more pedestrian-friendly road environment compared to conventional urban road designs (Kaparias and Wang, 2020a). Yet, it is quite challenging to translate "friendliness" into numbers considering various design configurations and traffic condition scenarios. Starting with the first study hypothesis there is no reason to reject it. Indeed, the first empirical analysis showed a noticeable proportional increase in pedestrian crossings in the shared space section of Amalias Street considering all the simulated demand scenarios. More crossings seem to be produced every extra second of time headway between two consecutive vehicles in shared space. As expected, these relationships are not linear. Nevertheless, the last observations confirm the findings of previous studies that performed a before-and-after analysis and observed several modifications in pedestrian crossing behavior (Kaparias et al., 2016; Woodman et al., 2019). This behavior increases the number of complex interactions and affects driving behavior at the tactical level.

H2: Vehicles and pedestrians follow similar paths in shared space.

Simultaneously, several components in shared space seem to provide informal segregation of traffic flows. This segregation is practically proved by the differentiation of pedestrians' and vehicles' trajectories which was observed in German cases (Anvari et al., 2016; Batista and Friedrich, 2022; Moody and Melia, 2014). The study by Ruiz-Apilánez et al. (2017) also concluded that pedestrians tend to avoid the circulation zone of shared space when a vehicle approaches. Compared to conventional road designs, shared space should be treated as a design that offers more points to cross. Practically, it is divided into three zones: activity, safe, and circulation zone. Statistically significant relationships between the share of these zones considering the overall road width and pedestrian crossing rate were found in the second empirical analysis that was conducted. Hence, the second hypothesis should be rejected. Pedestrians do not follow the same paths as vehicles. One exception to this is bikes and e-scooters which seem to use the circulation zones, as it is reported in the study by Batista and Friedrich (2022).

H3: Compared to a conventional road environment, pedestrian crossings in shared space strongly reduce vehicle speeds.

The difference in the size of the intercept parameters proves the noticeable differences in average car speeds between the conventional and the shared space section. They were decreased by approximately 4 km/h in Section B; this is in line with the results of Kaparias and Wang (2020a). It was surprising that the variance of car speed in the conventional road section was much higher, although in shared space the volume of pedestrian crossings and therefore the interactions were higher. At the tactical level, drivers balance the overall complexity appearing in coexistence environments by following a more homogenous driving behavior consisting of similar travel speeds. This finding can be supported by the risk homeostasis theory described in the study by Hammond et al. (2013) regarding the concept of shared space. In the conventional road section, the pedestrian volume does not influence the average car speed. An intercept–only model was estimated; it shows the tendency of Greek drivers to follow a more aggressive behavior when approaching midblock crossings and non-signalized intersections (Papaioannou, 2007; Politis et al., 2012). Yet, in shared spaces, pedestrian crossings have a clear impact on driving behavior. These contradicting findings in the same street (!) underline the effectiveness of shared space to "calm" traffic speeds and aggressive drivers. Hence, the third hypothesis is valid.

H4: When the vehicle flow tends to capacity in shared space, there is no difference with a conventional road environment.

Shorter time headways and therefore higher flows of vehicle results in a considerably lower pedestrian crossing both in shared space and conventional road section. This was expected. Yet, by simulation of the empirical model, it was proved that even in high vehicle demand scenarios, the proportional difference of pedestrian crossing is always positive. Additionally, in all cases, the average car speeds are predicted to be lower in shared space compared to the conventional road. Nevertheless, it should be acknowledged that in Amalias Street, super high volumes (that tend to capacity) were never observed. Hence, these conclusions are based on the simulated results. Simulation analyses will contribute to providing a secure answer regarding the validity of this hypothesis.

H5: As shared space is more an umbrella term, the coexistence of road users is still influenced by the (informal) design of the road.

Shared space is not a unique design. It is more of an umbrella term and different forms were reported. This research study is the first one that takes into account the variations in shared space configuration by considering four cases. The model outputs prove that the provision of more space to pedestrians (i.e., activity or safe zones) further encourages and assists crossing. In other words, it reinforces their dominance in this road environment. This has been also observed in shared space with large activity zones like Sonnenfelsplatz or Skvallertorgen Intersection (Cheng et al., 2021; Hamilton-Baillie, 2008b; Jaredson, 2002; Rudloff et al., 2014; Schönauer et al., 2012a). By adding a circulation zone, the trajectories of pedestrian users seem to be channeled and concentrated at the edges of shared space. In situations with very high pedestrian flows, the pedestrian starts moving into groups in these channels, which means a lower pedestrian crossing rate, i.e., crossings per ped. Higher pedestrian crossing rates are associated with higher speed deviations in shared space which means a less homogenous driving behavior. The same happens with car drivers, where large circulation zone induces speeding and consequently high-speed compliance rates. So, the configuration of shared space determines the effectiveness of a shared space scheme.

H6: Coexistence is a feasible scenario. Shared space can create road environments that are less car-dominated and more human-oriented.

Coexistence can be defined as the state, in which pedestrians feel free enough to cross and share the entire road space while vehicles are not hindered but forced to move cautiously and slowly. Coexistence is also related to the homogeneity both of pedestrians' and vehicle drivers' behavior. In objective terms, it can be achieved by a speed compliance rate close to 1 and by a pedestrian crossing rate that prevents redundant speed variation while spreading pedestrian movements. Most cases, considering the one from the literature, are very close to this reality. Hence, coexistence seems to be a very feasible scenario. Nevertheless, some limitations should be considered at this point. First, the role of street equipment in informally segregating traffic flows was never discussed. Moreover, there was no observation from very extreme traffic situations to assess the performance of shared space with real data. Therefore, the prediction ability of all the developed models in high-flow scenarios requires serious improvement. Last, the low goodness of fit that most of the empirical models reported proves the existence of additional behavioral factors related to safety perceptions which may determine coexistence. Culture is one that surely impacts driving behavior. Shared space remains a game of road users' perceptions which should be further investigated.

4 Examination of safety perceptions

As previously discussed, the concept of shared space draws from the risk homeostasis theory, where individuals adjust their risk-taking behavior in response to their surroundings (Hammond & Musselwhite, 2013). This means that the interactions among road users may form the way based on which first/last mile modes can co-exist solving automatically the space allocation problem. Within this framework, the perceived safety of road users emerges as a pivotal factor that could influence the viability of mixing conventional and new transportation modes in shared space (Akgün-Tanbay et al., 2022; Tzouras et al., 2021).

Safety concerns should be divided into three broad categories, i.e., a) property safety which refers to freedom from threats of theft, b) personal safety which refers to freedom from threats of crime, harassment, etc., c) traffic safety which is about freedom from threats of injury due to a collision. (Bhagat-Conway et al., 2022). Gill et al. (2022) mention that perceived safety pertains to an individual's level of concern about being in a crash or injured. It contrasts with objective safety which is "measured" by analyzing actual accidents or conflicts recorded in the field (Gkekas et al., 2020; Tzouras et al., 2020). Being a subjective construct, perceived safety not only varies across different transport modes but also among different individuals. In the context of active modes, numerous studies also link perceived safety directly with comfort (Chataway et al., 2014; Dill & McNeil, 2013). For instance, a ride on an e-bike or e-scooter is deemed "safe" when it is also considered "comfortable" and vice versa (Bhagat-Conway et al., 2022).

This chapter presents a novel modeling approach that considers the influence of perceived safety on the decision-making process of potential users of micro-mobility options for their first/last mile travel needs in dense urban areas. The investigation delves into how perceived safety varies in different road environments and traffic scenarios, ultimately contributing valuable insights to the ongoing deliberations about the merits of integrating these modes within shared space or completely segregating them. Another objective is to delve into the impact of safety perceptions across four distinct first/last mile transport modes: private car, e-bike, e-scooter, and walking. By doing so, the aim is to uncover any discernible variations in perceived safety among these modes. The stated preferences experiment that is designed to meet the previously mentioned objectives focuses on a specific demographic subset, namely tech-savvy, well-educated young adults, ideally below the age of 40, who do not own a personal e-scooter. This choice is grounded in the existing evidence that underscores the dominance of this group in adopting micro-mobility options. Thus, focusing on this demographic allows for a thorough exploration of the road environment conditions under which emerging first/last mile modes like e-bikes and e-scooters can potentially induce shifts in mobility patterns within urban spaces.

4.1 Background

Previous research employed stated preference experiments to quantify perceived safety. **Table 12** summarizes major relevant studies on that topic. The work of Park and Park (2021) offered insights into how the external context of a car's environment—encompassing factors such as road conditions and weather—directly shapes the perception of safety and, consequently, the enjoyment experienced by elderly drivers, a demographic group of particular interest. Concurrently, the study conducted by Tzouras et al. (2020) delved into the realm of perceived safety considerations, with a focus on delineating the key challenges confronted by tram drivers in different road environments. Road design parameters and traffic flow conditions were linked with the subjective notion of perceived safety. Also, these models provided insights into tram drivers' experiences, they underscored that perceived safety might not hold substantial sway over the driving stress. Instead, the familiarity of a tram driver with a specific route emerged as a more substantial factor compared to safety perceptions, influencing the degree of driving stress experienced.

Regarding micro-mobility, the work of Calvey et al. (2015) centered on the analysis of cyclists' contentment and comfort perceptions to propose a novel inspection methodology for cycle lanes. The findings gleaned from this study underscored the interconnection between satisfaction, comfort, and safety. Additionally, surfaces other than asphalt were linked to increased vibrations experienced by cyclists, consequently leading to diminished comfort, compromised safety, and subsequently lower satisfaction levels. In a similar vein, Bai et al. (2017a) estimated an ordered probit regression model to investigate the perceived comfort levels of e-bike and e-scooter users across diverse urban contexts. The results from this model indicated that e-scooters were generally regarded as less comfortable in comparison to e-bikes. The width of mid-block cycle lanes was found to be proportionally related to cyclists' comfort perceptions.

Moving forward, the research by Branion-Calles et al. (2019) showed an intriguing association between the perception of safety in bicycling and the availability of bicycle infrastructure within certain urban areas. Indeed, the likelihood of perceiving bicycling as safe was higher in neighborhoods with at least 1 kilometer of bicycle network infrastructure. Noteworthy demographic trends within these examined cities revealed that cyclists predominantly comprised young males from lower-income groups, with bicycle ownership being a prerequisite. Useche et al. (2021) ventured into a comparison of risk perceptions between micro-mobility (daily) riders and non-riders, identifying that experienced cyclist displayed greater awareness of traffic regulations and a heightened risk perception. Kopplin et al. (2021) highlighted that the intention to utilize e-scooters for leisure purposes faced limitations due to safety concerns, particularly among individuals who did not possess a micro-mobility vehicle. A recent contribution by Fitch et al. (2022) involved an online video experiment targeting cyclists' perceived comfort. They treated bicycle comfort as a parallel concept to perceived safety. The study's findings revealed that the presence of dedicated bike infrastructure correlated with elevated comfort ratings (see **Figure 26**). However, on high-speed, high-volume arterials, even well-designed on-road bike facilities might fall short of enhancing comfort ratings, particularly among women and older participants.

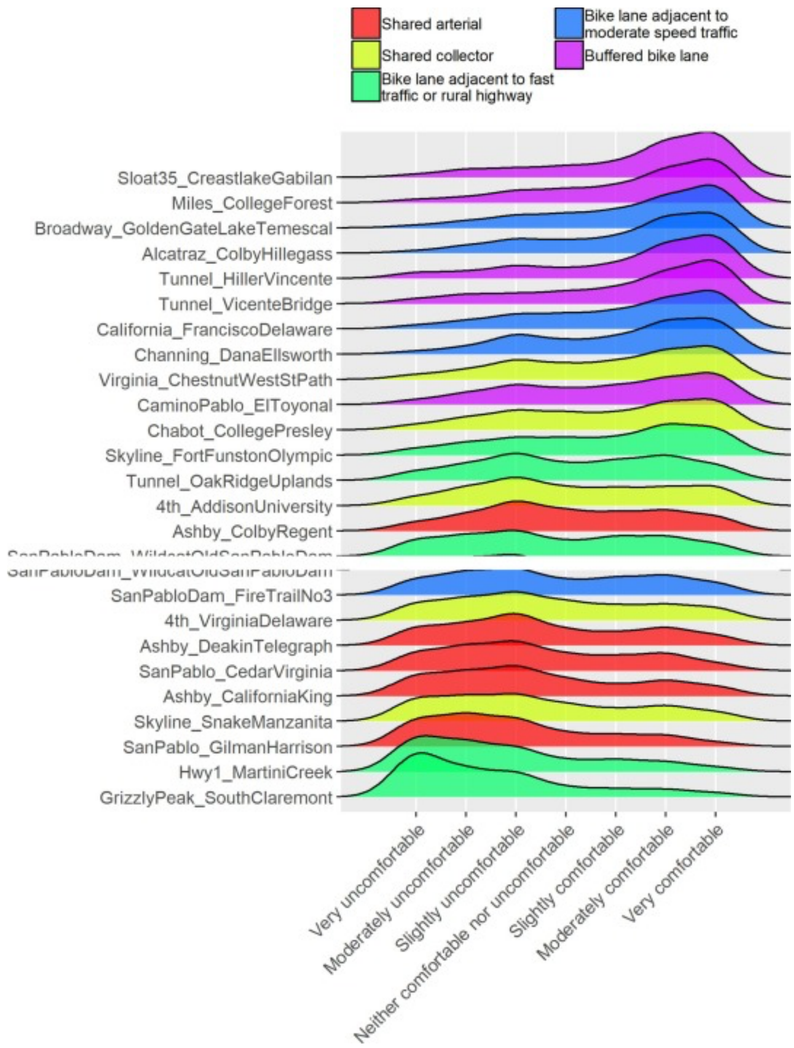

Figure 26: Kernel distribution of perceived comfort – safety of cyclists per road environment
Source: (Fitch et al., 2022)

The interchangeable use of perceived safety and comfort as subjective factors in transport models, particularly when modeling pedestrian travel behavior, raises questions. The research by Hidayati et al. (2020) exemplifies this issue, as it seems to blend these two factors and presents conflicting findings. In the urban context of Jakarta, Indonesia, perceived safety emerges as susceptible to the presence of motorcycles exhibiting reckless and risk-prone behaviors. On the other hand, in Kuala Lumpur, Malaysia, pedestrians' perceptions of safety and their chosen routes exhibit a correlation with the prevalence of fellow pedestrians and shops in the urban environment. The study conducted by Gill et al. (2022) argues that pedestrian safety perceptions and comfort diverge, particularly at non-signalized crosswalks. Their findings underscore the robust impact of yielding behavior on both safety and comfort perceptions, as can be seen in **Figure 27**. Interestingly, pedestrian safety perceptions appear to be more closely tied to vehicle acceleration and deceleration rates, while perceived comfort is influenced by vehicle speeds. Experienced pedestrians, those who engage in daily walking commutes, indicate lower levels of perceived comfort due to past incidents. However, the increased frequency of walking along city streets is linked to raised safety perceptions. In a broader context, the survey outcomes outlined by

Aceves-González et al. (2020) affirm that the perceived safety of pedestrians is a complex interplay of various factors linked to the road environment. These factors encompass aspects such as sidewalk curbs, pavement quality, the presence of pedestrian crossings, obstructions on sidewalks, and the availability of traffic lights.

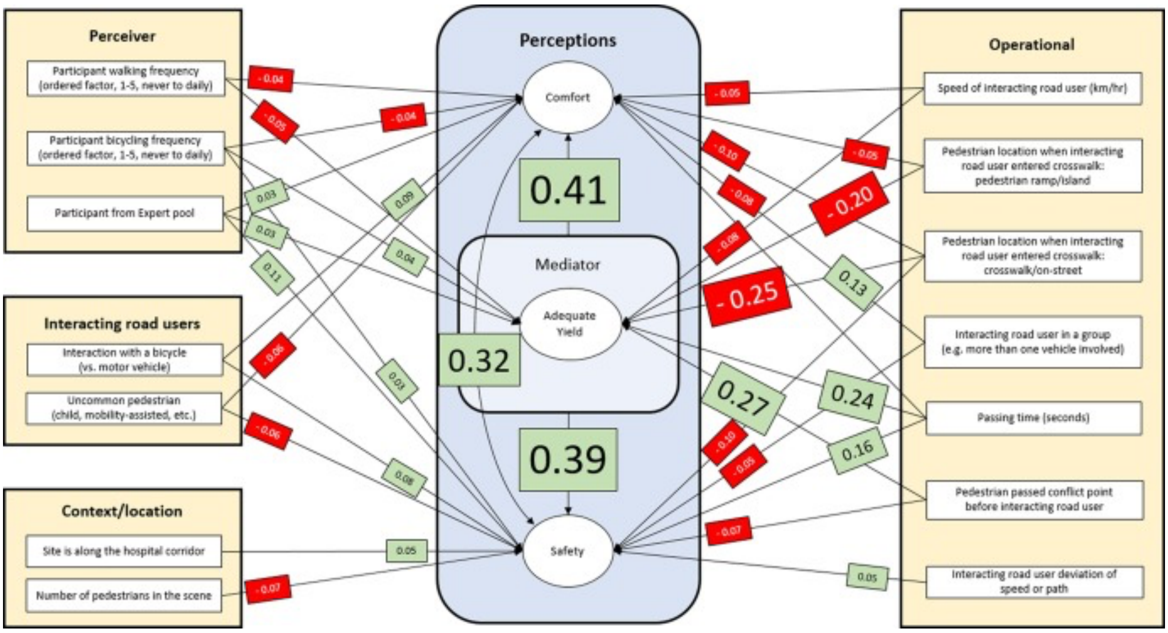

Figure 27: Interrelationships between pedestrians' comfort and safety
Source: (Gill et al., 2022)

Mixed traffic areas, like shared spaces, offer a unique setting to study how intricate traffic interactions influence the perceived safety and, in turn, the behavior of travelers. Gkekas et al. (2020) revealed that, compared to pedestrians, cyclists are less worried about potential conflicts between different modes of transport. Even though cyclists prefer to steer clear of areas with a high concentration of pedestrians, this behavior is offset by the additional time required to take safer detours and their desire to avoid motor vehicles at all costs. Kaparias et al (2012) found that the perception of car drivers is shaped by whether or not there are children present in these shared spaces. Aspects like vehicle traffic, safe zones, lighting conditions, as well as individual age and gender were crucial in influencing how safe pedestrians felt in these spaces. In a follow-up study, Kaparias and Li, in 2021, unearthed that heavy pedestrian loads and (static) obstacles resulted in reduced willingness of two-wheeler riders to use these shared areas. A similar research approach was employed by Akgün-Tanbay (2022). They discovered that experienced users typically don't view shared spaces as disorderly as initially thought, with younger females, in particular, showing distinct perceptions.

Table 12: Summary of previous studies' findings about perceived safety

Study	Road user type	Data collection/analysis method	Noticed factors/Findings
Calvey et al. (2015)	cyclists	- questionnaire survey with Likert Scale	- non-asphalt pavements increase vibrations resulting in reduced comfort, safety, and therefore satisfaction.
Bai et al. (2017a)	cyclists	- image-based rating experiment - ordered probit	- comfort perceptions are proportional to the width of the mid-block cycle lane; - females and middle-aged or older users expressed were more concerned.
Branion-Calles et al. (2019)	cyclists	- three repeat cross-sectional surveys - weighted multinomial regression model	- odds of perceiving bicycling as safe are increased in urban areas with at least 1 km available bicycle infrastructure.
Gkekas et al. (2020)	cyclists pedestrians	- intercept survey	- cyclists are less concerned about intermodal conflicts compared to pedestrians; - cyclists tend to avoid pedestrian-dominated areas and motorized traffic.
Hidayati et al., (2020)	pedestrians	- on - street interviews - survey responses	- perceived safety of pedestrians is influenced by the volume of motorcycles who follow a risk-taking behavior.
Tzouras et al. (2020)	tram drivers	- image-based rating experiment - ordered logit	- road design and flow conditions influence perceived - perceived safety is not a factor of driving stress
Aceves-González et al (2020)	pedestrians	- physical audit - on-street questionnaire	- curbs and surface quality, the existence of pedestrian crossings, obstacles on the sidewalk and traffic lights influence perceived safety.
Park D. and Park S. E. (2021)	car drivers	- face-to-face survey - structural equations modeling	- weather, road conditions, etc. affect the perceived safety of elderly drivers especially.
Kaparias et al (2012)	car drivers pedestrians	- two web-based stated preferences experiments - binary regression models	- car drivers' perceptions are influenced by the presence/absence of children and pedestrian density; - vehicle traffic, provision of safe zones, lighting level, age, and gender determined the perceived safety of pedestrians.
Akgün-Tanbay et al. (2022)	cyclists e-scooter riders pedestrians	- face-to-face survey - ordered logit	-experienced users seem to not find shared space chaotic; - females underrated the perceived safety of walking and cycling.
Useche et al. (2021)	cyclists	- Cycling Behavior Questionnaire	- experienced cyclists seem to be more aware of traffic regulations and have a higher risk perception.
Kopplin et al. (2021)	e-scooter riders	- questionnaire survey with Likert Scale - Unified Theory of Acceptance and Use of Technology	- the intention to use an e-scooter as a fun object is limited by safety concerns expressed mainly by people who do not own one.
Gill et al. (2022)	pedestrians	- online survey with videos - generalized structural equations model	- perceived safety of pedestrians relates to vehicle acceleration/deceleration rate, while perceived comfort is influenced by vehicle speed; - more frequent walking on city streets results in increased perceived safety.
Fitch et al. (2022)	cyclists	- online video experiment - ordered logit	- in high-speed, high-volume arterials, the construction of a well-designed on-road bike facility may not be enough to raise comfort ratings.

4.2 Methodological approach

According to Gill et al. (2022), user perceptions can be quantified by collecting either first-person or third-person evaluations. In the first approach, the respondents experience a traffic situation in a real or simulated world before rating their perceptions, while in third-person rating experiments, the respondents inspect a road environment in which they have not taken part before providing a score. In the present case, a third-person, double stated preference experiment is utilized.

First, participants are shown a series of images depicting various hypothetical road environment scenarios. They are then asked to rate their perception of safety for each mode of transport. Following this, based on their safety assessments, participants are prompted to select a mode of transport for their first/last mile trip. Moreover, the elements of time and cost are incorporated into the choice process. It is hypothesized that the safety perceptions of cyclists do not significantly differ from e-cyclists. E-bike is a promising solution to overcome a very important barrier of cycling, i.e., the hilly terrain (Ling et al., 2017; Liu & Suzuki, 2019). Of course, e-bikes cannot be grouped with e-scooters, as previous studies have reported significant variations in users' comfort perceptions (Bai et al., 2017a) and routing behavior (Useche et al., 2022; Younes & Baiocchi, 2022) between them.

4.2.1 Selection of variables and variable levels

In this study, two main dependent variables are examined. First is the perceived safety, an ordinal variable rated on a 7-point Likert scale, where 1 implies a "very unsafe" perception, 4 means "moderately safe," and 7 signifies "very safe." This scale was chosen for its precision in mirroring participants' perceptions and minimizing ambiguity, compared to a 5-point scale (Joshi et al., 2015). The second variable is the choice of transport for the first/last mile mode choice of his/her trip, comprising four modes: car, e-bike, e-scooter, and walking. This mode choice is also assessed as a function of the perceived safety. This is a nominal variable. Moreover, this choice is further broken down into four binary variables, each denoting the selection or rejection of a particular transport method. This segmentation aims to measure users' willingness to take detours for enhanced safety. Recent studies on cycle route choices have employed a similar method (Meister et al., 2022; Reggiani et al., 2022).

As for the independent variables (refer to **Table 13**), the study evaluates socio-demographic factors like gender, age, educational background, and monthly earnings. These factors aren't just ornamental; they potentially wield influence over safety perceptions and consequently the choice of transport (Bhagat-Conway et al., 2022). Other data collected includes current travel preferences, frequency of using each mode, possession of a driving license, and owning a vehicle or micro-mobility device. Nevertheless, all these individual-specific variables are not included in the scenario design process, as they cannot be controlled a priori.

The experiment uses four distinct infrastructure designs for a standard 17.5 m wide urban road (see **Figure 28**). Type 1 is car-centric with limited walking space. Type 2 promotes walkability with broader sidewalks. Type 0 is a multi-modal corridor giving equal space to all transport modes. Type 3 embodies a shared space concept, with reduced speed limits and visually distinguished sidewalks. With palpable visual demarcations for sidewalks and tempered speed limits, it attempts to cultivate cohabitation without stringent physical segregation. Shared spaces, as defined by Kaparias and Wang (2020) is an umbrella term that prioritizes harmonious coexistence without physical barriers. The various design proposals for shared space seem to influence pedestrian crossing behavior which disturbs traffic flow, according to the observations of Batista and Friedrich (2022). Furthermore, the analysis incorporates another layer of detail with the inclusion of pedestrian crossings, both signalized and non-signalized. The quality of pavements, bifurcated into 'good' and 'bad' based on discernible features like cracks or the presence of cobblestones, emerges as another pivotal variable influencing safety perceptions. Additionally, the study factors in the physical impediments scattered across roads, particularly sidewalks, as they potentially hinder the movement of vulnerable road users. Traffic complexities are defined by only these three categories, as further divisions could overcomplicate safety models. Regarding the traffic flow components, three primary categories: vehicles (cars, trucks, buses), bikes (encompassing e-scooters, e-bikes, motorcycles), and pedestrians are identified. Further divisions could overcomplicate safety models.

Figure 28: Presentation of the four main infrastructure types/scenes

Lastly, travel time and costs emerge as the primary factors that drive or deter specific route and mode choices. To export the variable levels, in pedestrians, e-scooters, and e-bikes, a fixed speed of 5, 15, and 20 km/h is considered, respectively. Therefore, the deviations in time are due to a higher or lower distance that can be followed by these micro-mobility road users to avoid unsafe interactions with motorized traffic. The variance in car travel times is due to traffic congestion causing significant delays. The prices of existing micro-mobility are finally considered to select travel cost levels, while the travel cost of walking is fixed at zero.

Table 13: Presentation of independent variables

Independent Variables	No. of levels	Variable Levels				
		Level 0	**Level 1**	**Level 2**	**Level 3**	**Level 4**
A. Variables related to socio-demographic characteristics						
Gender	2	male	female			
Age	2	≥ 30 years old	< 30 years old			
Education Level	5	no education	primary	secondary	higher	master or PhD
Monthly Income (per individual)	5	no income	< 750 €/month	750-1500 €/month	1500-2500 €/month	≥ 2500 €/month
B. Variables related to travel behavior (revealed preferences)						
Driving license	2	no	yes			
Car-ownership	4	none	1 car	2 cars	3 or more cars	
Car use frequency	4	almost never	sometimes in a year	sometimes in a month	sometimes in a week	daily
Bicycle (or e-bike)/e-scooter ownership	2	none	1 or more bicycles/e-scooters			
Bicycle (or e-bike)/e-scooter use frequency	5	almost never	sometimes in a year	sometimes in a month	sometimes in a week	daily
C. Variables related to the road environment						
Road infrastructure	4	urban road with cycle lane	urban road with sidewalks < 1.5 m wide	urban road with sidewalks ≥ 1.5 m wide	Shared space	
Pavement condition	2	bad condition	good condition			
Obstacles	2	no obstacles	many obstacles			
“Zebra” Pedestrian crossings	3	without “zebra” pedestrian crossings	with “zebra” pedestrian crossings not controlled by traffic lights	with “zebra” pedestrian crossing controlled by traffic lights		
D. Variables related to the traffic conditions						
Vehicle density	3		100 veh/km/dir	60 veh/km/dir	20 veh/km/dir	
Bike density	3		80 bikes/km/dir	50 bikes/km/dir	10 bikes/km/dir	
Pedestrians in the road environment	3		25 pedestrians in the road environment	15 pedestrians in the road environment	5 pedestrians in the road environment	
E. Variables related to the trip attributes						
Travel time	3		car: 40 e-bike: 25 e-scooter: 30 walk: 45 mins	car: 20 e-bike: 15 e-scooter: 20 walk: 30 mins	car: 5 e-bike: 5 e-scooter: 10 walk: 15 mins	
Travel cost	3		car: 6.5 e-bike: 4.5 e-scooter: 3.5 walk: 0 euros	car: 5 e-bike: 3 e-scooter: 2 walk: 0 euros	car: 3.5 e-bike: 1.5 e-scooter: 0.5 walk: 0 euros	

4.2.2 Models formulation

In this chapter, two distinct modeling structures are devised: one focusing on perceived safety, and the other on route/mode choice determinants.

Beginning with the perceived safety model, its formulation rests on two key equations. **Equation 18** deduces latent perceptions of safety through a set of different attributes related to personal characteristics and the road environment. The preliminary segment of this equation encloses sociodemographic indicators and factors related to travel behaviors, both of which can potentially shape safety perceptions. These parameters cannot be controlled in the survey design process. It is important to highlight the potential presence of collinearities within these variables, which might restrict the inclusion of some parameters. To incorporate categorical variables and thereby probe potential non-linear relations between categories, the model function deploys dummy coded variables (Daly et al., 2016). Indeed, the equation delves into the intricacies of cross-section designs and static objects picturing the road environment. Lastly, the final segment of this equation factors in parameters relating to the dynamics of traffic flow. Hence, the third parenthesis encloses the moving objects of the urban road environment. One latent perceived safety function is constructed per transport mode. This results in a different set of beta coefficients per transport mode increasing the number of unknown factors.

$$\begin{aligned} psafe^*_{\mathrm{l,j,m}} + \varepsilon_{\mathrm{l,j,m}} &= \left(\sum_{i=1}^{4} \beta_{soc_{\mathrm{i,m}}} \times soc_{\mathrm{i,j}} + \sum_{i=1}^{5} \beta_{beh_{\mathrm{i,m}}} \times beh_{\mathrm{i,j}}\right) \\ &+ \left(\beta_{infr_{1,\mathrm{m}}} \times \mathrm{infr}_{1,\mathrm{l}} + \beta_{infr_{2,\mathrm{m}}} \times \mathrm{infr}_{2,\mathrm{l}} + \beta_{infr_{3,\mathrm{m}}} \times \mathrm{infr}_{3,\mathrm{l}} + \beta_{pav_{\mathrm{m}}} \times pav_{\mathrm{l}} + \beta_{obs_{\mathrm{m}}} \times obs_{\mathrm{l}} \right. \\ &\left. + \beta_{crs_{1,\mathrm{m}}} \times crs_{1,\mathrm{l}} + \beta_{crs_{1,m}} \times crs_{1,\mathrm{l}}\right) + \left(\beta_{veh_{\mathrm{m}}} \times veh_{\mathrm{l}} + \beta_{bike_{\mathrm{m}}} \times bike_{\mathrm{l}} + \beta_{ped_{\mathrm{m}}} \times ped_{\mathrm{l}}\right) \\ &+ \varepsilon_{\mathrm{l,j,m}} \qquad (18) \end{aligned}$$

where:

$psafe^*_{\mathrm{l,j,m}}$: latent variable of the perceived safety of individual j using mode m in urban road link l (or observation l),

$\varepsilon_{\mathrm{l,j,m}}$: error term,

$soc_{\mathrm{i,j}}$: sociodemographic characteristics of individual j,

$beh_{\mathrm{i,j}}$: travel behavior attributes of individual j,

$infr_{1,\mathrm{l}}$: 1, if there is an urban road with sidewalks less than 1.5 m wide and without a cycle lane in urban road link l – type 1,

$infr_{2,\mathrm{l}}$: 1, if there is an urban road with sidewalks equal to or more than 1.5 m wide and without a cycle lane in urban road link l – type 2,

$infr_{3,\mathrm{l}}$: 1, if shared space in urban road link l – type 3 (all $infr$ parameters equal to 0, if there is an urban road with sidewalks equal to or more than 1.5 m wide and with cycle lane – type 0),

pav_{i}: 1, if the pavement of the urban road is in good condition urban road link l,

obs_{i}: 1, if there are obstacles in the road environment urban road link l,

$crs_{1,\mathrm{l}}$: 1, if there is a non-signalized zebra pedestrian crossing in the next 200 meters of urban road link l;

$crs_{2,\mathrm{l}}$: 1, if there is a signalized zebra pedestrian crossing in the next 200 meters of urban road link l (all crs parameters equal to 0 if there is no zebra pedestrian crossing in the next 200 meters),
veh_{l}: car density in vehicles per km per direction of urban road link l,
$bike_{\mathrm{l}}$: bike density in bikes per km per direction of urban road link l,
ped_{l}: number of pedestrians in the road environment (next 50 m) of urban road link l.

Transitioning to **Equation 19**, the range of perceived safety, which varies from 1 to 7, is discerned using an array of kappa thresholds. Kappa thresholds differ per transport mode too. Consequently, the perceived safety model emerges as a multi-dimensional tool, bearing the capability to cater to individual preferences, specific urban road links, and different first/last mile transport models. For this model calibration, an intricate combination of nineteen beta parameters and six kappa thresholds for each mode is necessitated. These are the unknown parameters that should be determined based on a set of individuals' perceived safety ratings objecting to minimizing the error term of the perceived safety function.

$$psafe_{\mathrm{j,l,m}} = \begin{cases} 1, & -\infty < psafe^{*}_{\mathrm{l,j,m}} \le k_{1,m},\ \ very\ unsafe \\ 2, & k_{1,m} \le psafe^{*}_{\mathrm{l,j,m}} \le k_{2,m} \\ 3, & k_{2,m} \le psafe^{*}_{\mathrm{l,j,m}} \le k_{3,m} \\ 4, & k_{3,m} \le psafe^{*}_{\mathrm{l,j,m}} \le k_{4,m} \\ 5, & k_{4,m} \le psafe^{*}_{\mathrm{l,j,m}} \le k_{5,m} \\ 6, & k_{5,m} \le psafe^{*}_{\mathrm{l,j,m}} \le k_{6}, m \\ 7, & k_{6,m} \le psafe^{*}_{\mathrm{l,j,m}} < +\infty, \quad very\ safe \end{cases} \tag{19}$$

<u>where:</u>
$psafe_{\mathrm{l,j,m}}$: perceived safety level of individual j using mode m in urban road link l,
$\beta_{infr_{1,\mathrm{m}}}, \beta_{infr_{2,\mathrm{m}}}, \dots, \beta_{ped,m}$: beta parameters of the latent perceived safety function of mode m,
$k_{1,m}, k_{2,m}, \dots, k_{6,m}$: perceived safety kappa thresholds of mode m.

The utility function of each of the examined transport modes contains only three basic parameters, namely: travel time, cost, and perceived safety (see **Equation 20**). While prior research integrated a plethora of environmental variables into the utility function of micro-mobility modes (Meister et al., 2022; Nigro et al., 2022; Ziemke et al., 2017, 2019), this investigation adopts a streamlined approach. Such simplicity not only ensures alignment with the overarching objectives of this research but also facilitates its seamless incorporation into various modeling or simulation frameworks. Thus, additional variables, be they road environment or persons' characteristics, are all included in the variable of perceived safety, which inherently varies across modes, routes, and individuals. Levels of perceived safety under the threshold of 4 increase the mode disutility. Furthermore, the utility function is extended by integrating parameters related to trip duration and associated costs. Function calibration requires the identification of three beta parameters and a mode-specific alternative constant, which are determined based on choice data.

$$
\begin{aligned}
U_{\mathrm{r,j,m}} = V_{\mathrm{r,j,m}} + \varepsilon_{\mathrm{r,j,m}} \\
&= ASC_m + \beta_{time_{\mathrm{m}}} \times time_{\mathrm{m,r}} + \beta_{cost_{\mathrm{m}}} \times cost_{\mathrm{m,r}} + \beta_{psafe_{\mathrm{m}}} \times \left(psafe_{\mathrm{j,r,m}} - 4 \right) + \varepsilon_{\mathrm{j,r,m}} \\
&= \\
&= ASC_m + \left(\frac{\beta_{time_{\mathrm{m}}}}{v_m} + \beta_{cost_{\mathrm{m}}} \times cd_m \right) \times d_r + \beta_{psafe_{\mathrm{m}}} \times \left(psafe_{\mathrm{j,r,m}} - 4 \right) \\
&+ \varepsilon_{\mathrm{j,r,m}} \quad (20)
\end{aligned}
$$

<u>where</u>:
$U_{\mathrm{j,r,m}}$: utility of using mode m in first/last mile route r by individual j;
$V_{\mathrm{r,j,m}}$: systematic utility of using mode m in first/last mile route r by individual j;
$\beta_{time_{\mathrm{m}}}, \beta_{cost_{\mathrm{m}}}, \beta_{psafe_{\mathrm{m}}}$: beta parameters of the utility function of mode m;
$\varepsilon_{\mathrm{j,l,m}}$: error term
ASC_m: alternative specific constant of mode m;
$time_{\mathrm{m,r}}$: travel time of using mode m in first/last mile route r;
$cost_{\mathrm{m,r}}$: travel cost of using mode m in first/last mile route r;
v_m: travel speed of mode m;
cd_m: cost distance rate of mode m;
$psafe_{\mathrm{j,l,m}}$: perceived safety level of mode m in first/last mile route r, as experienced by individual j.

The route modeling dimension is rooted in the concept of the Value-of-Safety (see **Equation 21**). By introducing a mathematical metamorphosis to the previously mentioned utility function, this Value-of-Safety can be referenced in terms of distance. Essentially, this transformed metric reveals the extent to which individuals are willing to increase their travel distance to experience an enhanced level of perceived safety.

$$
VoS_m = \frac{\beta_{psafe_{\mathrm{m}}}}{\beta_{d_m}} = \frac{\beta_{psafe_{\mathrm{m}}}}{\left(\frac{\beta_{time_{\mathrm{m}}}}{v_m} + \beta_{cost_{\mathrm{m}}} \times cd_m \right)} \quad (21)
$$

4.2.3 Survey design

The survey design process in this study is complex, given the multitude of variables, intricate models, and a double-stated preference experiment involving both scenes and live images. **Figure 29** outlines the steps using a straightforward flowchart.

In general, the approach relies on two matched fractional factorial designs. For the rating experiment, the possible scenarios add up to $4 * 2 * 2 * 3 * 3 * 3 = 432$. However, to keep things simpler, an orthogonal table is used to ensure no correlations among the explanatory variables of perceived safety model, which brings the total down to 36 scenarios. These are then grouped into three blocks to make the survey completion process quicker. As a result, a participant only needs to evaluate 12 of these scenarios for perceived safety.

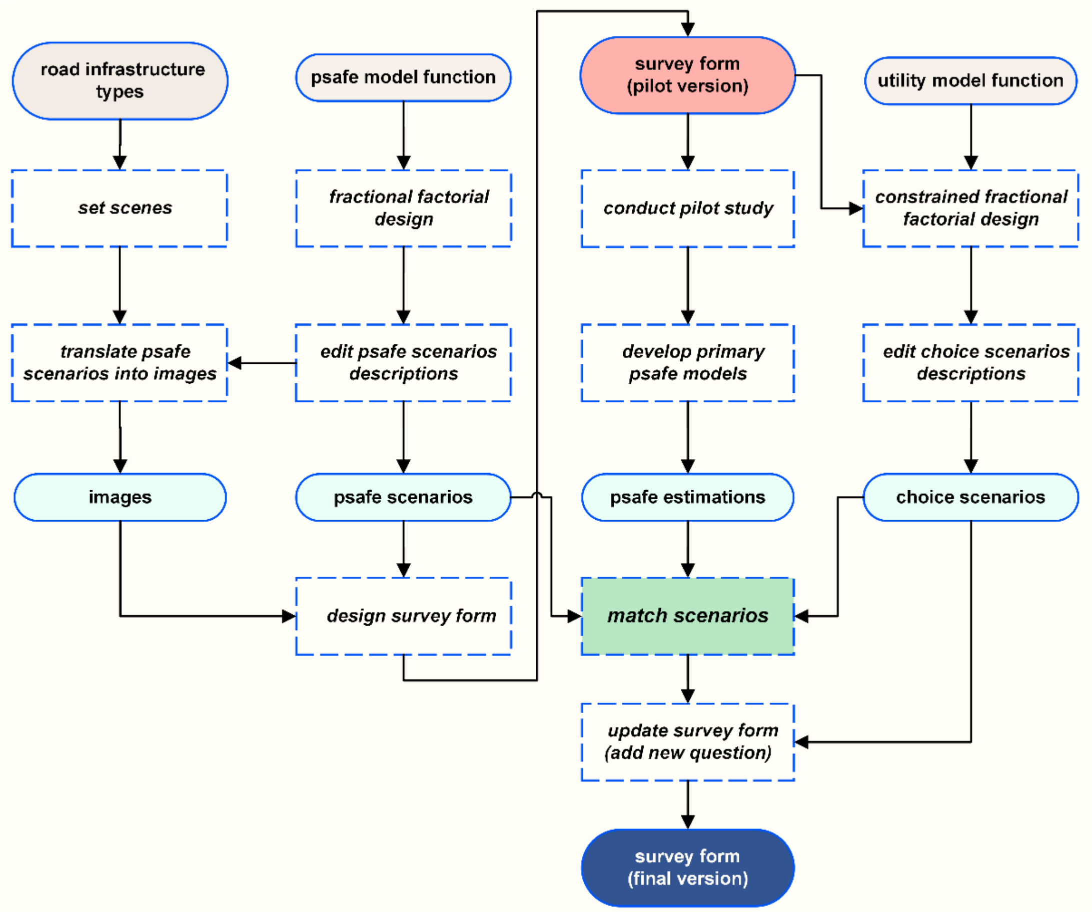

Figure 29: Methodological flow diagram of the design process of the image-based double stated preferences experiment

Alongside this, four illustrative scenes are produced, showcasing different infrastructure types as mentioned before. When designing these scenes, the Greek Urban Road Design principles were followed and respected (Hellenic Ministry of Infrastructure and Transport, 2001, 2015). For aesthetic consistency, trees were added to any sidewalk wider than 1.5 meters, a common feature in Athens. Only the first type lacks trees, being dominated by vehicles. These foundational scenes were then altered by adding stationary elements (like crosswalks) and moving ones (cars, bikes, pedestrians). What makes this study unique is the inclusion of live images where road users are shown to move slightly (Rossetti & Daziano, 2022; Tzouras et al., 2020). The pavement conditions are also depicted, and each scene is paired with a text description to aid understanding. To quantify perceived safety, respondents are asked to answer a simple question, namely: *"How safe would you feel on this road?* Four ratings are provided by each respondent, i.e., one per transport model. A sample scenario from the questionnaire form can be found in **Figure 30**.

Scenario 28

You are here:

Please consider that:

1) In this road, **there is no bike lane**,
2) The **speed limit** is equal to **30 km/h**,
3) There are **wide sidewalks** with width bigger than **2.1 meters**,
4) The condition of the pavement is **bad**,
5) **There are zebra pedestrian crossings** that are **controlled by traffic lights**,
6) On the sidewalk, **there are many obstacles** that may hinder your movement,

How safe would you feed in this road? Rate from 1 (very unsafe) to 7 (very safe).

		1: very unsafe	2	3	4: moderate	5	6	7: very safe
to drive a car	4: moderate							
to ride an e-bike	6							
to ride an e-scooter	4: moderate							
to walk	3							

8. Your daily route consists of urban roads with traffic conditions like above. Which transport mode would you select, if you were aware of the travel time and cost you are going to spend?

- ◯ Car (time: 20 minutes and cost: 5.0 euros)
- ◯ E-bike (time: 5 minutes and cost: 3.0 euros)
- ◯ E-scooter (time: 6 minutes and cost: 0.5 euros)
- ◯ Walk (time: 30 minutes and no cost)

Figure 30: Sample scenario from the survey form

The design of the second stated preference experiment is constrained by the first one. The main objective of this process is not only to find scenarios that ensure zero correlation among the independent variables, but their total number is a factor of or equal to the total number of perceived safety scenarios. Meaning, each choice scenario should align with at least one safety perception scenario. The factors from **Equation 20** come into play here. With perceived safety acting as the standalone variable, the orthogonal design reveals which safety score to attach to each choice scenario. To start, 10 experts from the transport planning discipline initially rated perceived safety per pilot scenario that was provided and transport mode. After estimating prior beta parameters and thresholds, these scenarios were paired to minimize the correlations between perceived safety and other factors of the utility function of each transport mode. The final survey design shows a small positive correlation (0.06) between perceived safety and travel time and a small negative one (-0.07) with travel cost. Using this framework, the pilot survey was refined, incorporating a new question that ties both survey parts together: *Which transport mode would you select, if you were aware of the travel time and cost you are going to spend?".*

4.2.4 Models' estimation technique

An ordinal logistic regression (or ordered logit) is performed to estimate the unknown parameters of the perceived safety model. Ordered logit is based on the proportional odds assumption which means that the odds ratio remains constant for all the different Likert Scale intervals (Liddell & Kruschke, 2018; Scott Long, 2015). Hence, there is only one set of beta coefficients per interval to estimate the latent variable (Tzouras et al., 2020). The value of the odds ratio can be interpreted as: for a unit increase in x the odds of being in a perceived safety level equal to or less than or n change by a fixed factor exp(-b) (Tzamourani et al., 2022). The validity of the proportional odds assumption can be evaluated by conducting a X^2 test. If it is found to be invalid, then the dependent ordinal variable should be treated as nominal utilizing classical modeling techniques, such as binary logit or multinomial logit. In **Equation 22**, the ordered logit probability function is shown. Random beta variables have been integrated. To capture heterogeneity in safety perceptions among individuals. Besides the data are panelized which means that there are serious dependencies in the ratings provided by each respondent (Chorus et al., 2013). This study implements a Simulated Maximum Likelihood Estimation (MLE) method to compute panel effects and random beta parameters. The maximization of the joint probability is achieved through a Monte-Carlo Simulation using a pre-specified number of Halton draws. In the end, both fixed unknown variables and the normal distribution of the random ones are exported. The joint probability function to estimate the perceived safety level is given in **Equation 23**.

$$
\begin{aligned}
P(psafe_{\mathrm{l,j,m}} = \mathrm{n} \mid X) &= P(psafe^{*}_{\mathrm{j,l,m}} \leq k_{\mathrm{n,m}}) - P(psafe^{*}_{\mathrm{j,l,m}} \leq k_{\mathrm{n-1,m}}) \\
&= F(k_{\mathrm{n,m}} - psafe^{*}_{\mathrm{j,l,m}}) - F(k_{\mathrm{n-1},m} - psafe^{*}_{\mathrm{j,l,m}}) \\
&= F\left(k_{\mathrm{n,m}} - \sum_{i} \beta_{i,m} \times x_{i,l} + \sum_{t} B_{i,m} \times x_{i,l}\right) - F\left(k_{\mathrm{n-1},m} - \sum_{i} \beta_{i,m} \times x_{i,l} + \sum_{t} B_{i,m} \times x_{i,l}\right) \\
&= \frac{\exp(k_n - \sum_i \beta_{i,m} \times x_{i,l} + \sum_i B_{i,m} \times X_{i,l})}{1 + \exp(k_n - \sum_i \beta_{i,m} \times x_{i,l} + \sum_i B_{i,m} \times X_{i,l})} \\
&+ \frac{\exp(k_{n-1} - \sum_i \beta_{i,m} \times x_{i,l} + \sum_i B_{i,m} \times X_{i,l})}{1 + \exp(k_{n-1} - \sum_i \beta_{i,m} \times x_{i,l} + \sum_i B_{i,m} \times X_{i,l})} \quad (22)
\end{aligned}
$$

where:

n: perceived safety level (scores from 1 to 7),

k_n: perceived safety kappa thresholds of mode m (where $k_0 = -\infty$ and $k_7 = +\infty$),
β_i: random beta variables of perceived safety (where $\beta_0 = 0$, no random constant in the model),
B_t: fixed beta variables of perceived safety (where $B_0 = 0$, no fixed constant in the model),
X: the set of x variables; variable values refer to urban link (or observation) l,
F: cumulative logistic distribution function ($F(x) = \frac{1}{1+\exp(-x)}$).

$$maximize\ L = \int \prod_{l=1}^{L} \prod_{j=1}^{J} P\left(psafe_{\mathrm{l,j,m}} = \mathrm{n} \mid x\right)^{y_{\mathrm{l,j,m}}(n)} \times g(\beta_{\mathrm{i}}) \times d\beta_{\mathrm{i}} \quad (23)$$

<u>where</u>:

L: likelihood,
$y_{\mathrm{l,j,m}}(n)$: 1, if perceived safety level n of using mode m is chosen by individual j in urban link (observation l),
$g(\beta_i|\theta)$: normal probability density function which describes random variable $\beta_i \sim N(\overline{\beta_i}, \sigma_{\beta_i})$.

Binary logistic regression (binary logit) has been utilized in the past to estimate marginal utilities that can indicate the willingness of one traveler to use a new transport mode (Kepaptsoglou et al., 2020; Sorkou et al., 2022) or to choose a particular path (Rossetti & Daziano, 2022; Saplıoğlu & Aydın, 2018). In this study, binary logit is applied to approach the Value-of-Safety (VoS) based on the estimated betas per transport mode. Mode choices can be converted to a binary variable (0 or 1) developed for each transport mode: i.e., to use or not. The probability function of a binary logit model is simpler compared to an ordered logit (see **Equation 24**). In essence, tt gives the chance that the systematic variation of the utility is greater than the error. Again, to capture panel effects, some beta parameters are selected to be random. A new simulated MLE is also performed; the joint probability function of binary logit is given in **Equation 25**.

$$P\left(\varepsilon_{\mathrm{r,j,m}} \le V_{\mathbf{r,j,m}} \mid X\right) = F\left(\sum_i \beta_{i,m} \times x_{i,r} + \sum_i B_{\mathrm{i,m}} \times X_{i,r}\right) = \frac{\exp\left(\sum_i \beta_{i,m} \times x_{i,r} + \sum_i B_{\mathrm{i,m}} \times X_{i,r}\right)}{1 + \exp\left(\sum_i \beta_{i,m} \times x_{i,r} + \sum_i B_{\mathrm{i,m}} \times X_{i,r}\right)} \quad (24)$$

<u>where</u>:

β_{i}: random beta variables of perceived safety (where $\beta_0 = 0$),
B_{t}: fixed beta variables of perceived safety (where $B_0 = ASC_m$).

$$maximize\ L = \int \prod_{r=1}^{R} \prod_{j=1}^{J} P\left(\varepsilon_{\mathrm{r,j,m}} \le V_{\mathrm{r,j,m}} \mid X\right)^{y_{\mathrm{r,j}}(n)} \times g(\beta_i|\theta) \times d\beta_i \quad (25)$$

<u>where</u>:

$y_{\mathrm{l,j,m}}(n)$: 1, if mode m is chosen by individual j to cover first/last mile route r.

In the last step, mixed logit is preferred to develop models that describe the first/last mile mode choice model taking safety perceptions into account. As a technique, panel mixed logit considers not only dependencies among the choices of a respondent but also dependencies that may exist among provided travel options (Molin et al., 2009). This is often called the "red-blue bus problem" (Ben-Akiva

& Bierlaire, 1999) which often leads to overestimated probabilities. To test this, the Alternative Specific Constant (ASC) of each transport mode is selected to be random. In other respects, the logit probability function of the discrete choice model is nothing more than an upgraded version of the binary logit function; a similar estimation technique is used at the end (see **Equations 26 and 27**).

$$P\left(V_{\mathrm{r,j,m}} + \varepsilon_{\mathrm{r,j,m}} > V_{\mathrm{r,j,p}} + \varepsilon_{\mathrm{r,j,p}} \mid x\right) = \frac{\exp\left(\sum_i \beta_{i,m} \times x_{i,r} + \sum_i B_{\mathrm{i,m}} \times X_{i,r}\right)}{\sum_{p=1}^{P} \exp\left(\sum_i \beta_{i,m} \times x_{i,r} + \sum_i B_{\mathrm{i,m}} \times X_{i,r}\right)} \quad (26)$$

$$maximize\ L = \int \prod_{r=1}^{R} \prod_{j=1}^{J} P\left(V_{\mathrm{r,j,m}} + \varepsilon_{\mathrm{r,j,m}} > V_{\mathrm{r,j,p}} + \varepsilon_{\mathrm{r,j,p}} \mid x\right)^{y_{\mathrm{r,j,m}}(n)} \times g(\beta_i|\theta) \times d\beta_i \quad (27)$$

where:
$V_{r,j,p}$: systematic utility of using mode p in first/last mile route r by individual j, $\forall\, p \neq m$,
β_{i}: random beta variables of perceived safety (where $\beta_0 = ASC_m$),
B_{t}: fixed beta variables of perceived safety (where $B_0 = 0$).

All the models are estimated using the newest version of the open-source Python package Pandas Biogeme (i.e., 3.2.10) developed by Prof. M. Bierlaire at Ecole Polytechnique Fédérale de Lausanne (EFPL), Switzerland (Bierlaire, 2019).

4.3 Development of perceived safety models

Overall, 129 individuals responded to the call and took part in the study. Out of these, 67 (51.9%) were men, and 62 (48.1%) were women. 71% were in the age range of 18 to 30. 64% of the group consisted of university students or graduates. The reported average monthly earnings of the participants were roughly 1250€. A mere 4.7% (6 out of 129) of the participants did not possess a driving license. At the same time, 96.9% mentioned that their household has a car, but only 43.1% drive it daily. Interestingly, 6% had a micro-mobility vehicle like an e-scooter, e-bike, or traditional bicycle. These individuals use their micro-mobility vehicles at least weekly, whereas the other 94% use such means either annually (56%) or monthly (33%). The final data set recorded 5771 ratings of subjective safety and 1417 choices. Through an Analysis of Variance (ANOVA), only characteristics like gender, age (under 30 or above), and possession of a driving license emerged as meaningful indicators of perceived safety levels. Therefore, these elements were introduced in the modeling phase.

The median perceived safety score was 5/7. However, there were notable variances in scores based on the transport mode. In approximately 50% of scenarios, participants rated e-scooter as the most unsafe option, giving it a score of "1: very unsafe". In contrast, walking and car driving received high safety scores (above 5/7) in 40.1% and 34.1% of instances respectively. Age played a role in these scores: younger individuals (below 30) averaged a score of 5/7, but older participants gave a median score of 4/7 for all transport types. Women generally felt less safe, as shown by mean scores - 4.49/7 for men and 4.29/7 for women. Those with driving licenses generally gave higher safety scores, but the group without licenses was too small to draw substantial conclusions. **Figure 31** illustrates the above-mentioned statistical trends.

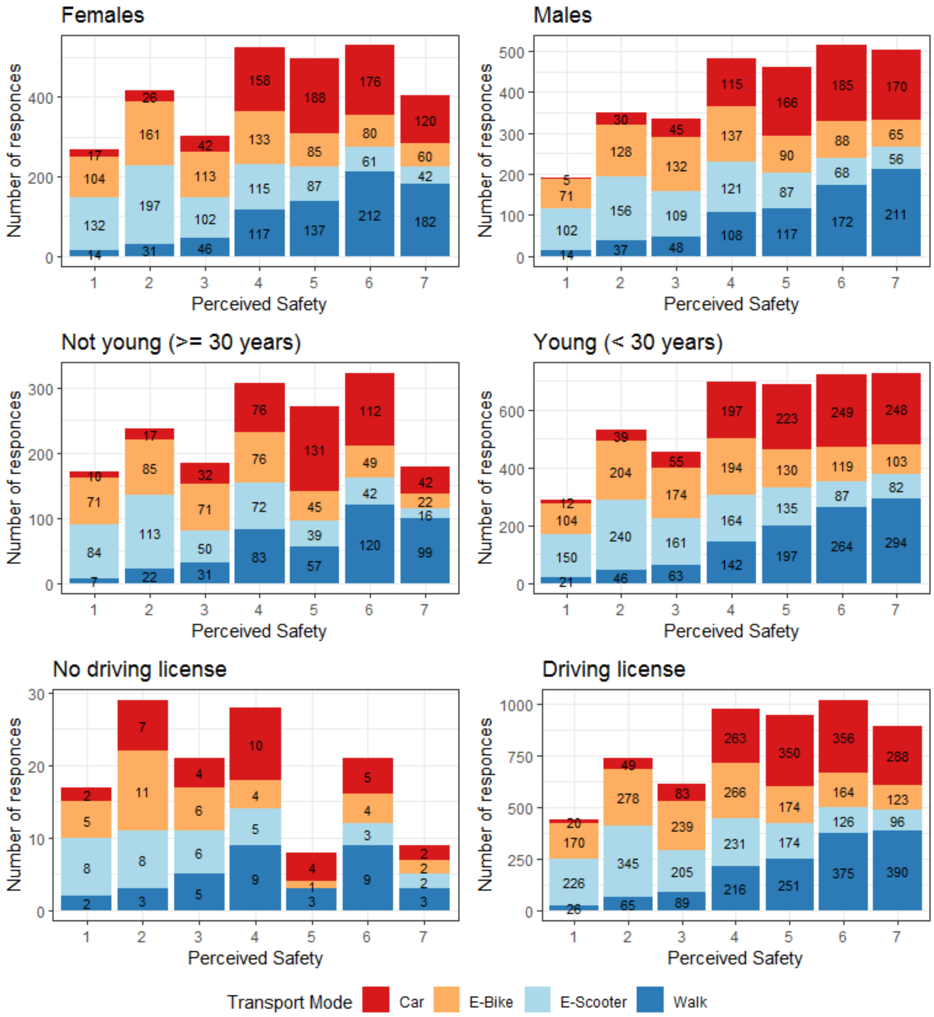

Figure 31: Stacked bars that present perceived safety ratings per transport mode and social group.

Figure 32 shows how mixed traffic conditions influence perceived safety scores. A high density of vehicles or pedestrians appears to decrease the likelihood a respondent will rate the perceived safety of car driving with the highest score, i.e., 7. E-bike safety perception is impacted more by vehicle density, but for e-scooters, there's no clear relationship. If bike density surpasses 50 bikes/km/dir, pedestrians' perceived safety decreases according to survey responses.

A Kendall correlation test was utilized to identify potential correlations, especially among socio-demographic and travel behavior characteristics. The correlation analysis confirmed no significant correlations among explanatory variables considering a 95% confidence level. Then, the proportional odds assumption was examined using a chi-squared test, comparing models with and without this assumption. For a 95% confidence level, this assumption holds for e-bike and e-scooter safety perceptions but fails for private cars and walking. This means that binary or multinomial logit models may more accurately represent safety perceptions. As a result, situations can be more effectively divided into "safe" or "not safe" for driving/walking. This also highlights the variation in safety perceptions. However, ordered logistic regression continues to be used in the next modeling steps, facilitating comparison between the estimated beta coefficients.

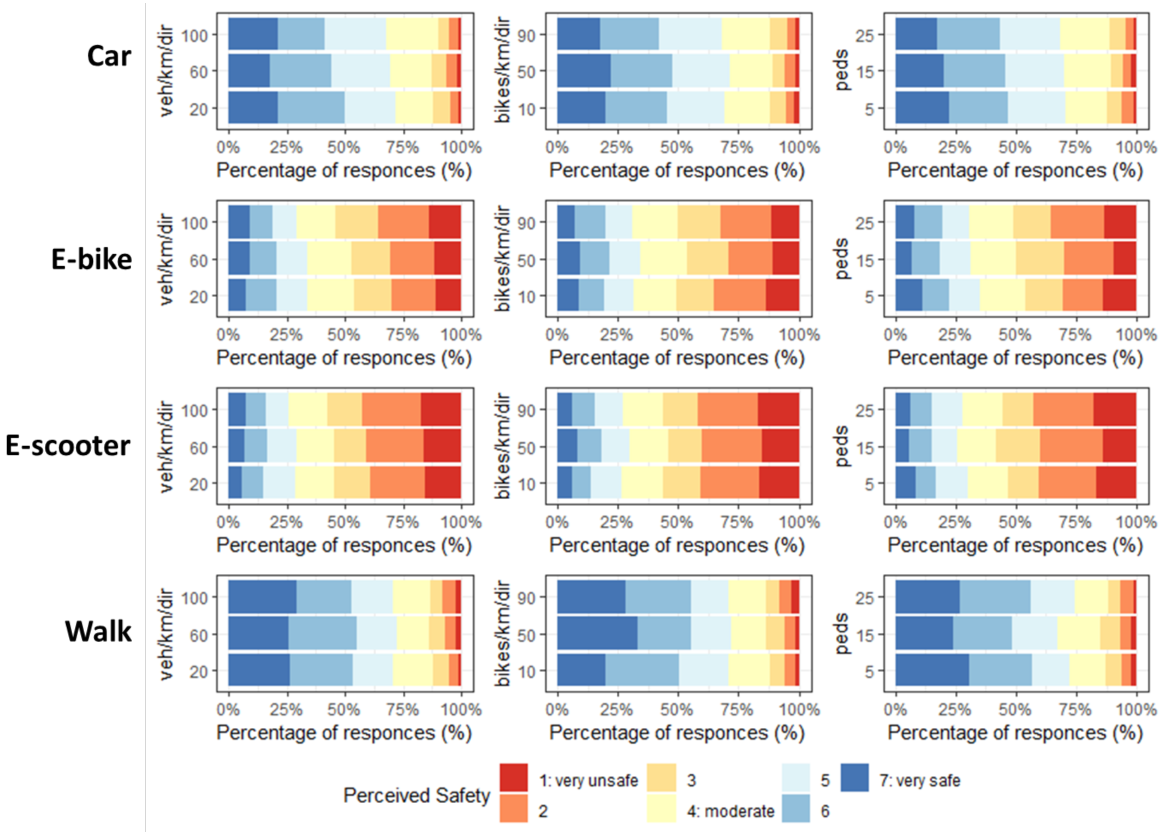

Figure 32: Horizontal 100% stacked bars that present the impact of each traffic condition variable on perceived safety ratings per transport mode.

Table 14 presents the model results. For car driving safety perception, infrastructure type, obstacles, and road surface quality are statistically significant at a 95% confidence level. Surprisingly, the beta value for unsignalized pedestrian crossings was negative across all modes of transport (car: -0.780, e-bike: -0.458, e-scooter: -0.565 and walk: -1.702 utils), whereas signalized crossings did noy show a meaningful difference from no “zebra” crossing case. E-bike users' perceptions were significantly influenced by car traffic density (-0.005 utils/veh/km). All infrastructure-related parameters had negative values, indicating type 3 was seen as safest for both e-bikes and e-scooters. E-scooter users were not impacted by surrounding traffic, while pedestrian safety perceptions were influenced by high bike (including e-bikes and e-scooter) densities (-0.005 utils/bikes/km).

When estimating safety perception models, the beta values for infrastructure type were chosen to be random. **Figure 33** depicts the variation in individual safety perceptions, with beta coefficients having insignificant standard deviations shown by vertical lines. Centering on mean values, shared spaces are viewed as safer for e-bike, e-scooter, or walking (car: -0.937, e-bike: -3.930, e-scooter: -2.738 and walk: -0.521 utils) when compared to infrastructure types 1 (car: -0.840, e-bike: -5.649, e-scooter: -4.531 and walk: -2.466 utils) and 2 (car: -0.154, e-bike: -4.801, e-scooter: -3.410 and walk: -0.909 utils).

Concurrently, the heterogeneity in opinions of individuals about this unconventional design seems to be lower compared to type 1 which is the highest in all transport modes, except e-bikes.

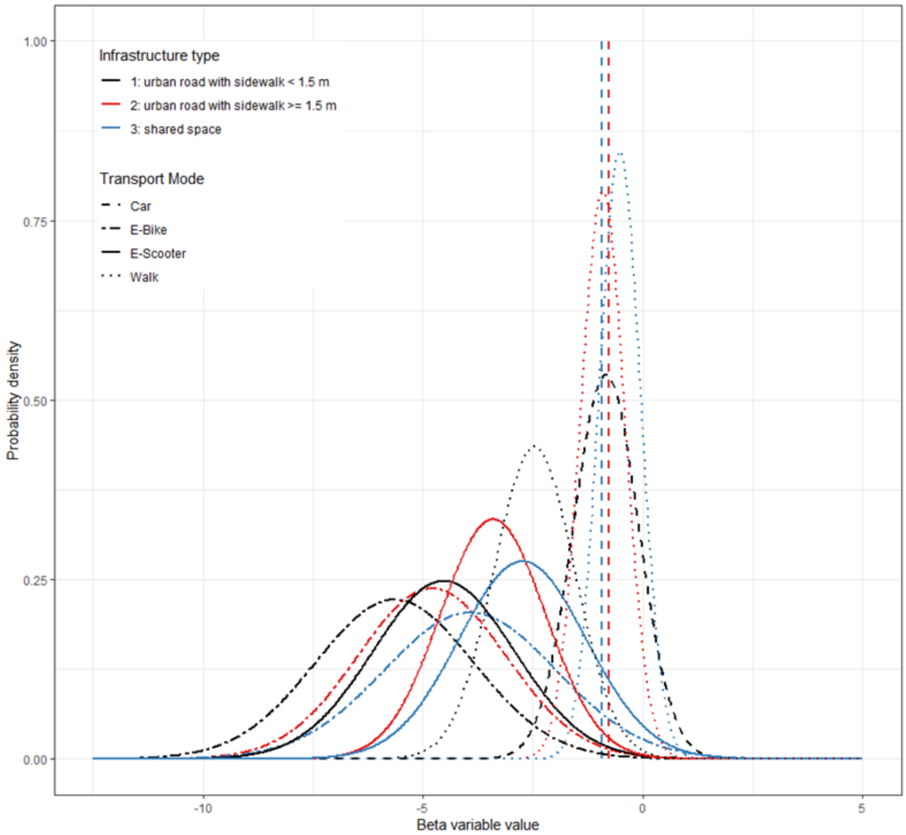

Figure 33: Normal distributions of infrastructure type random beta parameters per transport mode

4.4 Exploring the impact of perceived safety

In the model assessments, the perceived safety ratings given by respondents for each scenario and transport method are used. The predictions from the perceived safety model are not incorporated at this stage, ensuring that the two modeling phases are independent of each other.

For each mode of transport, a binary logistic regression is employed to model the first/last mile route selection. Variables like travel time, cost, and perceived safety are chosen to be random. **Table 15** displays the outcomes of this procedure. Evidently, in every instance, perceived safety emerges as a statistically significant positive factor, indicating that the greater its score, the higher the willingness to use this transport mode in a specific route. Notably, the beta coefficient for the travel time associated with e-bike usage is positive at 0.020 utils/min. Its standard deviation is almost zero with 95% confidence, suggesting a strong consensus among users who view e-bikes more for leisure. Also, the e-bike model's ASC is not significant, indicating that factors such as service cost and the perceived safety of the chosen route adequately explain people's hesitancy to use e-bikes. The model for choosing e-scooters for daily commutes showed the highest McFadden's Rho value at 0.546. This high level of fit emphasizes the importance of safety perceptions in mode selection. The beta parameter for perceived safety has an insignificant standard deviation, indicating a consensus among respondents. For e-scooters, unlike e-bikes, both travel time and cost have negative beta values. Among all the transport modes, walking has the lowest mean value for the perceived safety coefficient, with specific values being: car: 0.298, e-bike: 0.636, e-scooter: 0.431, and walk: 0.119 utils/lev.

To derive the Value-of-Safety (VoS) using both random and fixed parameters, a new Monte-Carlo simulation is conducted. This involves 20,000 draws from normal distributions using parameters defined in the binary logit models. Specific speed and cost rates are applied, namely: car at 40 km/h and 0.15 EUR/km, e-bike at 20 km/h and 0.75 EUR/km, e-scooter at 15 km/h and 0.94 EUR/km and walking at 5 km/h with no cost. **Figure 34** gives the results of this analysis, with detailed statistics also presented. For car users, the average VoS is -2.64 km/lev, signifying that drivers are prepared to forgo 2.64 km to gain an additional safety level. For e-bikes, one safety level is worth 2.61 km, while for e-scooters, it is significantly less at about -660 m. Pedestrians are willing to reduce their route by just 180 ± 3.2 m to ensure a safer journey (+1 safety level).

Lastly, a Mixed Logit model is estimated using 5,000 Halton draws to depict mode choices in first/last mile journeys, as presented in **Table 16**. To account for interdependencies among choices, both the ASCs and perceived safety's beta coefficients are treated as random. The results indicate a pronounced heterogeneity in individual transport mode choices, with significant standard deviations for constant coefficients. However, the mean ASC values for both e-bike and e-scooter use are close to zero. Both travel time and cost emerge as significant factors with negative beta coefficients, with the McFaddens' Rho valued at 0.336.

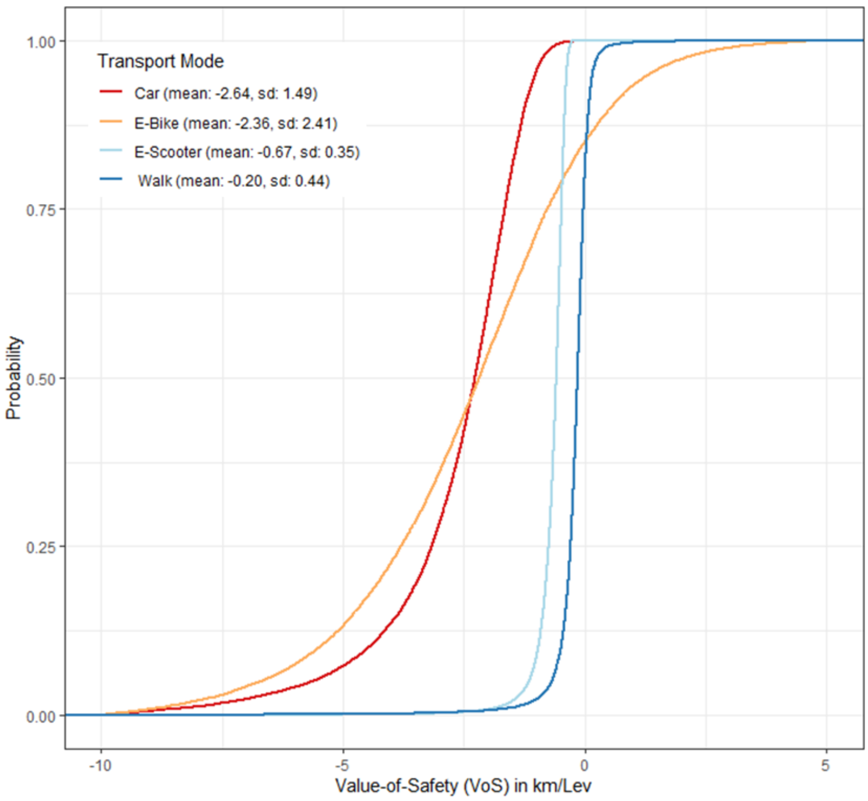

Figure 34: Cumulative distribution functions of the Value-of -Safety per transport mode – Monte-Carlo simulation

Table 14: Perceived safety models

	Car			E-bike			E-scooter			Walk		
	Est.	**Std. E**	**P(>|z|)**	**Est.**	**Std. E**	**P(>|z|)**	**Est.**	**Std. E**	**P(>|z|)**	**Est.**	**Std. E**	**P(>|z|)**
Gender (1, if male)	0.622	0.235	0.008	0.349	0.215	0.104	0.408	0.230	0.076	-0.055	0.246	0.823
Age group (1, if < 30 years old)	0.707	0.252	0.005	0.758	0.229	0.001	0.739	0.248	0.003	0.455	0.260	0.080
Driving license (1, if yes)	2.678	0.762	< 0.001	0.221	0.714	0.757	-0.320	0.936	0.733	2.266	0.630	< 0.001
With pedestrian crossings, not controlled by traffic lights (1, if yes)	-0.780	0.130	< 0.001	-0.458	0.136	0.001	-0.565	0.137	0.000	-1.702	0.142	< 0.001
With pedestrian crossings controlled by traffic lights (1, if yes)	0.023	0.129	0.858	0.052	0.135	0.701	0.056	0.135	0.678	0.030	0.132	0.818
With good pavement condition (1, if yes)	1.447	0.127	< 0.001	0.918	0.115	< 0.001	1.043	0.119	< 0.001	0.258	0.118	0.028
Without obstacles (1, if yes)	0.236	0.115	0.040	0.408	0.108	< 0.001	0.549	0.114	< 0.001	1.065	0.119	< 0.001
Vehicle density (veh/km/dir)	-0.002	0.002	0.480	-0.005	0.002	0.017	-0.002	0.002	0.322	0.002	0.002	0.334
Bike density (bikes/km/dir)	-0.001	0.002	0.434	0.000	0.002	0.827	-0.002	0.002	0.417	0.004	0.002	0.050
Pedestrians in the road env (peds)	-0.005	0.010	0.584	-0.009	0.008	0.257	-0.004	0.008	0.625	0.006	0.009	0.503
Infrastructure type – Mean values												
Urban road with sidewalks < 1.5 m wide (1, if yes)	-0.840	0.188	< 0.001	-5.649	0.286	< 0.001	-4.531	0.278	< 0.001	-2.466	0.204	< 0.001
Urban road with sidewalks > 1.5 m wide (1, if yes)	-0.781	0.154	< 0.001	-4.801	0.257	< 0.001	-3.410	0.214	< 0.001	-0.909	0.162	< 0.001
Shared space (1, if yes)	-0.937	0.167	< 0.001	-3.930	0.256	< 0.001	-2.738	0.228	< 0.001	-0.521	0.170	0.002
Infrastructure type – Std. Dev. values												
Urban road with sidewalks < 1.5 m wide	0.745	0.232	0.001	1.797	0.201	< 0.001	1.609	0.225	< 0.001	0.917	0.207	< 0.001
Urban road with sidewalks > 1.5 m wide	0.124	0.403	0.759	1.679	0.180	< 0.001	1.195	0.256	< 0.001	0.504	0.304	0.097
Shared space	0.321	0.402	0.425	1.958	0.216	< 0.001	1.449	0.241	< 0.001	0.471	0.279	0.092
kappa 1	-2.927		< 0.001	-6.720		< 0.001	-4.960		< 0.001	-4.133		< 0.001
kappa 2	-1.315		< 0.001	-4.259		< 0.001	-2.518		< 0.001	-2.400		< 0.001
kappa 3	-0.195		< 0.001	-2.649		< 0.001	-1.295		< 0.001	-1.242		< 0.001
kappa 4	1.643		< 0.001	-0.859		< 0.001	0.103		< 0.001	0.423		< 0.001
kappa 5	3.351		< 0.001	0.497		< 0.001	1.372		< 0.001	1.788		< 0.001
kappa 6	5.433		< 0.001	2.232		< 0.001	2.848		< 0.001	3.758		< 0.001
Number of observations	1443			1443			1443			1443		
Number of individuals	129			129			129			129		
Null loglikelihood (zero-coefficients)	-2777			-2845			-2933			-2951		
Loglikelihood at convergence	-2065			-2191			-2231			-2054		
Halton draws	2000			2000			2000			2000		

Table 15: Binary logit (BL) route choice models (with random beta parameters)

	BL route model - Car			BL route model E-bike			BL route model E-scooter			BL route model Walk		
	Est.	Std. E	P(>|z|)	Est.	Std. E	P(>|z|)	Est.	Std. E	P(>|z|)	Est.	Std. E	P(>|z|)
Alternative specific constant	1.880	0.300	< 0.001	0.0031	0.225	0.890	-0.475	0.230	0.039	1.080	0.176	< 0.001
Mean values												
Travel time in minutes	-0.045	0.006	< 0.001	0.020	0.009	0.0281	- 0.042	0.013	0.008	-0.066	0.007	< 0.001
Travel cost in euros	-0.410	0.057	< 0.001	- 0.456	0.063	< 0.001	-0.606	0.109	< 0.001			
Perceived safety in levels	0.298	0.061	< 0.001	0.636	0.081	< 0.001	0.431	0.064	< 0.001	0.119	0.056	0.036
Std. Dev. values												
Travel time in minutes	0.032	0.008	< 0.001	0.003	0.012	0.782	0.043	0.011	< 0.001	- 0.025	0.005	< 0.001
Travel cost in euros	0.124	0.040	0.039	0.117	0.062	0.057	0.143	0.104	0.167			
Perceived safety in levels	0.085	0.0701	0.224	0.613	0.096	< 0.001	0.049	0.075	0.506	-0.139	0.064	0.027
Number of observations	1417			1417			1417			1417		
Number of individuals	120			120			120			120		
Null loglikelihood	-982.2			-982.2			-982.2			-982.2		
Loglikelihood at convergence	-811.5			-660.9			-455.9			-563.7		
McFadden's Rho	0.174			0.327			0.546			0.426		
Halton draws	5000			5000			5000			5000		

Table 16: Mixed logit (ML) mode choice models (with random alternative specific constants and beta parameters)

	ML mode choice model											
	Car			E-bike			E-scooter			Walk		
	Est.	Std. E	P(>|z|)	Est.	Std. E	P(>|z|)	Est.	Std. E	P(>|z|)	Est.	Std. E	P(>|z|)
Travel time in minutes	-0.053	0.006	< 0.001	-0.076	0.013	< 0.001	-0.078	0.011	< 0.001	-0.057	0.0038	< 0.001
Travel cost in euros	-0.424	0.065	< 0.001	-0.466	0.059	< 0.001	-0.560	0.077	< 0.001			
Mean Values												
Alternative specific constant				-0.174	0.428	0.684	-0.688	-0.439	0.117	-0.681	0.401	0.089
Perceived safety in levels	0.450	0.085	< 0.001	0.844	0.056	< 0.001	0.763	0.063	< 0.001	0.440	0.063	< 0.001
Std. Dev. values												
Alternative specific constant				1.260	0.208	< 0.001	1.320	0.259	< 0.001	1.490	0.248	< 0.001
Perceived safety in levels	0.206	0.097	0.034	0.228	0.072	0.001	0.074	0.083	0.372	0.173	0.086	0.044
Number of observations	1417											
Number of individuals	120											
Null loglikelihood	-982.2											
Loglikelihood at convergence	-811.5											
McFadden's Rho	0.174											
Halton draws	5000											

4.5 Discussion

The survey indicated that among various transport modes, e-scooters were generally perceived as the least safe in the road settings shown to participants. Following e-scooters, e-bikes were considered the next least safe, with walking and cars viewed as the safest among active modes. This perception mirrors findings from prior research which emphasized safety apprehensions and unease surrounding e-scooters as compared to e-bikes (Bai et al., 2017b; Kopplin et al., 2021). Female participants seemed to have more safety concerns about micro-mobility options, such as e-bikes and e-scooters, than their male counterparts. This gender-based difference aligns with earlier studies that observed women being more cautious in their safety assessments (Akgün-Tanbay et al., 2022; Fitch et al., 2022; Hidayati et al., 2020). Moreover, older individuals (those above 30) were less inclined to use micro-mobility means, especially e-scooters; they do not feel safe enough to ride in complex urban road environments. Consequently, younger individuals, particularly those well-acquainted with technology, are more attracted to micro-mobility services (Eccarius & Lu, 2020; Hosseinzadeh et al., 2021; Merlin et al., 2021; Nikiforiadis et al., 2021). This trend is observable in Athens, Greece, where the usage of e-scooters and e-bikes is less than 2%. The study explored potential reasons for this, pinpointing the lack of specialized cycling lanes as a significant factor. Most road users prefer designs that prioritize the segregation of traffic, unlike designs that allocate more space to vehicles. Prior research on cycling safety supports this preference, suggesting segregated cycling lanes positively impact users' mobility habits due to increased safety perception (Branion-Calles et al., 2019; Calvey et al., 2015; Chataway et al., 2014; Reggiani et al., 2022).

However, when considering road infrastructure, the availability of public space also plays a crucial role. Thus, the idea of shared spaces emerges as a potential solution, offering a balance for all road users. Interestingly, there is a broader consensus about the safety benefits of shared spaces, especially when compared to car-dominated road designs. Shared spaces might lead to uniform driving or riding behaviors, potentially reducing speed discrepancies (Kaparias & Wang, 2020; Karndacharuk et al., 2014; Tzouras et al., 2022).

This research concentrated on static objects - road features and found that pedestrians often view crosswalks without traffic signals as more dangerous than having no crosswalks at all. This observation echoes the results from Gill et al. (2022). However, it is worth highlighting that drivers in Greece are infamously known for not giving way at non-signalized pedestrian crossings. This behavior likely amplifies pedestrians' feelings of vulnerability and leads to general road user frustration. The condition of the road, including the presence of impediments, is a pivotal safety factor for both those on two wheels and pedestrians. Surfaces like cracked pavements, roads with potholes, or cobblestone streets enhance the vibrations felt on e-scooters, deterring novice micro-mobility users from choosing them, as has been indicated by several studies (Calvey et al., 2015; Kaparias & Li, 2021; Ma et al., 2021; Sorkou et al., 2022).

In terms of interactions with traffic, the perceived safety while driving a car was not notably affected by the presence of other vehicles or road users. Surprisingly, similar perceptions were noted for e-scooter riders. However, the dual nature of micro-mobility, as described by Tuncer et al. (2020), appears to pose a (perceived) risk to pedestrians. On the other hand, e-bike riders seem to desire more space from motorized traffic. In particular, their perceived safety drops with increasing traffic volume but does not have a strong relation to the presence of pedestrians. This aligns with Gkekas et al. (2020) who noted that cyclists are not as bothered by interactions in spaces shared with non-motorized users as pedestrians are.

One of the complex aspects of this method was linking perceived ratings from the initial stated preferences test to mode choices from the subsequent one. This research introduced an innovative way to structure such an investigation. A crucial takeaway from this analysis is the determination of VoS for each mode of transport. VoS illustrates the maximum added distance a traveler is prepared to undertake to ensure a safer trip by one safety level. Therefore, high VoS results in higher flexibility of the examined mode that is expressed in a relatively more detouring behavior. However, it is. essential to recognize that VoS is closely tied to each mode's travel speed. Contrary to expectations, e-bikes had a VoS nearly equal to that of private cars. This could be attributed to a positive beta parameter for e-bike travel time in the binary regression model. Rosseti and Daziano (2022) study reported a comparable finding regarding route choices for novice cyclists. Inexperienced cyclists tend to perceive e-bikes as a mode to have fun, train, or relax; yet this perception is not common to all of them. This heterogeneity is underscored by the wide range in the VoS for e-bikes, whereas e-scooters show greater consistency. The study's findings suggest that in precarious road conditions, potential e-scooter users would rather avoid the mode than alter their routes. Previous research has emphasized that e-scooters might not be the most adaptable mode for navigating dense urban areas, as their flexibility is largely constrained by user safety concerns (Aman et al., 2021; Branion-Calles et al., 2019; Sanders et al., 2020; Sorkou et al., 2022). The mixed logit model detailing mode selection pointed out significant interdependencies in the choices given to participants. Indeed, the standard deviations of the mode-specific constant were significant. Nonetheless, it was demonstrated that the inclination to use a micro-mobility vehicle can be systematically linked to perceived safety, particularly in urban areas lacking a dense cycling network infrastructure.

5 Development of network simulation tools

In this section, the development of two simulation experiments of shared space networks and their results are described. To do so, two already developed agent-based scenarios are utilized, namely: Open-Berlin and The Scenario Athens.

5.1 State of the art

First, the literature is reviewed with the aim to present previous simulation applications of shared space and the challenges. Additionally, characteristics of existing ABM tools are described; this helps to select the most suitable simulation package to approach the remaining research questions.

5.1.1 Simulation studies about shared space

Research has been made on microscopic modeling of road users' behavior in shared space. Most of them improved tools coming from the Social Force Model (SFM) to describe the complicated interactions occurring in these mixed-traffic road environments.

In 2011, a pioneering effort emerged from the research team at TU Graz, as they began developing a specialized micro-simulation for shared space areas and intersections (Schonauer, 2017; Schönauer et al., 2012b). Subsequent studies, like this by Rudloff and Schönauer et al. (2014) furthered this initiative, attempting to validate and calibrate the original model using PTV Vissim. Their innovative approach combined an infrastructure model with an operational SFM and integrated models for cars and bicycles. This approach also incorporated a tactical conflict-resolving game to accurately portray the varying behaviors of road users within a shared space. This enriched methodology, illustrated vividly in a methodological flow diagram (see **Figure 35**), was structured around three core components: the strategic infrastructure model, the tactical model, and the operational model. At its core, the infrastructure model defines the movement area, guiding fields to direct agents on lateral paths, and obstacles to maintain distance between agents. Remarkably akin to the shared space division approach, this model used Vissim SFM for pedestrians as its operational base. However, given the speed differences between vehicles and pedestrians, conflicts could not be entirely addressed by the SFM. This gap led to the introduction of a tactical game inspired by game theory. Using a non-symmetric hierarchical game structure, a leader-follower dynamic emerged, where the leader develops strategies, and followers adapt accordingly. This game-solving mechanism is based on random utility maximization, underlining the players' capacity to fully grasp each other's deterministic utility components. Consequently, the leader could strategically maximize expected utility, ensuring a more fluid and realistic shared space interaction.

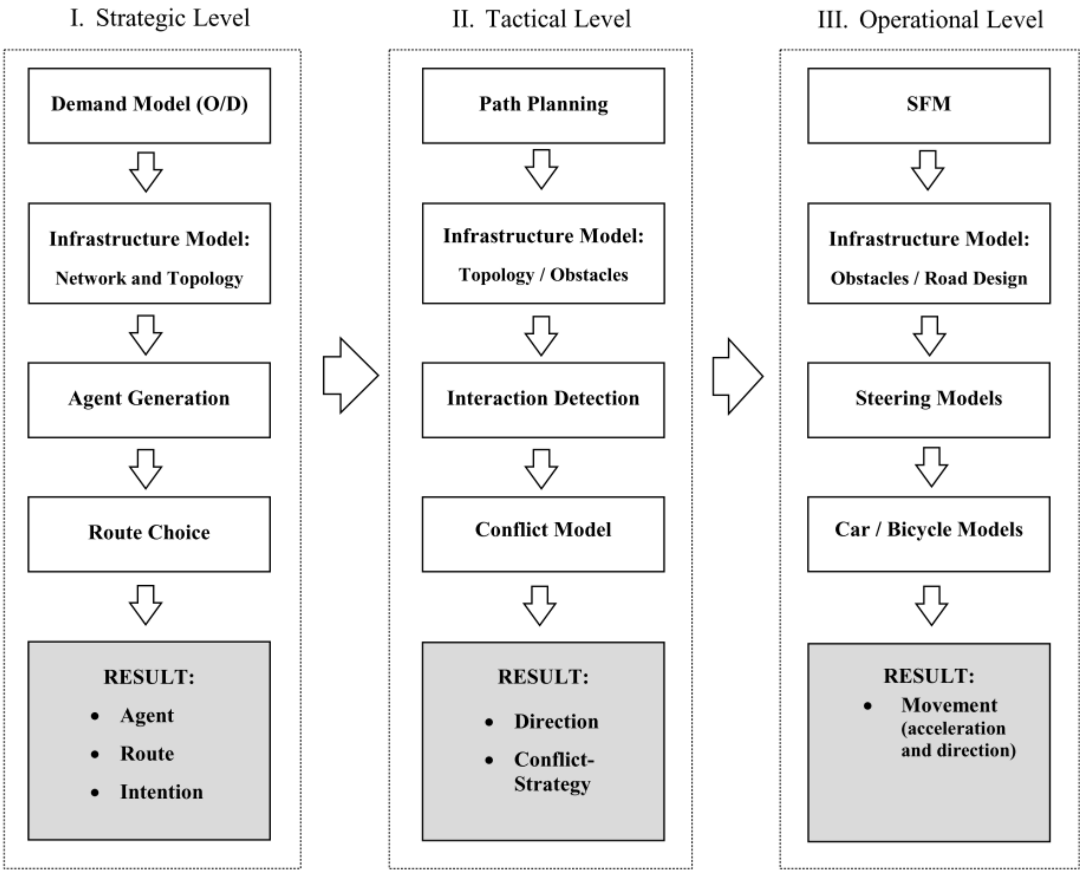

Figure 35: Methodological framework of Schönauer et al. model
Source: (Schonauer, 2017)

Pascucci et al. (2015b) attempted to build a multi-layer micro-simulation framework capable of simulating the movements of road users in shared spaces. Later, Rinke et al. (2017b) extended this framework by improving vehicle-pedestrian interactions and implementing models for cyclists and groups of pedestrians. In general, the model unfolds methodically, starting with preliminary operations: users emerge from origin points and are set on their Free Flow Trajectory while accounting for impulsive and repulsive forces to cope with upcoming interactions. This is immediately followed by the conflict detection, classification, and reaction stage, which identifies potential clashes between road users and pinpoints appropriate reactive measures. Once conflicts are addressed, users' new positions are recalculated through the move objects phase, using the acceleration data from the SFM.

The model intricately captures the behavioral nuances of different road users. In free flow, the primary objective of all road users is efficient navigation, with an emphasis on shortest paths and minimal obstruction from static challenges. The model employs a weighted visibility graph for this purpose, utilizing the Dijkstra algorithm for optimal route calculation, and refining paths for realism with point-to-point clothoids. Vehicles, constrained by their space and mobility, typically exercise caution, especially around vulnerable users (see **Figure 36**). Pedestrians, however, with their agility at slower speeds, easily alter direction and speed but tend to follow the shortest paths, making slight adjustments when necessary. Cyclists add complexity due to their unpredictable trajectories. In more congested environments, the model emphasizes collision prediction and precautionary actions, with users like pedestrians often slightly veering to the right to prevent impending collisions. The Social Force Model, foundational to this framework, sees users as vigilant entities constantly scanning their environment, particularly monitoring potential Competitive Users. Using methods like the Lagrangian polynomial, future trajectories of these competitive users are predicted, enabling proactive collision-avoidance strategies. This is particularly crucial in scenarios where immediate evasive action is required, with the model adapting its parameters to ensure safety and continuity in such shared spaces.

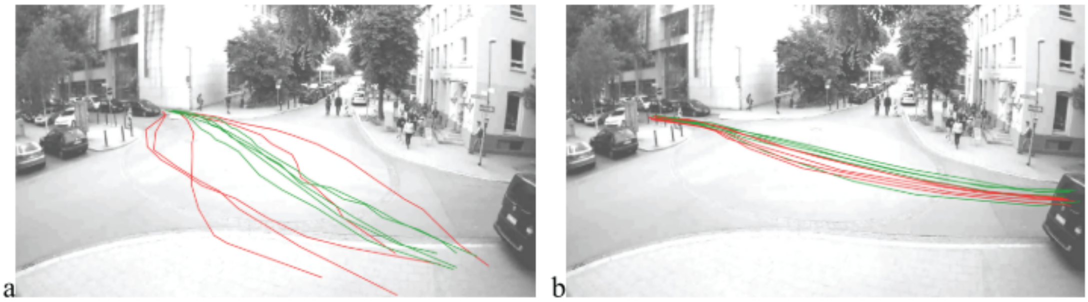

Figure 36: Modeled trajectories of pedestrians vs cars in shared space
Source: (Pascucci et al., 2015b)

Anvari et al. (2015) developed a three-layered mathematical model to simulate the movements of diverse agents, including both vehicles and pedestrians, within a shared space environment (see **Figure 37**). These spaces are distinguished by single surface pavements, no lane discipline, and identical priority for all road users. The foundational layer, known as the trajectory planning layer, ensures efficiency by determining the most direct route for participants, considering both their final and interim destinations considering the space's structural layout. Progressing to the second layer, the force-based layer refines this path by employing a modified Social Force Model. Here, vehicles and pedestrians are allocated distinct social and physical forces, simulating the nuanced interactions, mutual navigational negotiation mechanisms, and strategies to avoid static obstacles. Notably, this layer also encloses unique driving behaviors like overtaking and following, especially significant given the lack of specialized lanes. The final layer, termed the rule-based layer, introduces regulations controlling vehicle movements, correlating their steering capabilities with their speeds. This relationship is particularly grounded in the centrifugal acceleration a driver may experience. Furthermore, to preempt potential collisions, specific protocols are integrated, with conflicts being addressed and mitigated through well-defined avoidance mechanisms. An interesting detail of this approach is the introduction of left-hand traffic for vehicles moving in opposite directions, reinforcing the conflict-avoidance ethos. In a follow-up study, Anvari et al. (2016) utilized recorded trajectories from Exhibition Str. in London to calibrate and validate their models.

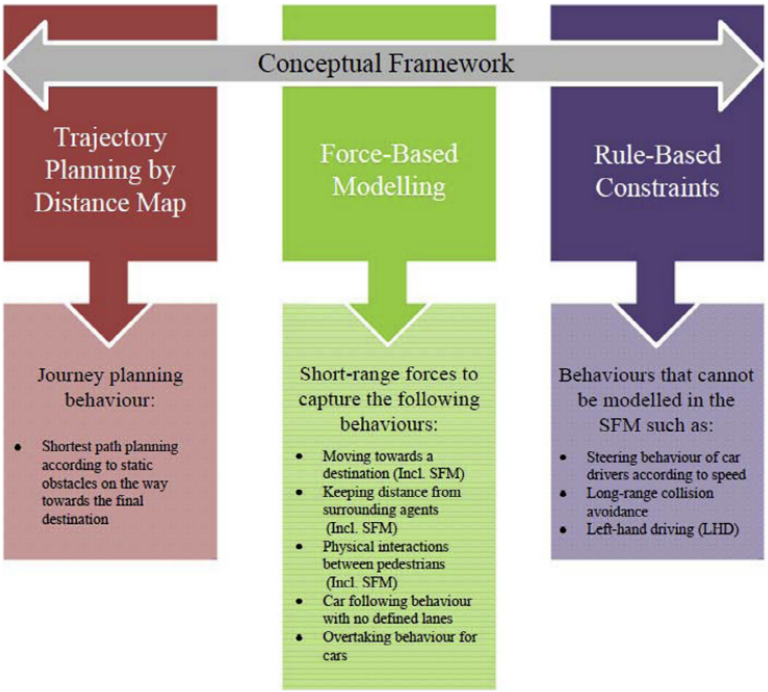

Figure 37: Methodological framework of Anvari et al. shared space simulation model
Source: (Anvari et al., 2015)

Popular commercial microscopic traffic simulation software like PTV Vissim and Aimsun currently lack built-in functionalities to accurately simulate shared space. Though numerous simulation models have emerged, they are not yet accessible to the general public, i.e., planners, engineers, and policymakers. The primary objective of the study of Schmid (2018b) was to devise a model that strikes a balance between complexity and the ability to assess the capacity and traffic quality of Free Crossing Areas (as shared spaces are called), especially when compared to traditional pedestrian crossing setups. PTV Vissim is adept at depicting individual vehicle and pedestrian behaviors, but its ability to control their mutual (and complex) interactions is restricted. This limitation stems from relying heavily on tools such as "priority rules" and "conflict areas", which, while suitable for standard crossings, fall short in the complex dynamics of shared space. When multiple users share a space and their unchanged behaviors result in a collision, the system should flags it as a conflict. There are instances where preemptively avoiding a collision is not feasible, perhaps due to misinterpretations or unobservable actions caused by obstructions. To tackle these challenges, the model employed a series of (very) thin pedestrian links, which, while slightly overlapping, ensure that pedestrians retain their diagonal movement. However, in Vissim, pedestrians inherently cannot "detect" cars. A novel solution involves representing every car with a set of "dummy pedestrians", made possible through event-driven scripts. Additionally, these scripts control the behavior of road users, determining if they are aggressive or prudent. In conclusion, a caveat to this model is its inherent limitations arising from oversimplified assumptions.

The research of Frosch, Martinelli and Unnikrishnan (2019b) aimed to evolve microsimulation traffic modeling in order to evaluate shared based on metrics like travel time and delay. To achieve a realistic representation, vehicular and pedestrian traffic volumes, alongside turning movements, were gathered to construct a simulation experiment in PTV Vissim. Traditional methods, such as conflict areas or priority rules, determined the right-of-way between vehicles and pedestrians, letting the modeler dictate flow precedence. However, an innovation introduced a flexible option within the conflict area tool, allowing simulated users to perceive potential conflicts. Decisions on precedence were influenced by a range of metrics, i.e., arrival time, speed, distance from potential conflict, and user aggression levels. Crucially, adjustments like reducing lane/link width to 6 feet enhanced the model's realism by prompting vehicles to yield only when collisions were imminent, mirroring genuine shared space dynamics. Ultimately, the study demonstrated that tools like Vissim could be adeptly leveraged to simulate and assess shared spaces as viable solutions to traffic congestion. This adaptable methodology provided planners and engineers with a replicable blueprint for analyzing unique shared space configurations.

5.1.2 Agent-Based simulation models

In recent years, especially over the past decade, large urban zones and road networks have seen traffic operations being replicated using Agent-Based Models (ABMs) (Kagho et al., 2020). These simulation frameworks have been expanded and assimilated into existing systems to model the repercussions and comprehensive performance of pioneering transport modes like shared autonomous vehicles, electric taxis, on-demand buses, electric scooters, etc. (Li et al., 2021).

TRANSIMS (TRANSportation ANalysis and Simulation System) developed by the Los Alamos National Laboratory for the US Department of Transportation, TRANSIMS is a pioneering agent-based model used primarily for large-scale traffic simulation (Jeihani et al., 2006; Simon et al., 1999). Its open-source microscopic simulation, coded in C++, is aimed at capturing the intricate travel behaviors in metropolitan networks that conventional four-stage models might miss (Raney et al., 2003). TRANSIMS can simulate trips of more than 30 million agents using high-performance compute clusters with more than 180 TB of disk space (Lee et al., 2014). TRANSIMS structure is divided into a) Population Synthesizer that constructs a simulated population, each with unique socio-demographic attributes, based on data sources like census records and road network information, b) Activity Demand Generator that establishes daily trip chains for each agent, detailing activity timings, locations, and preferences, c) Intermodal Route Planner that assigns time-sensitive optimal paths for every planned trip, d) Regional Micro-simulator that computes travel times and possible delays using a Cellular Automata strategy, which divides road sections into 7.5m cells, equivalent to one vehicle's space (Guo et al., 2013; Lee et al., 2014). Outputs from TRANSIMS offer extensive insights, from vehicle trajectories and road traffic volumes to average speeds and total vehicle distances.

Originating from Northwestern University, USA, **NetLogo**[16] is an intuitive, open-source multi-agent simulation platform crafted in JAVA (Tisue and Wilensky, 2004). Primarily designed for educational and research activities, it can model diverse interactive systems, including traffic interactions. NetLogo agent types comprise a) Patches which are Fixed agents representing the 2D environment, b) Turtles which are mobile agents with distinct behaviors, which in traffic simulations, represent vehicles, c) Links that represent relationships between agents and d) Observers which oversee the agents and collect necessary data. Vehicles, or "turtles", are independent entities whose microscopic movements, from accelerating to lane switching, are guided by specified models (Han et al., 2015). NetLogo considers attributes of vehicles and drivers, such as intended speed or reaction times. Using its vast library, users can program (i.e., setting the rules) agents for various applications (Hayatnagarkar and Murali Krishna, 2016). However, NetLogo does have scalability issues, which can affect the simulation of larger networks (Auld et al., 2016).

MATSim (Multi-Agent Transport Simulation) is a JAVA-based, open-source simulation platform collaboratively developed by the Swiss Federal Institute of Technology in Zürich (ETH Zurich) and the Technical University of Berlin (TU Berlin), (Axhausen et al., 2016). The platform has the capability to model large and complex networks populated with a vast number of agents. Owing to its mesoscopic nature, MATSim ensures a considerable reduction in computation time, especially when modeling expansive urban road systems (Charypar, 2008; Charypar et al., 2009a). The core mechanism of MATSim revolves around a stochastic co-evolutionary algorithm that targets a balance point where there is no further enhancement in the average scores of agent plans. This algorithm operates through a tri-fold simulation loop: In plan execution, MATSim utilizes a queue-based traffic simulation approach to deduce trip-specific travel times, which subsequently get integrated into the scoring functions. The scoring function relies on a utility function to evaluate each plan's value. The utility of any given plan diminishes with decreasing activity duration and increasing travel time or costs (Nagel et al., 2016). MATSim, in the replanning phase, reshufflesplans for a select group of agents by altering aspects such as the transport mode, travel route, or timing of activities. The algorithm's culmination involves the selection of a plan, steered by pre-established strategies. This could be a straightforward choice of the most optimal plan, or a selection influenced by probabilities stemming from a multinomial logit (MNL) model, among other methods. As for the outputs generated by MATSim, they span a range from modal distributions and cumulative passenger hours by transport mode to average scores and intricate event sequences. The outputs of MATSim are modal split, total passenger hours and km per mode, average scores, distribution of trip arrival times, and series of events that can be visualized using specialized software (Tzouras et al., 2021). MATSim outputs can be analyzed for multiple purposes, such as CO2

[16] NETLOGO website: http://ccl.northwestern.edu/netlogo/

emission (Novosel et al., 2015) or spreading of COVID-19 in Berlin[17]. On the computational front, there are some considerations. For instance, to simulate merely 10% of the population of a metropolitan zone (like Paris or Berlin), MATSim demands over five hours (Horl et al., 2019). Additionally, for effective operation, it necessitates a minimum of 4 GB RAM and an available disk space of 200 GB (Rieser et al., 2014).

SimMobility[18] presents an alternative approach to simulation experiments beyond a single day. As a multi-scale simulation platform, it adeptly models the myriad interactions observed in both land-use and transport domains. Seamlessly integrating econometric activity-based frameworks with dynamic traffic assignments, this platform finds its roots in the dedicated efforts of the Future Urban Mobility Research Group at the Singapore-MIT Alliance for Research and Technology (Adnan et al., 2016; Kagho et al., 2020). Uniquely crafted using the C++ language, SimMobility stands out in the open-source simulation space (Azevedo et al., 2017). One of its hallmark features is its innate capacity to unify varied models under a singular model framework (Li et al., 2021). At its core, SimMobility operates via three distinct modules: The short-term simulator focuses on the daily scale and it minutely simulates trips. Within this module, the MITSIM open-source microscopic traffic simulation takes center stage, modeling intricate driving behaviors. This includes elements like car-following, intricate lane transitions, and more, all while accounting for the nuances of driver characteristics, such as response times. Furthermore, intersection interactions are modeled using advanced traffic conflict techniques, like conflict detection and prevention of collisions (Azevedo et al., 2017). The mid-term simulator dives into traveler behavior and overarching mobility trends. Here, travel-related decisions, such as when to depart, the mode of transport, and chosen routes, are influenced by the sequential application of a series of choice models. These decisions emerge from a Monte Carlo simulation-based approach. The long-term simulator predicts accessibility patterns and consequential shifts in land use. This is achieved through the use of econometric models that include, but are not limited to, housing market changes, job location preferences, and household vehicle ownership patterns (Meng et al., 2019). However, the extensive computational scope of SimMobility does come with demands. For a large-scale simulation scenario, such as modeling around 5.2 million agents in a context like Singapore, the platform requires a robust computing environment. Specifically, a computation time exceeding 28 hours on a high-end workstation equipped with 32 cores and 125 GB RAM is necessary (Oh et al., 2020).

AnyLogic[19] is a commercial simulation platform crafted by the AnyLogic Company using the JAVA programming language. Specializing in detailed microscopic agent-based simulations, it leverages discrete-event modeling to depict dynamic systems, including intricate urban traffic networks.

[17] MATSim Episim: https://github.com/matsim-org/matsim-episim-libs
[18] Mobility Future Collaborative, SimMobility website: https://mfc.mit.edu/simmobility
[19] Anylogic discrete event modeling: https://www.anylogic.com/use-of-simulation/discrete-event-simulation/

In this platform, each vehicle is visualized as an individual agent. The behavior of these agents in AnyLogic is defined through a series of guidelines, or a rule-based model, which is visually represented by a flowchart (Borshchev, 2014). Additionally, AnyLogic boasts its own library containing a collection of preset algorithmic models. These models mimic driving behaviors through an intricate physical microsimulation process. When it comes to the platform's outputs, they offer a consolidated view of network efficiency, encapsulating aspects like service levels, delays in travel, traffic density, and average vehicular speeds.

POLARIS (Planning and Operations Language for Agent-Based Regional Integral Simulation)[20], created by the Transportation Research and Analysis Computing Center at the Argonne National Laboratory, is a product of the C++ programming language. This open-source platform boasts the capability to simulate metropolitan areas within a notably concise computational span (Kagho et al., 2020). Its efficiency is attributed to the incorporation of the Thread-Caching Malloc (TCMalloc) and a concurrent discrete event engine (Auld et al., 2016). Remarkably, POLARIS managed to simulate a whopping 27 million trips in the Chicago Metropolitan area in just 1.2 hours, employing two eight-core processors and a 64 GB RAM (Auld et al., 2016). Described as a mesoscopic transport simulator, POLARIS is renowned for its adaptability (Li et al., 2021). This is seen in its unique "plug-n-play" system, which empowers users to seamlessly integrate various model extensions. Its structural backbone comprises two pivotal elements: an Agent-Based Model (ABM) dedicated entirely to transport networks, and a toolkit crafted for the effortless design of diverse simulation scenarios (Auld et al., 2016). Additionally, the platform integrates a dynamic activity-based model, namely Agent-based Dynamic Activity Planning and Travel Scheduling (ADAPTS), which takes charge of activity planning and scheduling, culminating in the execution of trips. This implies that POLARIS does not segregate demand creation from traffic simulation. POLARIS utilizes Newell's Simplified Kinematic Wave Traffic Flow model to depict road link traffic flow (Gurumurthy et al., 2020). This translates to a queue-based traffic simulation model. Yet, it IS worth noting that POLARIS has an edge; it can integrate scenarios that feature Intelligent Transport System (ITS) Infrastructure and specific traffic management tactics. Mode choices within the platform hinge on probabilistic models like nested logit, while vehicle routing leverages a user equilibrium traffic assignment model. Being in line with other ABMs, POLARIS offers detailed data sets, which can be bundled up and dissected statistically through the POLARIS Analyzer. Notable outputs from this system encompass metrics such as travel delays, average speeds on specific links, and traffic flows within those links.

[20] POLARIS Transportation System Simulation Tool: https://www.anl.gov/es/polaris-transportation-system-simulation-tool

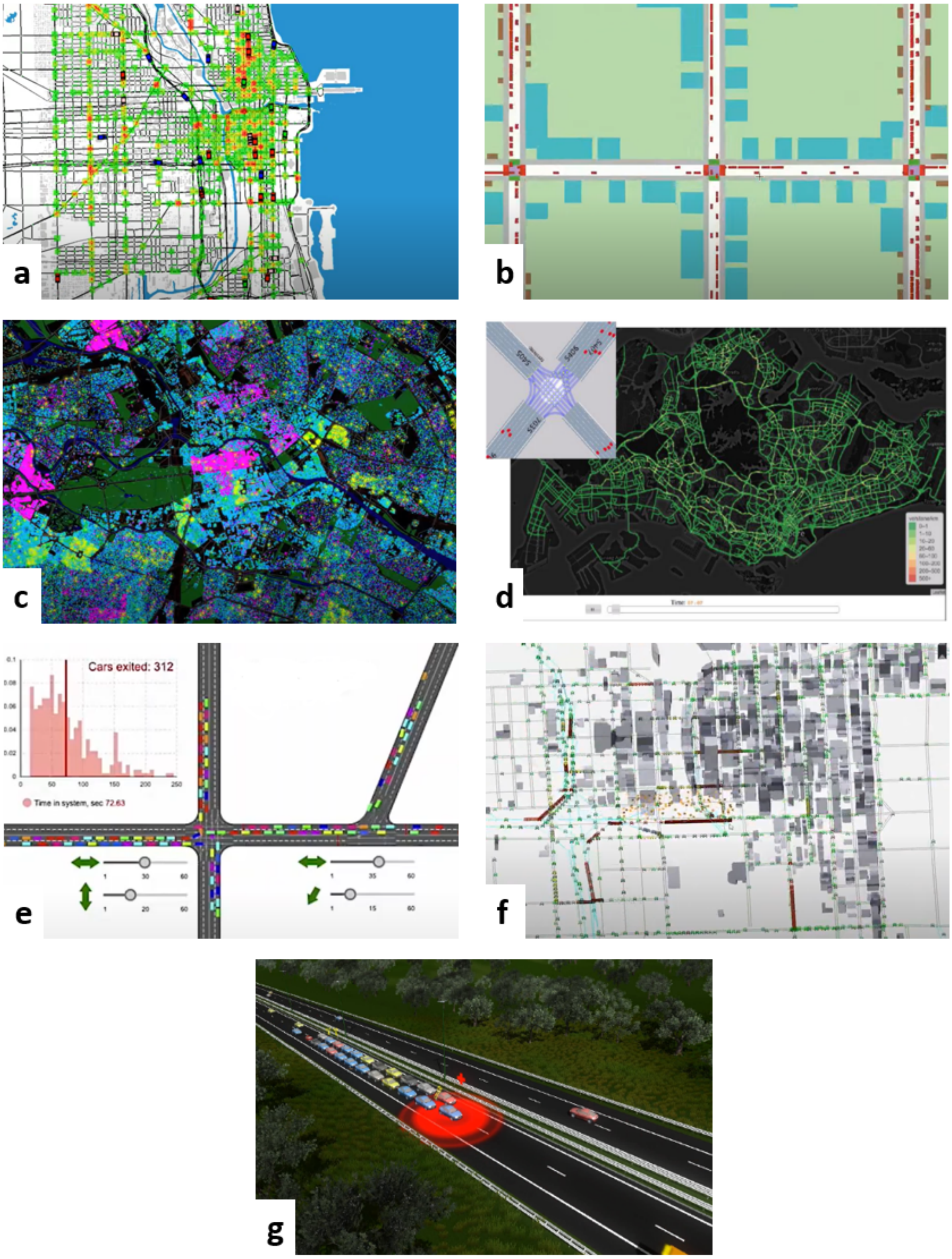

Figure 38: Screenshots of ABM simulation visualizations:
(a) TRANSIMS (Source: https://www.youtube.com/watch?v=tR6mXsRh99g&t=2s&ab_channel=ArgonneTRACC), (b) NetLogo (Source: https://www.youtube.com/watch?v=knP7JHR097Q&ab_channel=CamiloTopali), (c) MATSim (Source: https://www.youtube.com/watch?v=rWTFg1UkZTc&ab_channel=MichaelBalmer) , (d) SimMobility (Source: https://www.youtube.com/watch?v=zNyYKlPA5RE&t=397s&ab_channel=TRBVIS), Anylogic (Source: https://www.youtube.com/watch?v=EHP47tM6ctc&t=913s&ab_channel=AnyLogic)), (f) POLARIS (Source: https://www.youtube.com/watch?v=zjqbLChd5L8&t=182s&ab_channel=ArgonneTRACC), (g) SARL (Source: Buisson et al., 2019) (Videos accessed in October 2022)

Janus[21] stands as an open-source simulation platform, constructed entirely in SARL—a cutting-edge agent programming language birthed at the University of Technology in Belfort, France. When it comes to simulating traffic, Janus leverages the JaSim library (Galland et al., 2014). This library serves as a microsimulation model that adeptly replicates the movements of a diverse range of agents, from pedestrians and cars to bikes and beyond. A hallmark of its design is the "Influence – Reaction" strategy. Within the JaSim library, there's an array of collision-avoidance functions, which not only resolve potential clashes but also factor in the perceived safety—essentially the sense of security each virtual road user feels. What sets Janus apart is its meticulous attention to detail, facilitating a vivid visualization of agent interactions in a dynamic 3D simulated space. The behavioral aspects of traveling, like decisions and movements, are modeled using a standard multinomial logistic model, which pays heed to the unique characteristics of each individual. Prominent outcomes generated by Janus include specific travel durations for every agent and traffic density on individual links.

5.1.3 Qualitative assessment of simulation tools

The exploration of the wide-ranging impacts of shared space at the network level has largely remained a blind spot in the realm of urban transport modeling. One of the inherent challenges with most microsimulation tools, notwithstanding their sophistication, is the detailed dynamics they are engineered to replicate at the link level (i.e., one road segment or intersection). These tools require heightened computational power and time, particularly when the aim is to simulate large metropolitan urban networks with numerous agents. While empirical studies presented in Section 3 have provided parametrization using mathematical functions to illustrate capacity drops due to reduced travel speeds in shared space road environments, the trade-off between computational time and simulation detail still remains a concern well-documented in transport research (Cao et al., 2019; Charypar, 2008; Charypar et al., 2009a; Waraich et al., 2015a).

Agent-Based Models (ABMs) present a compelling solution, with their mesoscopic approach that captures the overall perspective of the entire transport system. Most ABMs, including MATSim, SimMobility, and POLARIS, can elucidate the spatiotemporal variations of demand in urban areas. However, the granularity differs across these tools. Multi-scale ABMs such as SimMobility and POLARIS can predict both mid-term (monthly) and long-term (annual) spatial changes in transport demand and activities. Yet, their application in modeling specific transport modes like bicycles or pedestrians at the link level has been limited. Conversely, tools executing physical microsimulations like Anylogic possess built-in functions to describe pedestrian behaviors and mixed traffic scenarios. But they falter when tasked with simulating extensive networks due to the exorbitant computational resources and time they demand.

[21] JANUS project website: http://www.sarl.io/runtime/janus/

While several simulation tools achieved to model traffic operation in various metropolitan regions globally, MATSim stands out not just for its application but its adaptability. MATSim has been the go-to for simulations of sprawling networks, having been employed in cities like Zurich (Becker et al., 2020) and Berlin (Ziemke, Kaddoura, and Nagel, 2019). What sets MATSim apart is its inherent flexibility; it has been employed across a plethora of scenarios, with upgraded simulation functions catering to the unique requirements of each case. The "MATSim loop," as it os often referred to, is adeptly designed to be malleable, seamlessly adapting to challenges posed by the introduction of novel transport services.

The unparalleled versatility and adaptability of MATSim make it the ideal choice for this study. The focus remains to assess the consequences of a radical transformation in road environments. Athens, given its unique urban structure and transport dynamics, also offers a conducive setting for leveraging MATSim potential. Not only is MATSim open source, fostering innovation through its customizable framework, but it also has the capability to perform both mental and physical simulations. In the context of shared space, MATSim ability to take into account factors like speed compliance (physical simulation experiment) and perceived safety (mental simulation experiment) is paramount, as these are the main driving forces determining the viability and success of the shared space concept.

5.2 Physical simulation experiment

The physical simulation application discusses whether the implementation of lower speed limits can improve or downgrade the overall efficiency of the transport system. Therefore, it aims to explore the impacts of shared space at a metropolitan road network level. Lower speed limits mean lower free flow speed and capacity. Hence, in this experiment, the supply of the transport system is modified in each scenario. Of course, the test scenarios present some extreme realities, where a serious proportion of city roads are transformed into shared space.

5.2.1 Methodological approach

The methodological approach combines a network update tool (called: network updater) with an ABM, namely: MATSim. The aim of the first tool is to prepare the road network, which will be imported into the simulations. Therefore, transport supply is modified by using it, while initial demand remains constant in all the experimental tests of this study. **Figure 39** shows the overall methodological framework. The MATSim Loop has been fully explained in the previous paragraphs. Hence, in this subsection, the simulation parameters and therefore the main assumption of the simulation experiment will be only mentioned.

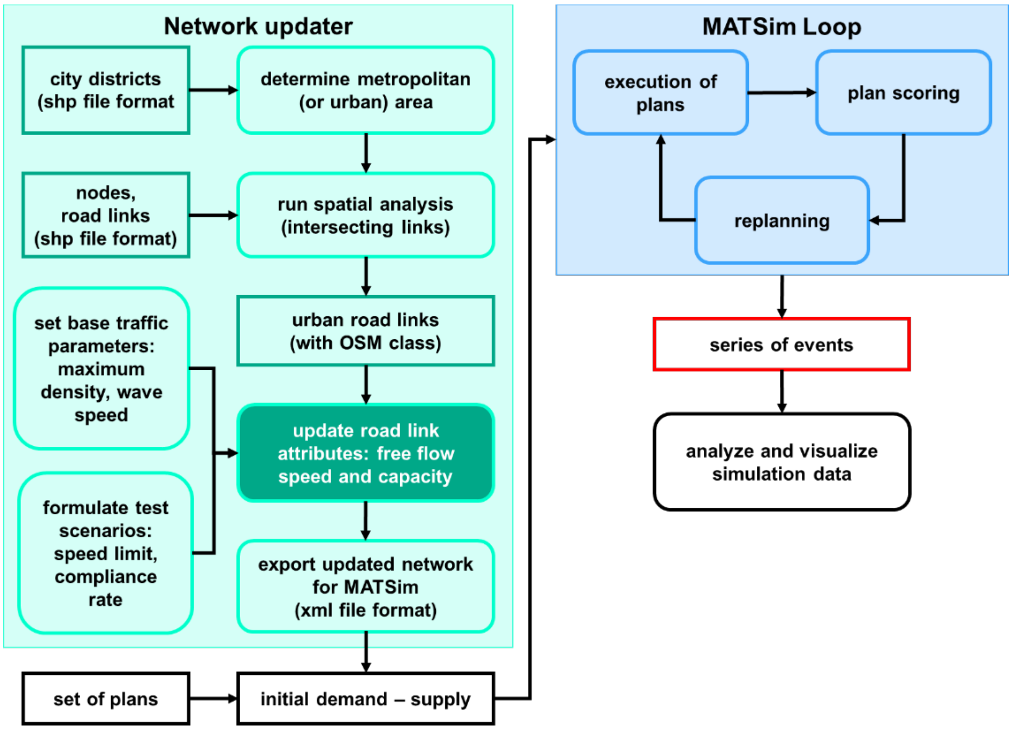

Figure 39: Methodological flow diagram of the first simulation experiment

An external tool called "network updater" developed using Python programming language processes network links by updating their traffic parameters, i.e., free flow speed and capacity. The first function identifies the urban road links, i.e., links that are within the metropolitan urban area of each city. Shapefiles (polygons) with the metropolitan districts or municipalities of the examined city must be provided. Using a spatial analysis tool (i.e., intersections) the network updater quickly identifies the link IDs that are within the metropolitan urban area creating a new link attribute. For example, Berlin is divided into 12 municipal boroughs[22], namely: Mitte, Friedrichshain-Kreuzberg, Pankow, Charlottenburg - Wilmersdorf, Spandau, Steglitz - Zehlendorf, Tempelhof - Schöneberg, Neukölln, Treptow - Köpenick, Marzahn - Hellersdorf, Lichtenberg and Reinickendorf. Hence, traffic parameters are updated only in the urban links that are within the previously mentioned boroughs.

Scenarios for traffic are developed by setting speed limits and adherence rates based on OSM class (Zilske et al., 2011).. The core components to update the network are these two parameters. By taking the product of the speed limit and the compliance rate, one can deduce the free flow speed. However, modifying the speed limit can either increase or decrease the link capacity, which refers to the highest flow a link can accommodate in an hour. For traffic operations on links, a triangular fundamental diagram is assumed. When traffic is flowing smoothly and drivers behave uniformly, there is a direct correlation between the flow of traffic and its density. The capacity is determined by where the congestion starts (Flötteröd, 2016). A set wave speed of negative 13.5 km/h is assumed, with a jam

[22] Open Data Berlin: https://opendata-esri-de.opendata.arcgis.com/

density of 125 vehicles per kilometer. The number of lanes on a link, available from OSM, also affects this maximum density. The formulas for this model are depicted in **Equations 28** and **29**.

$$uf_i = ulim_j \times cf_j \quad (28)$$

$$c_i = \frac{uf_i \times w \times (l_i * kjam)}{uf_i + w} = l_i * \left(\frac{ulim_j \times cf_j \times w \times kjam}{ulim_j \times cf_j + kjam}\right) \quad (29)$$

where:
c_i: road capacity of link i in veh/h,
w: wave speed in km/h – assumed fixed to 13.5 km/h,
$kjam$: congestion density per lane of link i in veh/km – assumed fixed to 125 veh/km,
$u_{f,i}$: free flow speed of link i in km/h,
$ulim_j$: speed limit of OSM class j,
cf_j: compliance rate of OSM class j,
l_i: number of traffic lanes in the link i.

To handle the vast number of links efficiently, the network update tool has been fine-tuned. It first determines which OSM classes require updating based on user input. This tool then calculates the free flow speed and capacity for those specific OSM classes. From there, a subset of urban road links within those classes is generated, and the new traffic parameters are applied. If a road has more than one lane, its capacity is adjusted based on **Equation 29**. Importantly, the updater does not alter any public transport links since they are not part of this procedure.

It is worth mentioning that in MATSim, travel speed is measured in m/s, not km/h, and link capacity is given in vehicles per hour in the network file. Additionally, the Open-Berlin Scenario does not account for interactions at intersections or traffic lights. To factor in these delays, the benchmark scenario slashes all free flow speeds by half (Ziemke et al., 2019a). This same approach is used in all the experimental scenarios of this research.

5.2.2 Study case and scenario formulation

The MATSim Open-Berlin Scenario[23] offers a transport simulation setting for the Berlin metropolitan region (Ziemke et al., 2019a). This scenario operates using publicly accessible data that comes without restrictions. It encompasses comprehensive daily agendas of agents who symbolize all adults residing in Berlin and Brandenburg. These plans are crafted to authentically represent the traffic flow in Berlin, including all significant transport modes: i.e., car driver, car passenger (or ride), bicycle, walking, freight, and public transport modes.

Online, two distinct versions of this scenario are available. The initial version replicates the activities of 1% of the entire population, while the latter reflects the activities of 10%. In both

[23] Open – Berlin github: https://github.com/matsim-scenarios/matsim-berlin

adaptations, there's a proportional reduction in network capacities. The 10% version has undergone calibration through real-world traffic data. In contrast, the 1% version is primed for experimental and educational purposes. To save on computational resources, this study predominantly utilizes the 1% base scenario. The objective here is not to end up with precise future impact predictions, but to approach the potential consequences of shared space networks by contrasting hypothetical scenarios. In the next paragraphs, it is important to review and analytically present the current configuration of this (base) scenario to better interpret the experimental results in the next steps.

Delving deeper into the foundational elements of this base scenario is vital for a clear interpretation of forthcoming experimental outcomes. Two primary components feed into this scenario: the transport network (including public transport) and the initial plans of the agents. In the Open-Berlin framework, the road infrastructure is derived from OpenStreetMap (OSM). This network boasts 73689 nodes coupled with 159039 one-way car-exclusive links and an additional 43900 links dedicated to public transit (see **Figure 40**). The primary coordinate system utilized is EPSG: 31468. Beyond the metropolitan area urban roads, the network incorporates major connections bridging Berlin with its adjacent cities. To give the temporal and spatial fluctuations of demand, an activity-centric model named the Comprehensive Econometric Microsimulator for Daily Activity-Travel Patterns (often abbreviated as CEMDAP), developed by Bhat et al. (2004), is employed. This phase draws from sociodemographic insights and commuter data sourced from national censuses and regional surveys to create a realistic portrayal of adult residents' travel tendencies. This synthetic dataset offers trip sequences, detailing each trip starting point, endpoint, timing, mode, and objective.

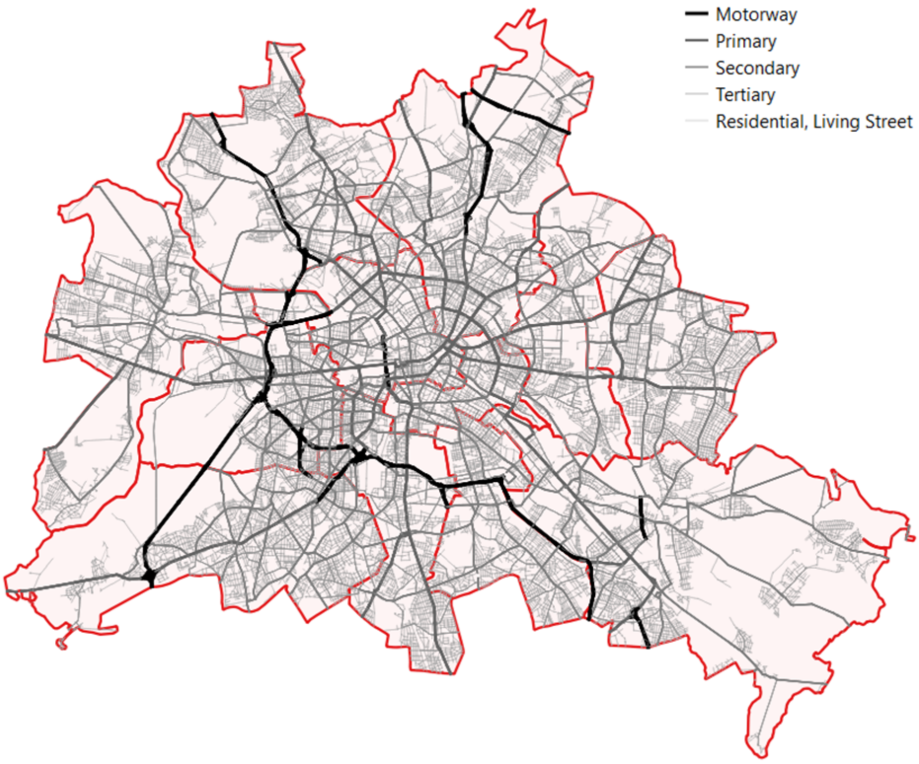

Figure 40: Urban Road network of Berlin and OSM classes – road network hierarchy

Furthermore, transit schedules, highlighting the precise locations of stops/stations and corresponding public transport arrival and departure times, serve as another crucial input. Within the Open-Berlin Scenario, characteristics pertaining to both private and public vehicles, alongside the derived passenger car equivalents (pce), are integrated at the simulation's onset. Based on these parameters, a truck (represented as the freight mode) corresponds to 3.5 passenger car units (pcu). S-Bahn (train networks) and U-Bahn (subway networks) can accommodate upwards of 300 seated passengers and over 600 standing passengers. In comparison, buses and trams offer notably reduced capacities.

Within the Open-Berlin Scenario, cars, and public transport (excluding metro and train journeys) undergo simulation via a queue-based traffic simulation technique, known as QSim. In this setup, the flow of traffic into a link is curtailed in line with its capacity. Public transport modes operate exclusively within designated public transport links, strictly adhering to their transit timetables, resulting in variable travel speeds across links. Modes of transit like bicycles and walking are "teleported" within MATSim. This implies that agents are shifted from one activity site to the next with an inherent time delay, reflecting the time needed to traverse 1.3 times the beeline distance at a preset speed: 4 km/h for pedestrians and 12 km/h for cyclists. For public transport journeys in Open Berlin, a direct line distance (or radius) of 500 meters is established as the utmost distance for accessing or departing from bus stops and metro hubs.

The Open-Berlin scenario evaluates plans by examining the generalized time and distance-associated travel expenses. This generalized time expense pertains to the duration engaged in each activity and any deviations from the anticipated arrival time at the activity site (Nagel et al., 2016). The scenario does not deploy mode-specific beta parameters for time costs. However, it does incorporate distinct distance monetary rates (EUR/m) for each mode of transport. To elucidate, for private vehicles and motorcycles (or "rides"), this value is fixed at -0.0002 EUR/m, while for trucks, it stands at -0.0004 EUR/m. The public transport utility function taps into a daily monetary constant, pegged at 2.1 EUR/day, for its daily patrons. Conversely, active transit modes do not bear any distance expense. The model introduces distinct utility constants for each mode, with values such as car at -1 utils, ride at 0 utils, and so forth. In terms of the replanning mechanism, it crafts new plans for merely 15% of all agents during each cycle. Agents have three alternatives: a) alter the mode of transport (5%), b) adjust the departure timestamp (5%), or c) opt for a different route to optimize utility. For the remaining 85% of agents, the system chooses a plan from all previously executed plans (from preceding cycles) rooted in probabilities derived from an adjusted MNL model (i.e., BestScore strategy).

New scenarios offer various possible, probable, and preferable future developments or pathways toward achieving a specific future (Keseru et al., 2019). Scenario planning entails the systematic exploration of future possibilities, considering a wide range of variables such as technological advancements, changes in travel behavior, policy changes, interventions, and social preferences (Sunitiyoso et al., 2023). It necessitates creativity, recognizing that the future cannot be solely anticipated or accurately predicted, but can be strategically planned for (Lyons et al., 2021). Within the scope of this research, this research used the backcasting approach to formulate future scenarios. The backcasting approach is a method employed to envision and plan for a desired future condition by working backward from that intended outcome (Bibri and Krogstie, 2019). Unlike traditional forecasting approaches that predict the future, backcasting begins with a vision of the preferred future and subsequently identifies the necessary steps required to achieve that vision (González-González et al., 2019). As Berlin has made significant progress in reducing the speed limit, the Open-Berlin Scenario was modified slightly. This adjusted version now envisions a situation with greater car prevalence, enabling its comparison with other test scenarios. Importantly, this research does not intend to provide plans or practical recommendations for Berlin, but rather to analyze how traffic calming affects travel patterns. Specifically, the speed limits for residential and tertiary roads are 50 km/h, while secondary and primary routes are 20 km/h faster. The top speeds are on highways and main roads at 130 km/h and 90 km/h, respectively. For this scenario, it is assumed that everyone respects the given speed limits, with a compliance rate of 100%. This described scenario is termed the base scenario.

Table 17: Selected speed limits per scenario and OSM class

	Speed limits in km/h		
OSM class	**Scenarios 1**	**Scenarios 2**	**Scenarios 3**
motorway	130	130	130
motorway_link	130	130	130
trunk	90	90	90
trunk_link	90	90	90
primary	70	70	50
primary_link	70	70	50
secondary	70	50	30
tertiary	50	30	30
residential	50	30	15
living street	30	15	15
unclassified	30	15	15

In order to develop test scenarios, two more sets of speed limits (scenarios 2 and 3) were developed, alongside three distinct strategies to determine compliance rates (scenarios a, b, and c). These speed limits and compliance rates were then combined, producing a total of six (2x3) test scenarios. Special attention was given to secondary roads while defining these limits. From a 70 km/h limit in scenario 1, it was reduced to 50 km/h in scenario 2 and further to 30 km/h in scenario 3. In scenario 2, tertiary roads have a reduced speed limit of 30 km/h. Scenario 3 envisions an even stricter setting where almost all urban roads, barring primary, trunk, and motorways, have limits of 30 km/h or less (refer to **Table 17** for details). Elvik (2010a) concluded that a 10 km/h alteration in speed limit only results in a

2.5 km/h actual speed change. This contributed to the creation of scenarios a (detailed in **Table 18**). By performing interventions in the urban environment municipalities can ensure higher compliance with the new speed limits. Scenarios b refer to a compliance rate equal to 1 in all cases. Lastly, scenarios c presents an ideal reality, in which the free flow speeds in traffic calming areas are 0.9 times lower than the speed limit. This idea draws inspiration from shared spaces where observed speeds are often lower than the limits (Batista and Friedrich, 2022; Kaparias and Wang, 2020a). However, the dynamic interactions common in bustling shared spaces are not incorporated in this research to avoid overly complex simulation models and longer computation durations. Given all this, free flow speeds can be deduced using **Equation 27**. **Figure 41** presents these scenarios, highlighting free flow speeds with varying colors for each speed tier.

Table 18: Compliance rate scenarios

	Compliance rate
Scenarios a	A 10% decrease in speed limit reflects 2.5 km/h in mean speed. The compliance rate is calculated accordingly
Scenarios b	The free flow speed is equal to the speed limit. The compliance rate is equal to 1.
Scenarios c	In urban roads with a speed limit lower than or equal to 30 km/h, the compliance rate is equal to 0.9. In other roads, the compliance rate is equal to 1.

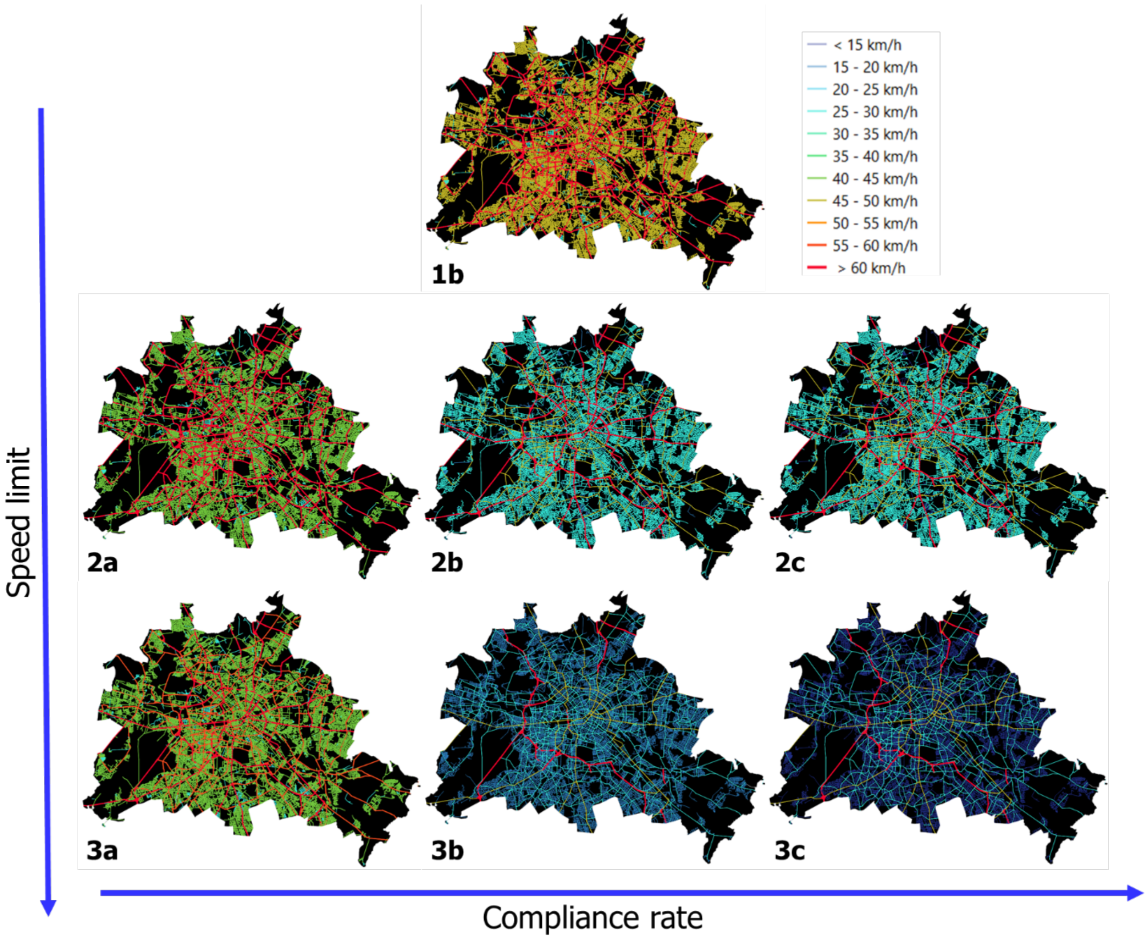

Figure 41: Presentation of formulated scenarios – estimated free flow speed per link

5.2.3 Simulation results and analysis

A PC desktop with Intel Core i7 - 4790 CPU processor and 16.0 GB RAM was used in this study. To run the co-evolutionary algorithm of MATSim, 6.0 GB of RAM memory was allocated. The computation time per scenario was approximately equal to 11 hours and 10 minutes (500 iterations), while the average computation time per iteration was less than 80 seconds. Therefore, a simulation time of 3 days 6 hours, and 10 minutes was required to export the results analyzed below.

In MATSim, the division of travel modes is represented in three distinct ways: the proportion of trips for each mode, passenger hours for every mode, and distance traveled (in kilometers) per mode. Based on the do-nothing scenario, which is scenario 1b, private cars were utilized for 38.5% of the trips in the last iteration. Walking-only trips came next at 21.1%, showing consistent numbers across other scenarios. The contribution of public transport is rather modest in scenario 1b at approximately 15%. However, as illustrated in **Figure 42**, this share escalates to 17.0%, 17.2%, and 21.5% in scenarios 2b, 2c, and 3c, respectively. Notably, in the final scenario, the gap in percentages between car trips and public transport journeys shrinks to under 5%. The introduction of reduced speed limits coupled with strong adherence encouraged more people to opt for bicycles in Berlin. As evidence, the percentage of bicycle trips increased from 16.3% in scenario 1b to a notable 20.4% in scenario 3c.

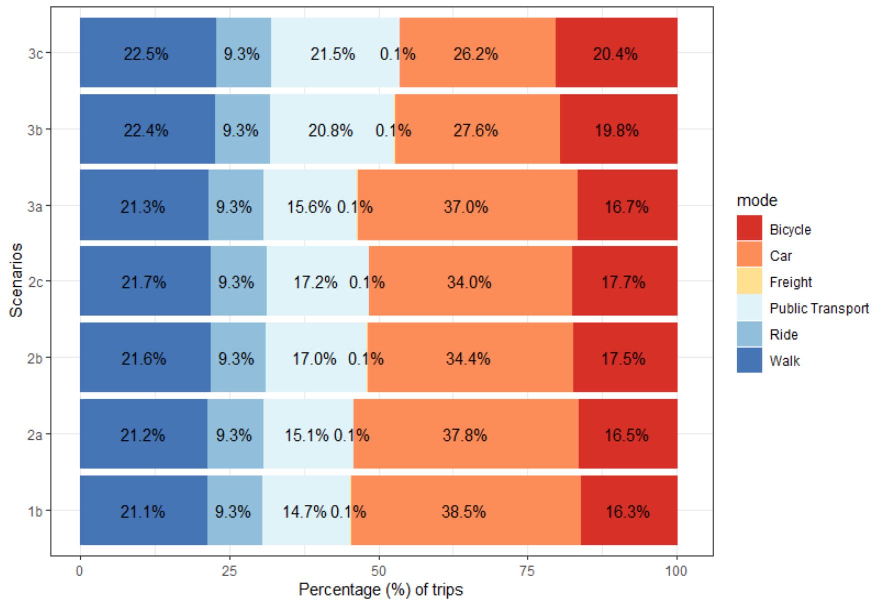

Figure 42: Modal split (% of trips) per scenario

When evaluating the aggregate passenger hours, there is an 11.61% increase from scenario 1b to scenario 3c. A pronounced difference is consistently seen between scenarios with low compliance rates (like 2a or 3a) versus those with high rates (like 2c or 3c), as depicted in **Figure 43** (on the left side). The maximum share of passenger hours, ranging between 32.6% and 33.0%, is attributed to walking trips, which is unsurprising given that walking is the most time-consuming mode. The most distinct variance across the scenarios can be found in car passenger hours, with a dip of 275,500 hours (or a 15% reduction) from scenario 1b to 3c. Conversely, public transport passenger hours climb to 16.2% and

16.6% in scenarios 3b and 3c, respectively. This signifies a near 30% growth in passenger hours overall. Bicycle hours remained relatively stable in scenarios where there was low compliance with the newly set speed limits.

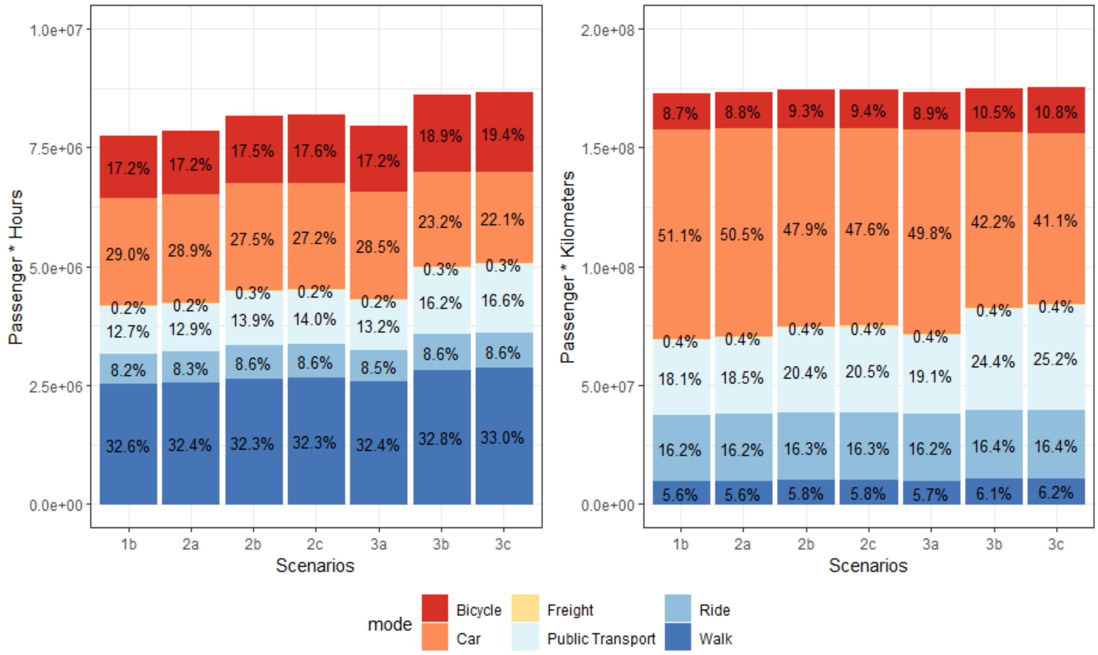

Figure 43: Passenger hours (left) and kilometers (right) per mode and per scenario.

The aggregate distance traveled by passengers remained consistent across the different scenarios. This consistency is anticipated since individuals could alter their trip timing, mode, and route, but were not able to cancel trips due to accessibility shifts. In the do-nothing scenario, car journeys account for 51.1% of the entire distance covered by participants. There is a forecasted reduction of 16.3% and 18.5% in the distance traveled by passengers in scenarios 3b and 3c respectively, as shown in **Figure 43** (on the right side). In stark contrast, distances covered by public transport are expected to witness an upward trajectory in high compliance scenarios: roughly 14% for scenarios 2b and 2c, and a notable 40% for scenarios 3b and 3c. Other travel modes displayed minimal disparities in terms of distance covered.

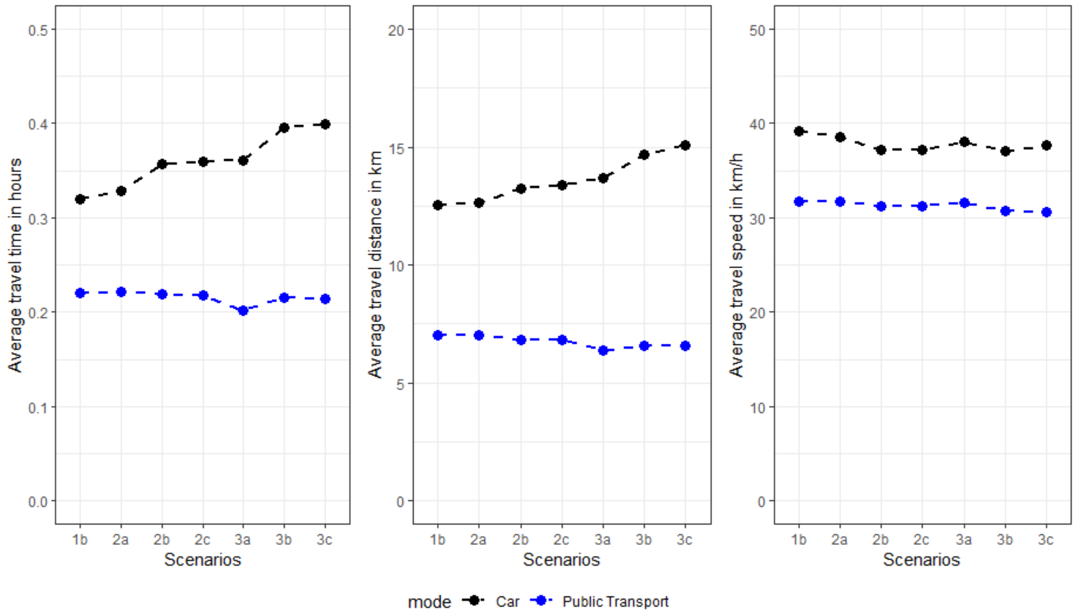

Figure 44: Average travel time (left), distance (middle), and speed (right) per scenario: car vs public transport.

Given that public transport emerges as a major rival to private car usage, relative metrics to provide clearer insights are utilized. The analysis introduces three indicators: average travel time, distance, and speed (see **Figure 44**). In scenario 1b, car trips have an estimated average duration of 19.2 minutes. This extends to 21.3 minutes in scenario 2b and is projected to peak at 23.8 minutes in scenario 3c. However, for public transport, the average trip time difference between scenarios 1b and 3c is under a minute. When examining travel distance, lowered speed limits seem to push individuals to use private cars for extended distances. Specifically, the rise in average distance traveled between scenarios 1b and 3c is anticipated to be an added 2.11 kilometers. Conversely, the mean trip distance via public transport is predicted to shrink by 6.1% between these two scenarios. Regarding speed, cars in scenario 1b traverse the network at an average pace of 39.2 km/h, but this drops to 37.6 km/h in scenario 3c.

Intriguingly, during peak hours (08:00-10:00 and 16:00-18:00) in the Berlin metro region, scenario 3c cars seem to move faster than in other scenarios. **Figure 45** histogram illustrates the spread of distances covered using private cars as the primary mode. Notably, in scenario 1b, a larger fraction of trips stay under the 10 km mark compared to other scenarios. In the evolved scenario, private cars are predominantly harnessed for distances surpassing this limit. Furthermore, **Figure 46** depicts a wider fluctuation in car travel speeds, with scenario 3c displaying numerous trips exceeding 30 km/h, possibly due to congestion points pushing average speeds closer to 25 km/h.

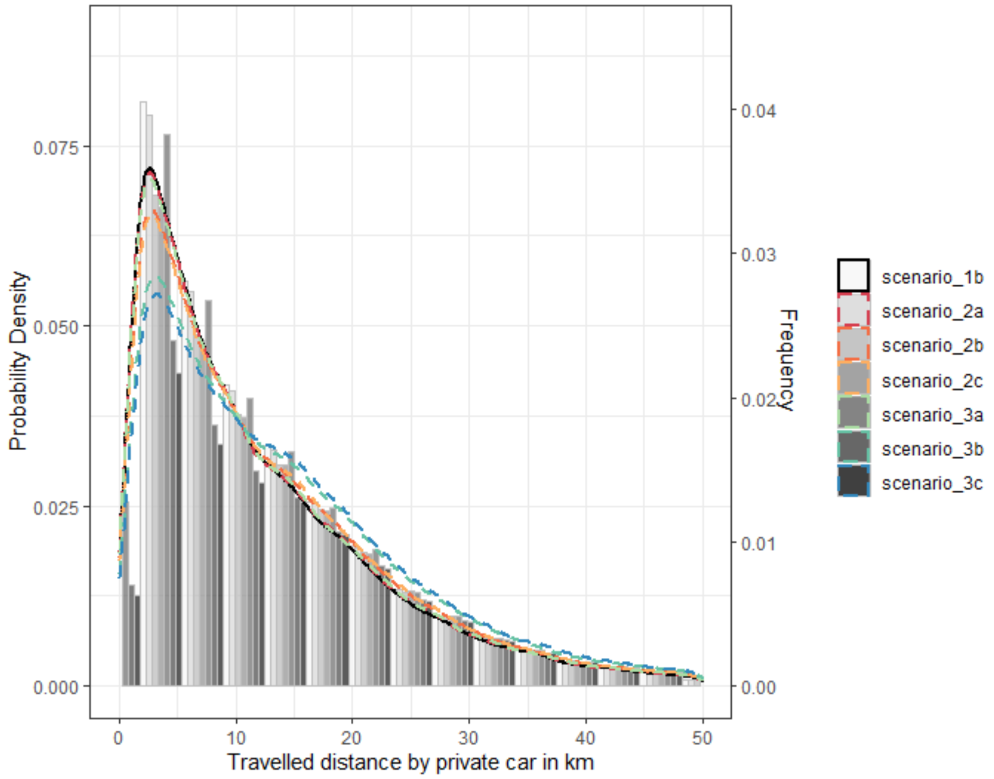

Figure 45: Distribution of trip distance using a private car

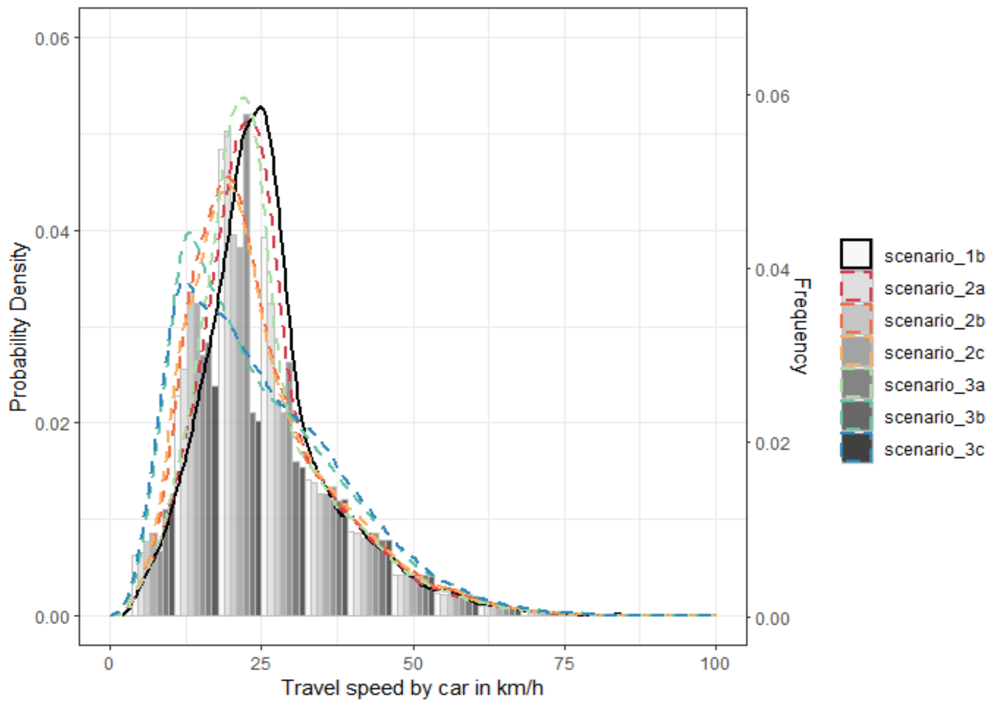

Figure 46: Distribution of travel speed using a private car.

In a subsequent step, both the road network and the events from the final iteration of each scenario were incorporated into a visualizing tool. From this data, traffic volumes and average speeds for each link can be deduced. To spot traffic congestion, relative speeds were employed, which refers to the ratio of observed average speeds to the maximum possible speeds. Given that these maximum speeds were already halved to account for delays at junctions, any ratio under 0.90 signifies congestion. Additionally, due to fluctuating traffic volumes at different times, the late afternoon peak (specifically 16:50) was chosen to benchmark scenarios against each other. The following maps offer a visual representation of these findings. Here, the width of a link represents car traffic volume, and congestion hotspots are emphasized in yellow and red. Notably, in scenarios 1b, 2a, and 3a, congestion is primarily observed in the urban core. Secondary and tertiary roads account for the majority of these congestion points. Imposing stricter speed limits on these roads, combined with high compliance, results in decreased car traffic across most roads, except for motorways and primary roads where speed limits are unchanged. Access to the city center is facilitated by the main road network that bridges the center with outlying areas. Motorists tend to favor these roads for their faster travel speeds and ability to cover greater distances efficiently. However, a glance at the visualized maps indicates a notable reduction in traffic passing through the city center.

Figure 47: Scenario 1b - traffic volumes and congestion points at peak hour: 16:50, i.e., the link width is related to the traffic volume; links with dark red: $rel = \frac{u_{ac}}{u_f} \leq 0.85$, with red: $rel \leq 0.875$; with orange: $rel \leq 0.90$, with yellow: $rel \leq 0.925$, with light yellow: $rel \leq 0.95$ and blue: $rel > 0.95$.

Figure 48: Scenario 2a - traffic volumes and congestion points at peak hours 16:50 (links colors/width as above)

Figure 49: Scenario 2b - traffic volumes and congestion points at peak hours: 16:50 (links colors/width as above)

Figure 50: Scenario 2c - traffic volumes and congestion points at peak hours: 16:50 (links colors/width as above)

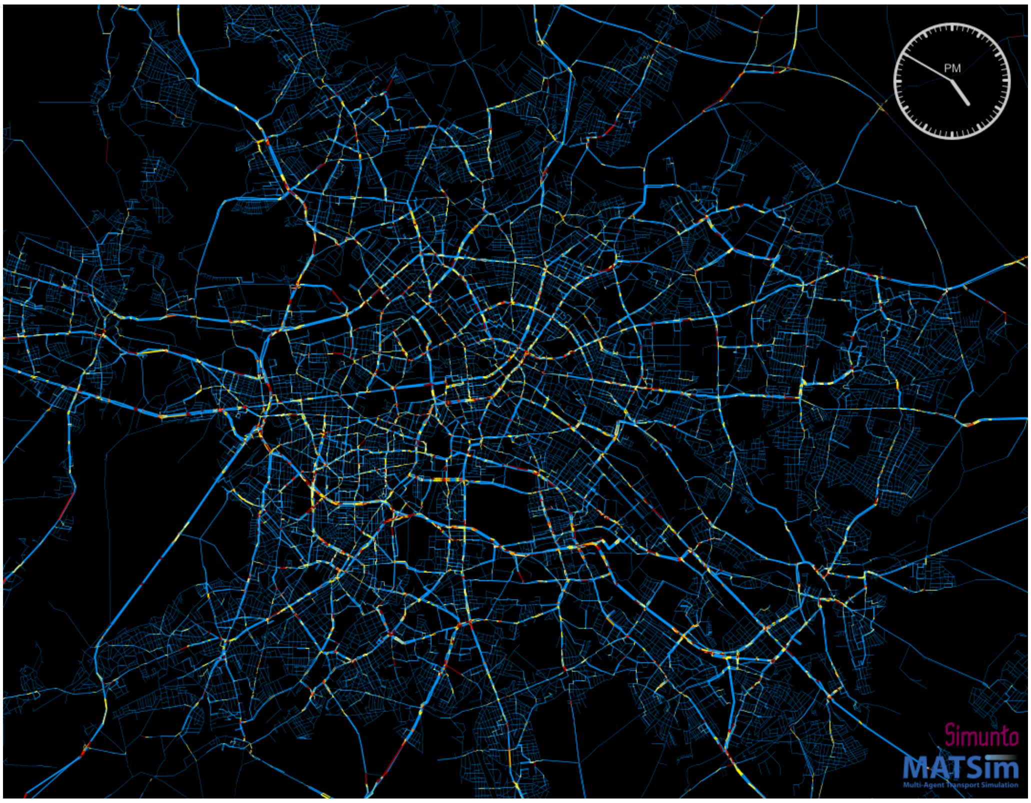

Figure 51: Scenario 3a - traffic volumes and congestion points at peak hours: 16:50 (links colors/width as above)

Figure 52: Scenario 3b - traffic volumes and congestion points at peak hours: 16:50 (links colors/width as above)

Figure 53: Scenario 3c - traffic volumes and congestion points at peak hours: 16:50 (links colors/width as above)

5.3 Mental simulation experiment

The mental simulation application considers perceived safety as the main factor that influences the network supply and therefore the mobility choices of agents. The road network that is simulated is now associated with additional attributes related to the road environment. The mental simulation experiment also examines how the accessibility of various road users is limited or improved by interventions in the road environment (like shared space) which sometimes raise safety concerns. In the end, this opens a discussion regarding the equity implications of the shared space concept.

5.3.1 Methodological approach

The general approach relies on several methods and tools. Initially, the MATSim scoring function is modified to incorporate the effect of perceived safety, determining the perceived scores for each network link in the process. This study adopts a unique mathematical technique to calculate accessibility rates for every agent, drawing from the simulation results. As a starting point for our simulation, a sample network from the Athens city center and a prototype population of agents are utilized. Furthermore, a conceptual scenario planning is employed to shape the simulation experiment. Once these steps are completed, calibrate the simulation model parameters are imported, ensuring they remain consistent across all scenario simulations. A visual representation of this methodology is provided in **Figure 54**.

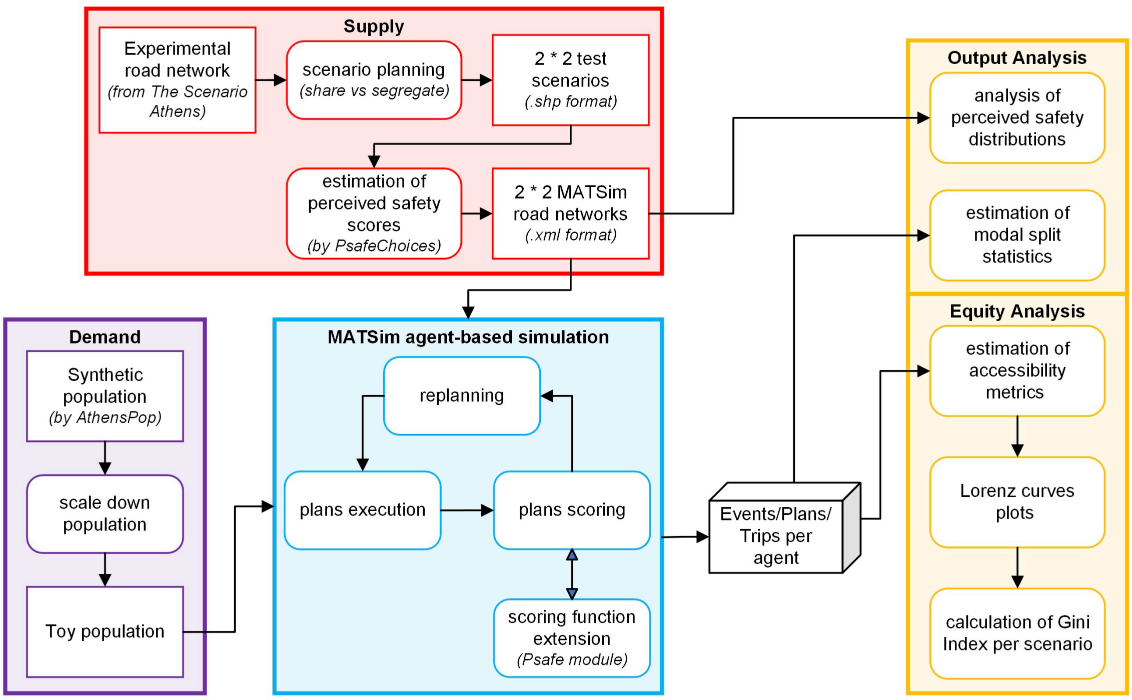

Figure 54: Methodological flow diagram of the second simulation experiment

A transport mode that raises safety issues when used in a road environment has restricted accessibility in that area. Perceived safety is an individual's assessment concerning the likelihood of an accident when utilizing a specific mode of transport (Bhagat-Conway et al., 2022). Past research has shown a strong relationship between perceived safety and factors in the road environment, such as the presence or absence of infrastructure dedicated to a particular transport mode (Cho et al., 2009; Gkekas et al., 2020; Park and Park, 2021). The modeling technique adopted in this research is both sophisticated and universal. It proposes that perceived safety is not uniform across all road links and can differ depending on the mode of transport, leading to unique model coefficients. Perceived safety levels can be measured using a Likert Scale; earlier research employed a 7-point scale encompassing only the essential safety levels distinguishable by a respondent (Hill and Boyle, 2007; Molin et al., 2017; Tzouras et al., 2020). While ordinal scales often employ numbers to denote a person's agreement level with a given statement, they do not offer metric data and need linearity checks. As a result, the dependent variable isn't continuous but is inferred from a latent variable and a series of kappa thresholds (Tzamourani et al., 2022). These kappa thresholds serve as model parameters, setting intervals, with every interval aligning with one level on the 7-point Likert Scale (Scott Long, 2015). It is worth noting that the intervals chosen can differ based on the mode of transport. The generic model function for perceived safety is presented in **Equation 30**.

$$psafe_{i,m} = J + 1 \quad if \quad k_{j,m} > psafe^{*}_{i,m} \geq k_{j+1,m} \qquad (30)$$

where:
$\mathrm{psafe}^{*}_{i,m}$: the latent variable of the perceived safety of using mode m (i.e., car, e-bike, and e-scooter) in the link i.
$\mathrm{psafe}_{i,m}$: the perceived safety level of using mode m in the link i. It is an integer variable with $\mathrm{J} \in [0, 6]$,
$\mathrm{k}_{j,m}$: kappa threshold of level j for using mode m. On a 7-point Scale, by definition: $\mathrm{k}_{0,m} \rightarrow -\infty$ and $\mathrm{k}_{7,m} \rightarrow +\infty$.

In this research, the model for perceived safety incorporates parameters such as the type of road infrastructure, the presence of pedestrian crossings, the condition of the pavement, and any obstacles present in the road environment. This model was previously developed by the research group at the National Technical University of Athens. Their aim was to identify routes in Athens' city center that were both quick and safe for e-scooter use (Tzouras et al., 2023). Using dummy variables, distinct categorical levels are set, enabling the formulation of 48 unique road environments through this new coding system. A detailed representation of the perceived safety model and its associated variables can be found in **Figure 55** and **Equation 31**. The comprehensive open-source toolkit to model perceived safety for each segment of the input road network is named the PsafeChoices[24] package. The perceived safety metric for each mode of transport serves as an added attribute for every link, in a manner similar to how attributes like the number of lanes or lane capacity described the road network supply in the previous experiment.

[24] PsafeChoices package repository: https://github.com/lotentua/Perceived_safety_choices

$$k_{j,m} > \beta_{infr,(1),m} \times infr_{(1)}i + \beta_{infr,(2),m} \times infr_{(2)}i + \beta_{infr,(3),m} \times infr_{(3)}i + \beta_{csr,(1),m} \times csr_{(1)}i + \beta_{csr,(2),m} \times csr_{(2)}i + \beta_{pav,m} \times pav\ i + \beta_{obs,m} \times obs\ i \geq k_{j+1,m} \quad (31)$$

where:

$\beta_{infr,(1),m}, \beta_{infr,(2),m}, \ldots, \beta_{obs,m}$: set of beta parameters; they differ per transport mode m,
$infr_{(1)}i$: 1, if urban road with sidewalk < 1.5 m. wide and without a cycle lane in the link i,
$infr_{(2)}i$: 1, if urban road with sidewalks ≥ 1.5 m. wide and without a cycle lane in the link i,
$infr_{(3)}i$: 1, if shared space (or traffic calming zone) with a 30 km/h speed limit in the link i,
$csr_{(1)}i$: 1, if (zebra) pedestrian crossings are not protected by traffic lights in the link i.
$csr_{(2)}i$: 1, if (zebra) pedestrian crossings protected by traffic lights in the link i,
pav i: 1, if the pavement of the urban road is in good condition (no cracks or dangerous spots, low frequency of vibrations while riding/cycling) in the link i,
obs i: 1, if no obstacles on the sidewalks of link i.

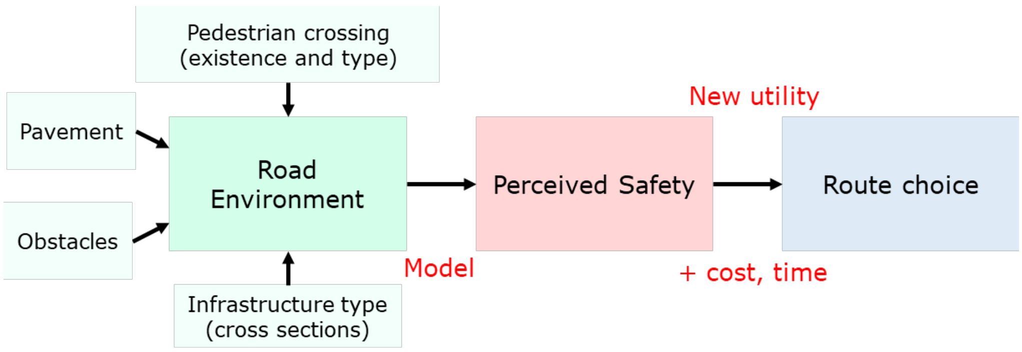

Figure 55: Methodological flow diagram of the PsafeChoices package

The Psafe Module enhances the MATSim scoring function to incorporate perceived safety. As depicted in **Equation 32**, travel disutility is now a factor of time, distance (i.e., expense), and safety. The beta coefficient (β) signifies the importance of safety perceptions in the choice process, affecting the choice of mode or path. A threshold level is established for perceived safety, where rates below this threshold amplify travel disadvantages and the opposite is true for rates above it. These perceived safety scores are multiplied by the length of each road segment, defined by the ($dmax_{m(q)}$ parameter). This illustrates the maximum length of a potentially unsafe route that a user is prepared to navigate during the beginning or end of their journey (Tzouras et al., 2023). Extended road stretches that go beyond this maximum acceptable unsafe length profoundly influence the overall safety perception, while minor interruptions are less impactful. This module offers a method to compute the aggregate perceived safety through a distance-weighted average. In this case, the maximum accepted unsafe distance is equal to the total distance of each trip.

$$S_{trav,m(q)} = \left[C_{m(q)} + \beta_{trav,m(q)} \times t_{trav,m(q)} + \beta_{mon} \times \Delta m_q + \left(\frac{\beta_{d,m(q)}}{\gamma_{d,m(q)}} + \beta_m \right) \times d_{trav,q} \right] + \left\{ \beta_{psafe,m(q)} \times \sum \left[\left(psafe_i - c_{psafe} \right) \times \frac{d_{trav,i}}{dmax_{m(q)}} \right] \right\} \quad (32)$$

where:
$C_{m(q)}$: mode-specific constant of mode m,
$\beta_{trav,m(q)}$: the marginal utility of travel time of mode m,
$t_{trav,m(q)}$: the travel time in hours of using mode in trip q,
β_{mon} : the marginal utility of money,
Δm_q: the change in the monetary budget in euros (equal to zero in this case),
$\beta_{d,m(q)}$: the marginal utility of distance of mode m,
$\gamma_{d,m(q)}$: the monetary distance rate of mode m,
$d_{trav,q}$: the travel distance of trip q in meters,
$\beta_{psafe,m(q)}$: the marginal utility of perceived safety of mode m,
$psafe_i$: the perceived safety level of link i in Levels,
c_{psafe}: the perceived safety threshold (Level 4 is recommended),
$dmax_{m(q)}$: the maximum accepted unsafe distance of mode m.

Hansen (1959) was the first to introduce the concept of spatial accessibility. It is worth noting that there are several methods to gauge accessibility at a macro level, encompassing a) tallying available opportunities, b) gravitational models, c) random utility-based evaluations, and d) distance-based metrics (Adhvaryu et al., 2019; Gonzalez-Feliu et al., 2014; Kwan, 1998). Each method provides distinct insights into urban accessibility. Delving into the distance-based perspective, spatial accessibility denotes the convenience of movement between two locations (Geurs and van Wee, 2004). In this context, the straight-line or Euclidean distance between points represents the most direct route. Consequently, the closer the actual travel path is to this direct route, the higher the level of spatial accessibility, providing travelers with increased comfort and ease. In light of this, the study will investigate the Potential Mobility Index (PMI) (van der Veen et al., 2020), specifically focusing on two indices; a) the comparison of the real travel distance from point A to B (derived from the ABM) with the straight-line distance between them and b) the comparison of the actual travel time for a route from point A to B (sourced from the ABM) with the time it would take on a straight-line path at a constant speed of 30km/h. The following equations illustrate these metrics:

$$RAD_a = \frac{\sum_t D'_{t(m,n)}}{\sum_t D_{t(m,n)}} \quad (33)$$

$$RAT_a = \frac{\sum_t T'_{t(m,n)}}{\sum_t T_{t(m,n)}} \quad (34)$$

where:
RAD: the relative access distance of agent a,
$D'_{t(m,n)}$: the actual distance of trip t, i.e., from node m to node n, as covered by agent a,
$D_{t(m,n)}$: the Euclidean distance of trip t, i.e., from node m to node n.
RAT: the relative access distance of agent a,
$T'_{t(m,n)}$: the actual travel time of trip t, i.e., from node m to node n, as covered by agent a,
$T_{t(m,n)}$: the travel time of trip t required to travel from node m to node n following a fixed speed of 30 km/h.

As previously mentioned, there's a tight connection between accessibility and transport equity. From a philosophical standpoint, the two predominant views on transport equity are egalitarianism and sufficientarianism. Egalitarianism underscores the significance of uniformly distributing resources and opportunities among all members of society (Van Wee and Geurs, 2011). Conversely, sufficientarianism posits that the primary concern should be ensuring everyone achieves an adequate level of resources or well-being, rather than an outright equal or unequal outcome. From this perspective, the emphasis lies on fulfilling fundamental needs and guaranteeing a base level of goods and services for everyone (Lucas, 2012).

Two popular tools for assessing the equity in the distribution of a particular effect or indicator within a transport project, viewed through an egalitarian lens, are the Lorenz curve and the Gini index. The Lorenz curve provides a visual representation of wealth distribution by plotting the cumulative percentage of wealth against the respective percentage of the population, arranged from the least wealthy to the most affluent. On the other hand, the Gini index offers a concise numerical representation of the Lorenz curve, encapsulating the overall inequality in a singular value (Delbosc and Currie, 2011). The more the Lorenz curve deviates from a 45-degree line, the greater the inequality. The Gini index has a range from 0 to 1: a score of 0 signifies perfect equality, while a score of 1 signifies absolute inequality (Guzman et al., 2020). The subsequent equation will be used to determine the Gini index.

$$G(Y_s) = 1 - \sum_{a=1}^{A} \left(P(x_a) + P(x_{a-1})\right) \times \left(P(y_{s,a}) + P(y_{s,a-1})\right) = 1 - \sum_{a=1}^{A} \left(\frac{y_{s,a} + y_{s,a-1}}{A^2}\right) \qquad (35)$$

<u>where</u>:
A: the total number of agents,
Y_S: the set of accessibility estimations – all agents in scenario s; in this case, $Y_s = RAD$ or$Y_s = RAT$,
$G(Y_s)$: the Gini index as a function of Y,
$P(X_a)$: the cumulative “population” proportion of agent a; in this case, $P(x_a) - P(x_{a-1}) = \frac{1}{A}$,
$P(y_{s,a})$: the cumulative proportion of the accessibility of agent a in scenario s.

In the context of sufficientarianism, it's crucial to set a benchmark that outlines the basic accessibility or transport quality individuals need for complete societal participation. This perspective extends beyond just having transportation choices; it underscores the principle of adequacy. Adopting this approach fosters a transport system that's not only inclusive and just but also bolsters the overall welfare and prospects of its users, especially those vulnerable to exclusion or missing out on crucial services and engagements. The corresponding equation used is as follows:

$$P_{thr}(Y_s) = P(y_{s,a} \leq thr_Y) \qquad (36)$$

<u>where</u>:
$P_{thr}(Y_s)$: the percentage of agents in scenario s which their accessibility is below the selected threshold,
thr: the selected threshold; in this case, $thr_{RAD} = 1.5$ and $thr_{RAD} = 15$.

5.3.2 Study case and scenarios formulation

The routing model was first tested in a simulated environment based in downtown Athens, Greece, focusing on routes less than 10 kilometers. The simulation experiment was conducted within Athens' municipality, which had a population of 637,798 according to the 2021 census. This area encompasses the city's commercial hub, filled with businesses, hotels, eateries, and more. Notably, government buildings and public services are located near Syntagma Square and Panepistimiou Avenue, making it a hotspot for daily commutes.

The majority of streets in the road network are narrow, one-way routes, and there are pedestrian-only areas, limiting private car usage. However, the presence of six metro stations and two tram stops makes public transport a more effective and appealing choice for commuting to and from downtown Athens. Data from September 2022 indicates that about 96.2% of trips entering or leaving the area are on foot. This trend aligns with Athens' general mobility patterns, where a mere 1.95% of journeys under 5 km are made by bikes or e-scooters. Although prior research has proposed a comprehensive cycling network linking Athens' center to surrounding municipalities, only a small portion of this has been realized.

To create the routing model, a road grid comprising 257 nodes and 400 connections was developed. The study region and its experimental road framework are depicted in **Figure 56**. To draw valid comparisons in routing behaviors, roads exclusively for pedestrians were not included. Exceptions include Aiolou Street and the pathway linking Dion. Aeropagitou to Apost. Pavlou Streets is a broad 1.38 km pedestrian path that links the Acropolis of Athens to the Ancient Market. This walking street accommodates both walkers and users of bicycles and e-scooters. Despite the emphasis on pedestrian routes, there are no designated bike paths in the network, except for temporary ones introduced on Vas. Olgas and Panepistimiou Avenues during the COVID-19 lockdown in May 2020 (Kyriakidis et al., 2022; Tzamourani et al., 2022). Notably, 76.8% of the road network's connections are one-directional. For ease of understanding, only nine outer areas are defined, each connecting to the primary network through a single one-way connection.

Scenario 0 represents the current state of the road infrastructure. It was designed using various spatial data, including the presence or absence of bike lanes, sidewalk dimensions, speed limits, pavement quality, obstacles, and pedestrian crosswalks. Photos from on-site visits were used to supplement or update the data where needed. For a proper assessment of perceived safety, the road environment needs to be detailed using the criteria mentioned in Equation 29, according to specific predetermined classifications. Infrastructure categories include: “1: Urban road with sidewalk less than 1.5 m. wide”, “2: Urban road with sidewalk more than 1.5 m. wide”, “3: Urban road with a cycle lane” and “4: Shared space”. Based on the photos, pavement quality is tagged as either “0: bad condition” or “1: good condition”. Obstacle presence is marked as “0: yes obstacles” and “1: no obstacles”. Additionally, pedestrian crosswalks on each link are categorized into three levels: “0: without pedestrian crossings", "1: with pedestrian crossings not controlled by traffic lights" and "2: with pedestrian crossing controlled by traffic lights". All this data is then compiled and structured into a single shapefile via a Geographic Information System (GIS), detailing the characteristics of each road connection.

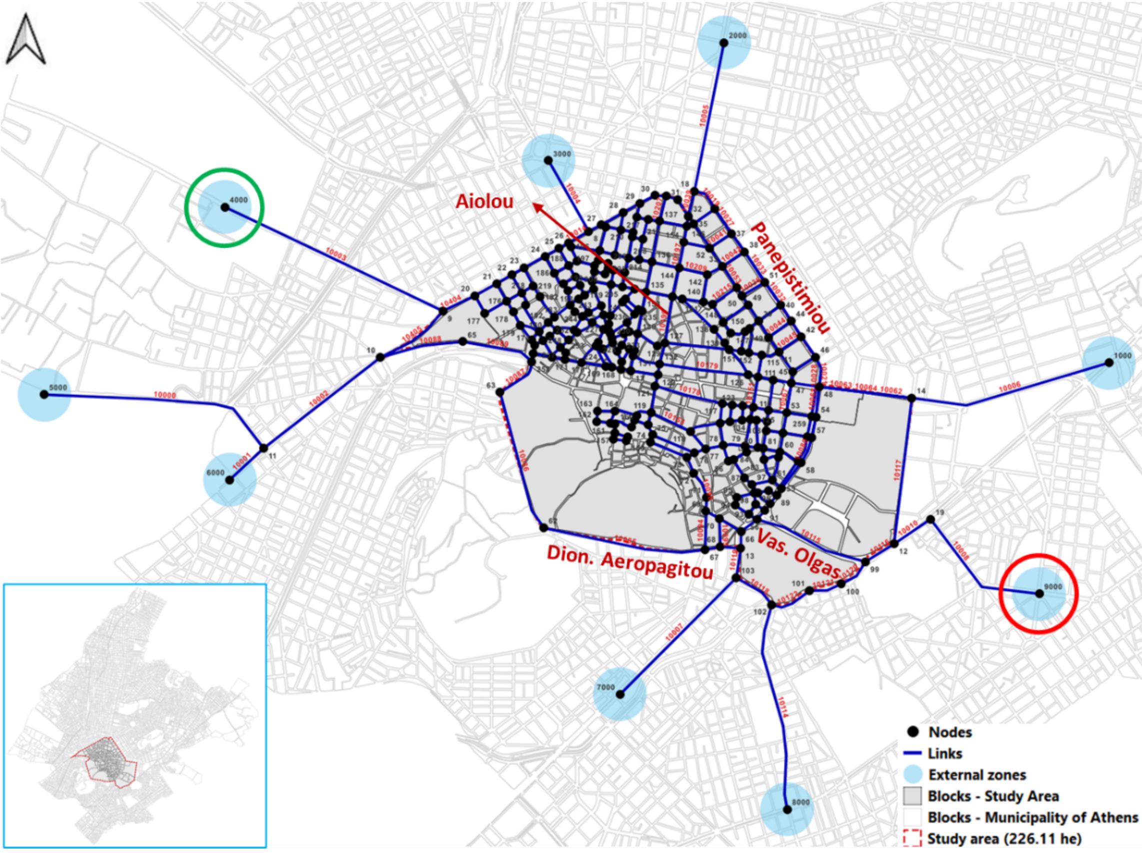

Figure 56: The "Scenario Athens"

This paper builds four scenarios that represent different rationales and spatial configurations. These four scenarios are based on a 2*2 scenario matrix, which is a common tool for envisioning the future (Ramirez and Wilkinson, 2014). The x-dimension of this matrix refers to the intensity of "shared space" and the y-dimension to the presence of cycling lanes or tracks. Conceptual diagrams displaying the four scenarios are presented in **Figure 57**. Apart from S0 which is the baseline scenario preserving the existing status quo, all the rest are built through the backcasting approach aiming to achieve sustainable and inclusive mobility conditions. S1 titled "Segregated infrastructure leads the way" prioritizes mostly cycling lanes or tracks, whereas S2 titled "To share is better" considers mainly shared space streets (in the form of areas). However, there is also S3 titled "Balancing segregation and sharing" that adopts a combinatorial approach both taking into account cycling lanes or tracks and shared space streets. Notably, this last scenario formulates shared space areas, circulated by segregated cycling infrastructure. The conceptual scenarios are imported into the simulation process by tuning the dummy explanatory variables of the perceived safety model.

Figure 57: Mental simulation scenarios presentation

Before initiating the model's full operation, it is essential to establish its beta parameters. For the perceived safety model, default parameters were set using an image-driven double-stated preference study carried out in Athens, Greece. Out of the 129 participants, the majority were younger individuals with little experience in using micro-mobility transport. They assessed the perceived safety across 12 designed scenarios. Using ordinal logistic regression, the safety perception models for cars, e-bikes, and e-scooters were determined (as seen in **Table 19**). The e-bike and e-scooter models exhibit a higher R^2 (greater than 0.30) indicating a better fit, and a reduced standard error ($\sigma = \pm 1$ Lev) when compared to the private car models, which have an R^2 less than 0.25. The kappa thresholds per transport mode are provided too.

Table 19: Explanatory variables of perceived safety and their default beta parameters per transport mode

Variable name	**Description of variable levels**	**Coefficient values (multiplier)**	**Dummy variable values**
Road infrastructure ($infr_{(\mathrm{n})}$)	urban road with sidewalk < 1.5 m. wide and without a cycle lane in the link i	$\beta_{infr,(1),\mathrm{car}} = -0.510$ $\beta_{infr,(1),\mathrm{ebike}} = -3.671$ $\beta_{infr,(1),\mathrm{escooter}} = -3.072$	$infr_{(1)}\mathrm{i} = 1$ $infr_{(2)}\mathrm{i} = 0$ $infr_{(3)}\mathrm{i} = 0$
	urban road with sidewalks ≥ 1.5 m. wide and without a cycle lane in the link i	$\beta_{infr,(2),\mathrm{car}} = -0.450$ $\beta_{infr,(2),\mathrm{ebike}} = -3.161$ $\beta_{infr,(2),\mathrm{escooter}} = -2.387$	$infr_{(1)}\mathrm{i} = 0$ $infr_{(2)}\mathrm{i} = 1$ $infr_{(3)}\mathrm{i} = 0$
	shared space (or traffic calming zone) with a 30 km/h speed limit in link i	$\beta_{infr,(3),\mathrm{car}} = -0.557$ $\beta_{infr,(3),\mathrm{ebike}} = -2.567$ $\beta_{infr,(3),\mathrm{escooter}} = -1.889$	$infr_{(1)}\mathrm{i} = 0$ $infr_{(2)}\mathrm{i} = 0$ $infr_{(3)}\mathrm{i} = 1$
	urban road with a cycle lane in the link i		$infr_{(1)}\mathrm{i} = 0$ $infr_{(2)}\mathrm{i} = 0$ $infr_{(3)}\mathrm{i} = 0$
“Zebra” pedestrian crossings ($csr_{(\mathrm{n})}$ i)	(zebra) pedestrian crossings not protected by traffic lights in link i	$\beta_{csr,(1),\mathrm{car}} = -0.499$ $\beta_{csr,(1),\mathrm{ebike}} = -0.217$ $\beta_{csr,(1),\mathrm{escooter}} = -0.290$	$\mathrm{csr}_{(1)}\mathrm{i} = 1$ $\mathrm{csr}_{(2)}\mathrm{i} = 0$
	(zebra) pedestrian crossings protected by traffic lights in link i	$\beta_{csr,(2),\mathrm{car}} = 0.044$ $\beta_{csr,(2),\mathrm{ebike}} = 0.016$ $\beta_{csr,(2),\mathrm{escooter}} = 0.017$	$\mathrm{csr}_{(1)}\mathrm{i} = 0$ $\mathrm{csr}_{(2)}\mathrm{i} = 1$
Pavement conditions (pav i)	the pavement of the urban road is in good condition (no cracks or dangerous spots, low frequency of vibrations while riding/cycling) in the link i	$\beta_{pav,\mathrm{car}} = 1.005$ $\beta_{pav,,\mathrm{ebike}} = 0.561$ $\beta_{pav,\mathrm{escooter}} = 0.662$	$pav\ \mathrm{i} = 1$
Obstacles (obs i)	no obstacles on the sidewalks of link i	$\beta_{obs,\mathrm{car}} = 0.178$ $\beta_{obs,,\mathrm{ebike}} = 0.290$ $\beta_{obs,\mathrm{escooter}} = 0.361$	obs i = 1
Kappa thresholds $k_{j,m}$	Kappa thresholds of perceived safety model per level j and transport mode m.	$(\mathrm{k}_{1,\mathrm{car}} = -4.310, \mathrm{k}_{2,\mathrm{car}} = -2.995, \mathrm{k}_{3,\mathrm{car}} = -2.150, \mathrm{k}_{4,\mathrm{car}} = -0.872, \mathrm{k}_{5,\mathrm{car}} = +0.307, \mathrm{k}_{6,car} = +1.570)$ $(\mathrm{k}_{1,\mathrm{ebike}} = -4.568, \mathrm{k}_{2,\mathrm{ebike}} = -3.145, \mathrm{k}_{3,\mathrm{ebike}} = -2.206, \mathrm{k}_{4,\mathrm{ebike}} = -1.058, \mathrm{k}_{5,\mathrm{ebike}} = -0.037, \mathrm{k}_{6,\mathrm{ebike}} = +1.315)$ $(\mathrm{k}_{1,\mathrm{escoot}} = -4.901, \mathrm{k}_{2,\mathrm{escoot}} = -3.537, \mathrm{k}_{3,\mathrm{escoot}} = -2.709, \mathrm{k}_{4,\mathrm{escoot}} = -1.573, \mathrm{k}_{5,\mathrm{escoot}} = -0.645, \mathrm{k}_{6,\mathrm{escoot}} = +0.687)$	

For successful implementation of the constructed module within a simulation process, three critical questions need to be addressed for each first/last mile transport mode: a) How many euros are travelers willing to pay for 1 hour less traveling? b) How many kilometers are travelers willing to exchange to experience one level more of perceived safety? c) How many minutes are travelers willing to exchange to experience one level more of perceived safety? The first query delves into the Value-of-Time (VoT_m), a pivotal, tangible metric that has been recognized as an indicative parameter of travel habits in past studies (Alonso-González et al., 2020; Steck et al., 2018). The subsequent question touches on the extent of exposure a commuter is ready to accept, referred to in this research as the Value-of-Safe-Distance ($VoSD_m$). The concluding question pertains to the Value-of-Safe-Time ($VoST_m$), which is indicative of trip comfort. Fundamentally, prolonged durations of perceived unsafe commutes culminate in higher discomfort and therefore lower trip utility especially for micro-mobility mode users (Akgün-Tanbay et al., 2022; Fitch et al., 2022b).

The ratios outlined above for individual transport modes furnish the foundational elements required to fine-tune the emerging MATSim scoring function. It is imperative to acknowledge the role of the marginal utility of money, which ought to be predetermined. Based on the model definition, this does not differ per transport mode (Nagel et al., 2016). This gives rise to a structured system comprising three distinct equations with an equivalent number of unknown variables (as referenced in **Equation 37**). Deciphering this system facilitates the identification of the principal parameters that drive the scoring function.

$$\begin{cases} VoT_m = \dfrac{\beta_{trav,m(q)}}{\beta_{mon}} \\ VoSD_m = \dfrac{\beta_{psafe,m(q)}}{\left(\dfrac{\beta_{d,m(q)}}{\gamma_{d,m(q)}} + \beta_{mon}\right)} \\ VoST_m = \dfrac{\beta_{psafe,m(q)}}{\beta_{trav,m(q)}} \end{cases} = \begin{cases} \beta_{trav,m(q)} = \beta_{mon} \times VoT_m \\ \left(\dfrac{\beta_{d,m(q)}}{\gamma_{d,m(q)}} + \beta_{mon}\right) = \dfrac{\beta_{psafe,m(q)}}{VoSD_m} \\ \beta_{psafe,m(q)} = \beta_{trav,m(q)} \times VoST_m \end{cases} \quad (37)$$

Table 20: Default parameter values of the scoring function

	Coefficient values		
Variable name	**Car**	**E-bike**	**E-scooter**
Value of Time	$VoT_{car} = +0.12\dfrac{euro}{min}$	$VoT_{ebike} = +0.16\dfrac{euro}{min}$	$VoT_{escooter} = +0.20\dfrac{euro}{min}$
Value of Safe Distance	$VoSD_{car} = -10.47\dfrac{km}{Lev}$	$VoSD_{ebike} = -7.50\dfrac{km}{Lev}$	$VoSD_{escooter} = -3.06\dfrac{km}{Lev}$
Value of Safe Time	$VoST_{car} = -14.67\dfrac{min}{Lev}$	$VoST_{ebike} = -21.00\dfrac{min}{Lev}$	$VoST_{escooter} = -15.20\dfrac{min}{Lev}$
Mode – specific constant	$C_{car} = 0\ utils$	$C_{ebike} = +0.10\ utils$	$C_{escooter} = -0.41\ utils$
Travel time	$\beta_{trav,car} = -1.8\ utils/h$	$\beta_{trav,ebike} = -2.4\ utils/h$	$\beta_{trav,escooter} = -3.0\ utils/h$
Travel distance	$\left(\dfrac{\beta_{d,car}}{\gamma_{d,car}} + \beta_{mon}\right) = -4.2 \times 10^{-5}\ utils/m$	$\left(\dfrac{\beta_{d,ebike}}{\gamma_{d,ebike}} + \beta_{mon}\right) = -11.2 \times 10^{-5}\ utils/m$	$\left(\dfrac{\beta_{d,escooter}}{\gamma_{d,escooter}} + \beta_{mon}\right) = -24.8 \times 10^{-5}\ utils/m$
Perceived safety	$\overline{\beta_{psafe,car}} + 0.44\dfrac{utlis}{Lev}$ $\sigma_{psafe,car} = \pm 0.20\dfrac{utlis}{Lev}$	$\overline{\beta_{psafe,ebike}} = +0.84\dfrac{utlis}{Lev}$ $\sigma_{psafe,ebike} = \pm 0.22\dfrac{utlis}{Lev}$	$\overline{\beta_{psafe,escooter}} = +0.76\dfrac{utlis}{Lev}$ $\sigma_{psafe,escooter} = \pm 0.07\dfrac{utlis}{Lev}$

The demand for our study is derived from the AthensPop[25] package, representing 0.1% of the metropolitan area population. The AthensPop package was developed by the research team of ARUP City Modeling Lab and the National Technical University of Athens. The main aim was to demonstrate methods and tools for the generation of a synthetic population with daily travel plans in the Athens Metropolitan Area. AthensPop creates some toy scenarios that can be used for educational and experimental purposes in Greece. The package employs statistical analysis, machine learning, and data fusion methodologies, typically through the Population Activity Modeler[26] (or PAM) an open-source library. PAM is a Python API for activity sequence modeling, focusing on the generation and modification of travel demand scenarios. Primary features of PAM are a) common format read/write files including MATSim plans files (in .xml format), b) sequence inference from travel diary, c) rules-based sequence modification, d) sequence visualization, e) facility sampling, and f) hooks for research extensions[27]. AthensPop and PAM can be used by planners to develop quick disaggregate demand scenarios in different districts of AMA. The resulting population has been scaled down to the study area.

At this point, it is crucial to highlight a set of twelve assumptions that have been incorporated into this simulation experiment. Every agent in the simulation is equipped with a private car, an e-bike, and an e-scooter, and they do not have the option to alternate between these modes during their trips. Interestingly, those opting for private car travel do not concern themselves with parking upon reaching their endpoint. All modes of transport strictly adhere to one-way directives, and it is noteworthy that e-scooters and e-bikes are permitted on included walking streets. To account for potential intersection delays, the free flow speeds on the links are dialed down by half. The simulation adopts a conservative approach, setting link capacities at just 5% of their actual potential, given that only 3077 agents are incorporated. For estimating capacities on each link, the model leans on kinematic wave equations, setting the wave speed at 13.5 km/h and jam density at 125 veh/km/lane. Safety concerns are factored in, with the maximum accepted unsafe distance equal to the entire trip length, giving the weighted average of perceived safety. Notably, plans get a boost when the perceived safety scores exceed 4, whereas links scoring below this threshold induce disutility. The model also accommodates behavioral dynamics: in every iteration cycle, 10% of agents modify their routes, another 10% switch their mode, while the remaining 80% select plans guided by the probabilities from a Multinomial Logit model. The entire simulation is designed to conclude after 500 iterations. It's imperative to note that all the previously mentioned assumptions remain consistent across all test scenarios.

[25] The AthensPop package repository: https://github.com/Theodore-Chatziioannou/athenspop
[26] PAM package repository: https://github.com/arup-group/pam
[27] PAM package documentation: https://arup-group.github.io/pam/0.2/

5.3.3 Simulation results and analysis

The methods utilized provided rather interesting results that reveal different aspects of perceived safety, accessibility, and equity. Using an Agent-Based model on MATSIM, the study recalculated the modal shares of cars, e-bikes, and e-scooters for each scenario, leading to notable findings. **Figure 58** displays these distributions based on the final iteration's results. It is evident that the modal share significantly varies depending on the objectives of each scenario. For instance, in Scenario 3, bicycle usage exceeds 30%, while car usage drops to 60%. However, the do-nothing scenario and the shared space priority scenario (S2) do not exhibit such shifts. They preserve car dominance, even if S2 has slightly reduced car usage. Regarding e-scooters, their share remains consistent across scenarios, hovering around 7%.

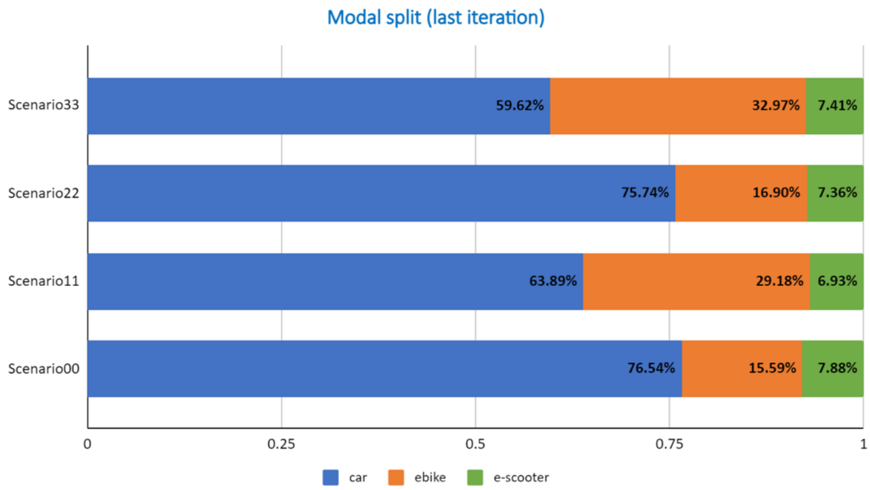

Figure 58: Modal split per mental simulation scenario

Perceived safety, in addition to modal share, emerges as a vital aspect to consider. When examining cars, Scenario 3 (S3) records the highest average perceived safety, rated at 5.982 out of 7. This contrasts with the lowest safety score found in Scenario 0 (S0), which stands at 5.479 out of 7 – indicating an improvement of 9.2% in S3. Other scenarios, like Scenario 1 and 2, also elevate the safety perception, but not as significantly as S3, with values of 5.827/7 and 5.980/7 respectively.

Focusing on e-bikes, S3 once again stands out with the top safety score of 4.390 out of 7. This is a marked enhancement from the lowest safety score in S0, which is 2.820 out of 7 – a remarkable growth of 55.67%. While Scenarios 1 and 2 also bolster the safety perception for e-bike riders, their scores (3.975/7 for S1 and 3.996/7 for S2) do not reach the heights of S3.

As for e-scooters, the trend does not vary significantly. S3 leads with an average safety score of 3.798 out of 7, whereas S0 lags behind at 2.501 out of 7 – marking a commendable uplift of 51.86%. Both Scenarios 2 and 3 follow closely, registering 3.587/7 and 3.439/7, respectively. In summary, it is evident that scenarios introducing segregated infrastructure boost safety across all transport modes. Simultaneously, shared space scenarios primarily enhance safety perceptions for cars, with bicycles benefitting to a lesser extent.

Analyzing accessibility changes across scenarios, both relative access distance and time per agent were calculated, and the results are visualized in histograms as shown in **Figure 59** and **Figure 60**. Notably, the histograms in the first figure appear to exhibit a normal distribution. This hints at a consistent pattern spanning different scenarios and transport modes, even though there are differences in their standard deviations and average values. In Scenario 0 (S0), cars exhibit the fewest number of trips under the 1.5 mark but maintain the smallest variation in data, indicated by the lowest standard deviation. E-bikes, on the other hand, have the smallest average value, albeit with a somewhat larger spread in the data. Meanwhile, e-scooters are marked by the broadest data spread, with a standard deviation of 2.44, suggesting they are typically used for longer distances. Transitioning to Scenario 1 (S1), the average distance for e-scooter trips declined from 1.81 to 1.54. However, the average values for the other modes remained largely unchanged. In Scenario 2 (S2), e-bikes seem to be the preferred mode for lengthier commutes, evidenced by their average value climbing to 1.83. Regarding Scenario 3 (S3), cars displayed the smallest average distance when compared to other scenarios. Furthermore, this scenario yielded the tightest data range for cars. Yet, e-scooters showed considerable variability, peaking with a standard deviation of 2.95. In essence, each scenario brought its unique pattern, emphasizing the importance of individual transport modes under different conditions.

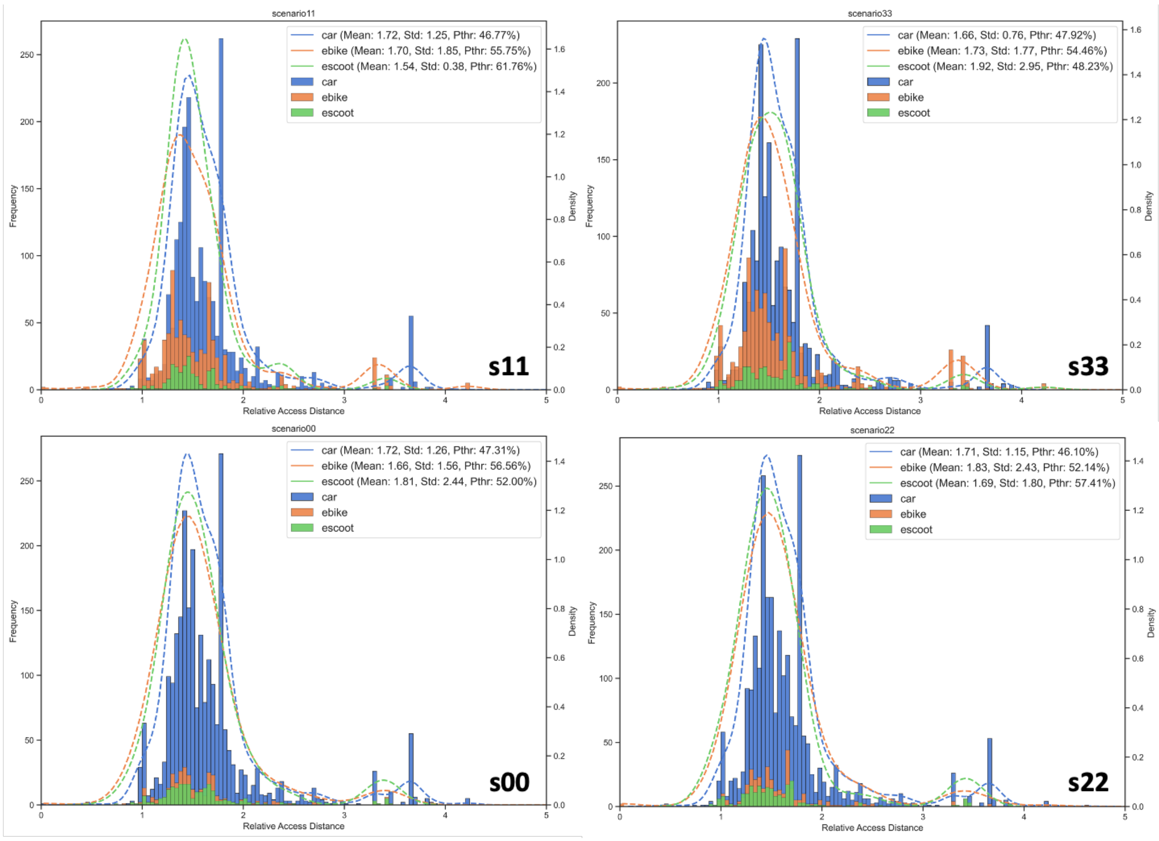

Figure 59: Histograms of relative access distance per mental simulation scenario and transport mode

Analyzing **Figure 60**, it is evident that the histograms do not align with a normal distribution. Diving deeper into the specifics: For Scenario 0 (S0), the average travel time for a private car is approximately 31.74 times longer than in optimal conditions. Even so, cars exhibit the smallest variability, as shown by the smallest standard deviation compared to the other modes. Both e-bikes and e-scooters exhibit considerable variability, with standard deviations of 95.20 and 73.73, respectively. In Scenario 1 (S1), there is a noteworthy decline in the average values for both e-bikes and e-scooters, moving from 31.04 to 19.01 and from 36.55 to 29.17, respectively. In contrast, travel times for cars saw a marginal increase. For Scenario 2 (S2), the average travel times for cars and e-scooters are nearly identical, hovering around 32.73. However, e-bikes displayed a spike in variability, with a standard deviation of 105.12, the highest among all scenarios. Turning our attention to Scenario 3 (S3), e-bikes emerge as a particularly appealing option. They not only see a reduction in their average travel time, comparable to that in S1, but also benefit from a relatively smaller data spread, suggesting consistent, faster travel options for cyclists. On the other hand, e-scooters maintained fairly consistent travel times, comparable to those in S0. In summary, each scenario portrays unique travel dynamics for the different modes of transport, highlighting the variances in travel times and route choices under different conditions.

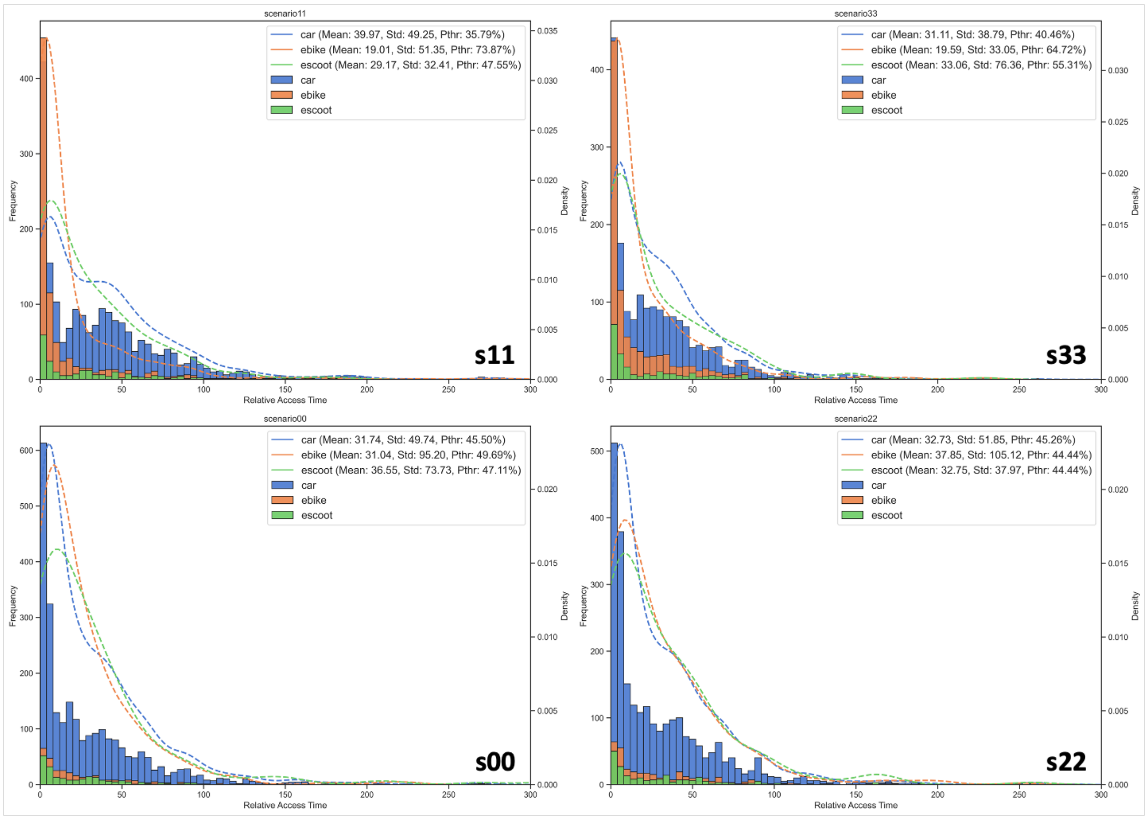

Figure 60: Histograms of relative access time per mental simulation scenario and transport mode

When viewed through the lens of sufficientarianism, the results align with the anticipated outcomes. Analyzing relative distance: For car users, Scenario 3 emerges superior with nearly 48% of the agents having satisfactory trips, while Scenario 2 falls short. For e-bike users, Scenario 1 fosters the most favorable conditions, with approximately 56.56% of users satisfied; however, Scenario 2 trails behind. As for e-scooters, Scenario 1 leads the way in providing sufficient conditions with 61.76%

satisfaction, whereas Scenario 3 records the lowest at 48.23%. In essence, a brighter future for transport would involve substantial investments in dedicated cycling lanes and tracks. Switching our attention to relative access time: For cars, Scenario 2 stands out as the best in terms of sufficiency. In contrast, Scenario 1 struggles, satisfying only around 35.79% of its users. For e-bike users, there is a significant shift. Scenario 1 shines with a commendable 73.87% satisfaction rate, leaving Scenario 2 in its wake. When evaluating e-scooters, Scenario 3 offers the most adequate conditions, as 55.31% of agents reach the satisfactory level. Yet again, Scenario 2 lags, catering to only 44.44% of its users. Interestingly, the sufficientarian perspective greatly emphasizes the advantages of specialized infrastructure.

Surprising insights emerge by observing the Lorenz Curves illustrated in **Figure 61** and **Figure 62**. An equity assessment grounded in egalitarian principles for distance metric unveils the following: Scenario 3 stands out, showcasing the most equitable landscape with a Gini Index at 0.1770. In contrast, Scenario 1 presents the peak value of the index at 0.1781, suggesting a more skewed distribution. Analyzing the time metric, Scenario 2 tops the list, marking itself as the most equitable with a Gini Index of 0.5784. Strikingly, Scenario 1, despite its dedicated cycling lanes, hints at larger disparities. It appears that while cycling lanes and tracks lead to a more uniform distribution in distance traveled, they engender distinct outcomes when time is the metric in focus. Consequently, if saving time is paramount, a scenario emphasizing shared space seems more favorable. This mismatch between accessibility and (egalitarian) equity has also been discussed by Pritchard et al. (2019) and Mora et al. (2021) demonstrating that accessible conditions do not necessarily mean equitable distribution and equal merits for everyone.

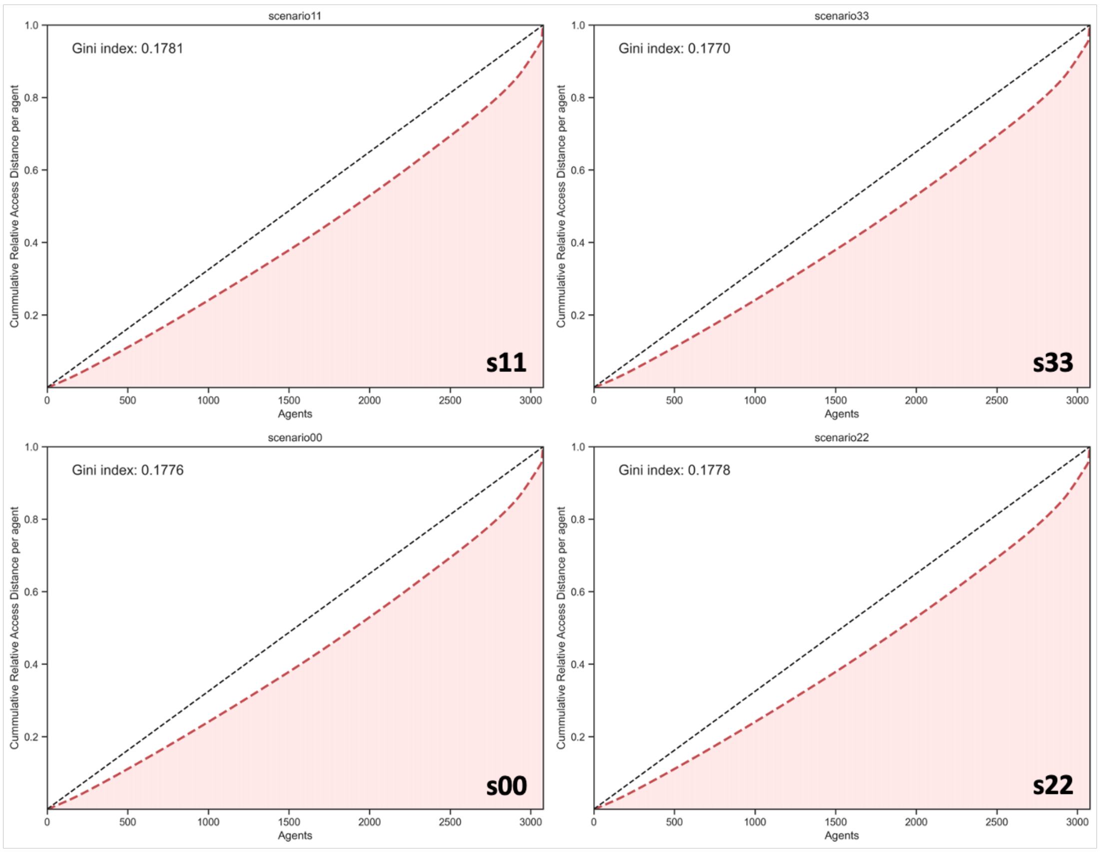

Figure 61: Gini index for each mental simulation scenario related to Relative Access Distance

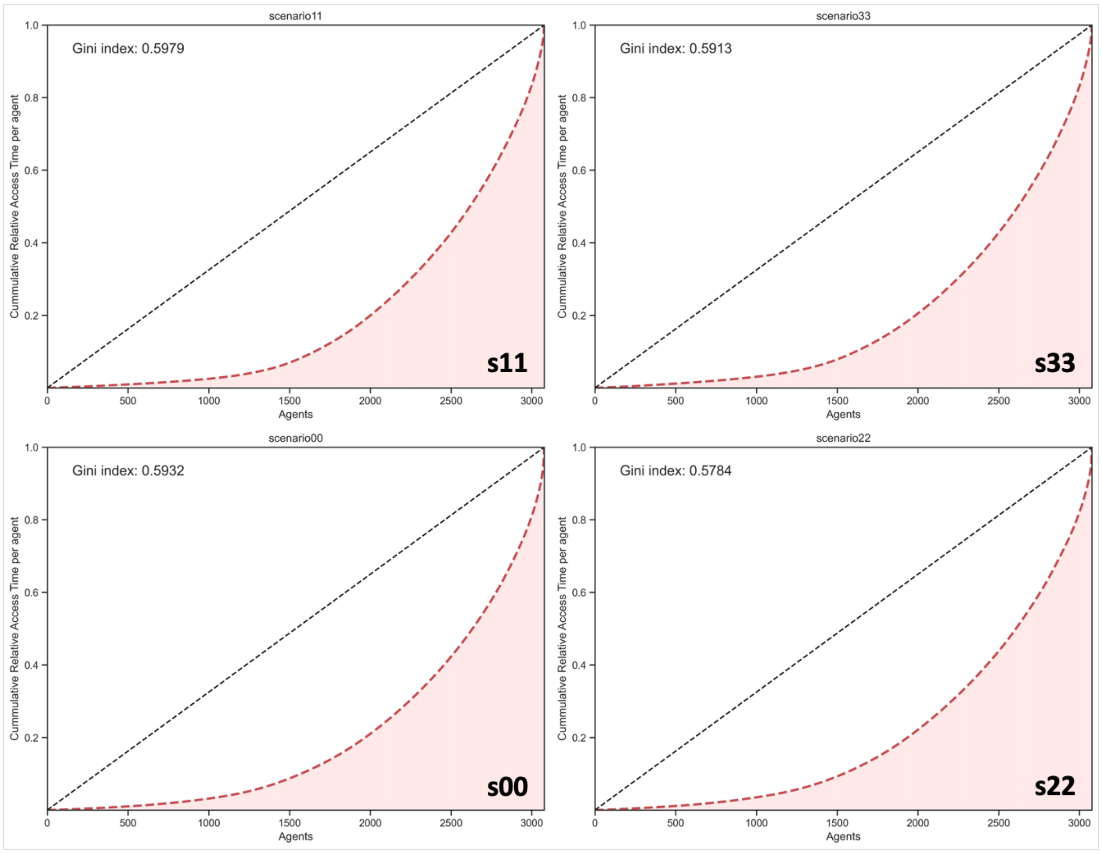

Figure 62: Gini index for each mental simulation scenario related to Relative Access Distance

5.4 Discussion

Compared to previous studies that updated the MATSim model framework to simulate mixed traffic, seepage behavior, (Agarwal and Lämmel, 2016), active modes, and complex interactions occurring on urban roads (Ziemke et al., 2019c), this study followed a different methodological approach. The first simulation experiment developed an external tool to update traffic parameters (i.e., road network supply) based on speed compliance, while the second one integrated the perceived safety factor in the scoring (utility) function of MATSim. Perceived safety acted as an additional attribute that also describes supply. These approaches make the simulation of large-scale shared space networks covering an entire metropolitan area or city center feasible, since it does not increase the complexity of the simulation process, balancing efficiently the trade-off between computation time and level of detail. This is a challenging issue, which has been widely discussed in previous studies dealing with agent-based modeling of metropolitan-scale transport networks (Cao et al., 2021; Charypar et al., 2009b; Tzouras et al., 2022b; Waraich et al., 2015b). Overall, MATSim has been used in a plethora of studies, as its simulation loop provides the right hooks to develop and integrate new modules and therefore simulate innovative and unconventional concepts, like shared space.

The results of the first simulation experiment in Berlin, Germany show that the reduction of speed limits leads to higher usage of public transport modes. The shares of trips, passenger hours, and passengers were considerably increased in all scenarios in which the speed limits were significantly decreased. Public transport (as the main transport mode) seems to be the main competitor of private car in metropolitan areas; this is something that has been observed by previous studies (Klinger, 2017; Milakis et al., 2008). This is strongly related to the travel distances between home and work, which are larger in metropolitan compared to medium or small-sized cities and therefore they cannot be covered by active modes only (Kepaptsoglou et al., 2020; Pnevmatikou et al., 2015). The increased usage of public transport leads to a noticeable reduction of passenger car kilometers and consequently congestion points at peak hours. Although speed limits were reduced on inner urban roads, the decrease in average travel speed using private cars was not so high, as was expected. On the contrary, at peak hours, an increase in average traffic speeds has been reported in this simulation experiment. This is in line with studies conducted on single traffic calming corridors, where travel delays did not rise noticeably due to the lower speed limits (Kaparias and Wang, 2020a). The variance of travel speeds seems to increase by creating traffic calming networks; these distributions indicate the existence of specific hierarchical levels and functions per road link which form an efficient road network. Individuals started traveling with private cars for longer distances, following motorways and private roads, where speed limits remained constant in all scenarios. Due to the elimination of congestion points in these corridors, travel speeds seem to not differ much from free flow speed. This relates to the concept of car-free cities, in which trips of 5 km are substituted by alternative and more sustainable travel modes, e.g., bus, cycling, and walking (Nieuwenhuijsen and Khreis, 2016). Also, this results in a dramatic decrease in vehicle kilometers using private modes, leading to lower energy consumption and less emissions. Nevertheless, drivers' compliance seems to be a catalytic factor that determines the effectiveness of policies related to the reduction of speed limits on urban roads. Considering the experimental results, scenarios with low compliance rates have no difference compared to the base scenario. Drivers' compliance is connected with the design of the urban road and some particular traffic calming measures (Elvik, 2010b; García et al., 2011); nevertheless, a shared space road environment seems to be a more promising and "smooth" design approach (Hammond and Musselwhite, 2013; Karndacharuk et al., 2014a).

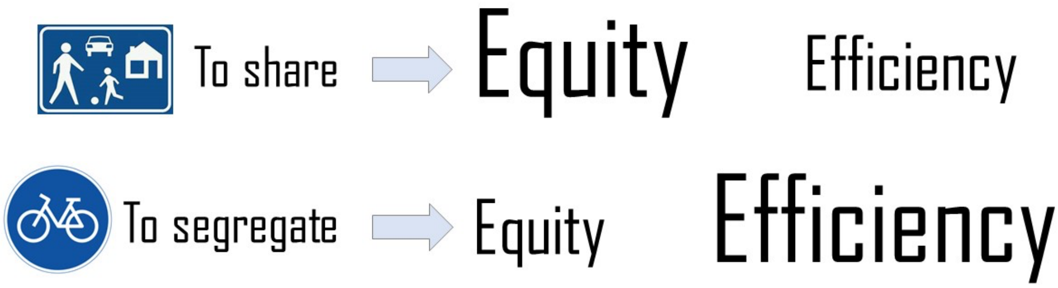

Figure 63: Answers to share or segregate dilemma.

This second simulation experiment in Athens made a significant contribution to the existing knowledge by examining in parallel perceived safety, accessibility, and equity under the bonnet of the future urban road. It combined scenario planning, accessibility, and equity analysis, building on an agent-based model. Hence, the second simulation experiment does not only provide findings about transport futures but also offers a solid method to be applied elsewhere. The results revealed in a solid way that different planning approaches cultivate different perceived safety, accessibility, and equity conditions. In an overview, results indicate that shared space and S2 cultivate the best conditions in terms of equity. Shared space networks ensure equitable conditions where each traveler regardless of mode might experience a smooth trip with less unsafe discontinuities. On the contrary combinatorial approach (S3) employing both shared space in inner areas and cycling lanes/tracks as "ring roads" surrounding shared space zones increases the use of e-bikes and provides way better accessibility. This finding and particularly this mismatch between accessibility and equity can be found in other related research works such as (Delbosc and Currie, 2011; Geurs and van Wee, 2004; Pritchard et al., 2019). It should be stressed that S1 and S3 provide better conditions compared to S2 when adopting a sufficientarianism approach. Related literature unveils that sufficientarianism and egalitarianism approaches lead to rather different outcomes (Mora et al., 2021) and it is crucial to respect social and political priorities. Comparing these two approaches, some studies note that sufficientarianism contributes really into mobility justice by enhancing the powerless and excluded ones; whereas egalitaraniasm hypothesizes a condition where everyone gets exactly the same like in S2, ignoring the unique attributes of travelers and different social groups (Guzman et al., 2017; van der Veen et al., 2020; Van Wee and Geurs, 2011).

Looking into future urban roads. A dilemma between segregate and share. So, what future should we follow? The answer depends on community priorities. In an overall view, a combinatorial perspective may have the greatest dynamic to promote sustainability and inclusivity. E-bike may be considered as a driver for sustainable mobility to prosper, as it can be concluded.

6 Conclusions

In this study, the dilemma of whether it is better to segregate or share urban spaces presented as a significant challenge that persisted throughout the research. Different angles of this research question were approached in the previous four chapters, namely: experts' perspectives and social acceptance, coexistence feasibility, perceived safety, transport network efficiency, equity, and accessibility. In this chapter, some critical conclusions about shared space and practical recommendations for transport and urban planners are provided. Still, further research around this dilemma should be conducted, as the study findings have also been influenced by the study's assumptions and limitations that will be mentioned.

6.1 Main findings and concept assessment

In response to the first sub-question (SRQ1) regarding the prevailing expert opinions on road users' coexistence and shared space, a range of perspectives emerged. Primarily, shared space, in contrast to mere traffic calming measures, serves as a platform for road users to safely coexist and dwell in a single road environment. In the end, it can be linked to a "Crosswalk Anywhere" approach, where traffic flows seem to informally navigate distinct channels, but the spatial distribution and the frequency of pedestrian crossings highly increase. This was confirmed by reviewing the literature. The overarching aim of shared space is to foster a road environment that prioritizes human interaction over car domination. This concept is seen as a potential answer to a dystopian future road environment, especially when autonomous vehicles will dominate, guiding technological advancements to manage the intricate interactions in such spaces. However, a juxtaposition arises: by nature, shared space contradicts some sustainable mobility concepts that promote traffic segregation like cycle lanes, pedestrianized zones, multimodal corridors, etc. While some experts believe that innovative technologies will ultimately sculpt more human-centric spaces, others retain reservations. Skeptics question the overall safety and efficacy, with some steadfastly supporting full traffic segregation as a safer alternative.

In addressing the second sub-question (SRQ2) about the social acceptability of shared space as a concept, varied responses surface based on individual perceptions. Notably, shared space appears to be a hybrid of push and pull measures, but the general public leans more conservatively. There is a noticeable tendency among the public to desire new infrastructure, often without thoroughly assessing its feasibility due to the lack of space or high cost. Interestingly, enlarging pedestrian spaces that are already deemed adequately wide and walkable seems to negatively influence social acceptance. Instead of merely expanding pedestrian space to foster a human-oriented and livable environment, there is a clear inclination towards designs that propose the addition of new, safe (as perceived) exclusive or semi-exclusive corridors for other sustainable mobility transport modes: bicycles, buses, etc. Such designs are perceived to bolster both the safety and efficiency of the transport system. While shared space as new infrastructure might initially seem like a pull measure, it is often paired with reduced speed limits and fewer lanes for motorized traffic, positioning it as a push measure. Consequently, it might be challenging for such concepts to gain widespread acceptance, especially when considering expansive shared space networks.

In response to the third sub-query (SRQ3) on the behavioral variances between traffic on a shared space link and a conventional road link, a comprehensive empirical analysis illuminated distinct differences. In shared spaces, the observation indicates that for every extra second of time headway between two consecutive vehicles, an increase in pedestrian crossings occurs. Such behavior augments the complexity of interactions and consequently influences driving tactics. Unexpectedly, despite the higher volume of pedestrian crossings and resultant interactions in shared spaces, the variance in car speeds on conventional roads was notably greater. This phenomenon suggests that drivers, when faced with the intricate and complex dynamics of shared spaces, tend to adopt a more homogenous driving behavior. This can be interpreted as a compensation measure. In contrast, on conventional roads in Greece, pedestrian crossings seemingly have no significant impact on the average car speed, which may be attributed to the presence of aggressive drivers who often overlook pedestrian priority. Additionally, as expected, both in shared spaces and conventional roads, higher vehicle flows marked by shorter time headways drastically reduce pedestrian crossings. Still, simulations based on the developed empirical models affirmed that even under scenarios of high vehicular demand, the ratio of pedestrian crossings remains positively skewed in shared spaces. Essentially, shared spaces, under most circumstances, support a human-centric approach, asserting pedestrian dominance.

Regarding the fourth sub-question (SRQ4) of whether all road users can harmoniously coexist within the same road space and the conditions facilitating such coexistence, a multi-faceted understanding emerges. Shared space typically consists of three abstract zones: the activity zone, the safe zone, and the circulation zone. Given prior conclusions, shared space is characterized by an increased rate of crossings. Pedestrians, in these spaces, do not traverse the same routes as vehicles, hinting at the unique nature of their movement. This observation prompts a reconsideration of the very definition of coexistence. In a practical sense, coexistence can be described as a scenario where pedestrians feel empowered to freely cross. Concurrently, vehicles, while not disturbed, are compelled to navigate with caution and at reduced speeds. In other words, such coexistence can exist when there is a speed compliance rate nearing one and a pedestrian crossing rate that does not cause unnecessary speed fluctuations and high braking. In the empirical analysis of four different shared spaces, certain patterns emerge. The data suggests that allocating more room for pedestrians, especially in activity or safe zones, positively influences crossing behavior. Introducing a wide circulation zone seems to direct pedestrian trajectories, channeling them toward the margins of shared space. A similar pattern is observed with vehicles; an expansive circulation zone encourages faster driving and a lack of respect for (reduced) speed limits. Thus, the practicality of achieving coexistence is intrinsically tied to the very design and abstract configuration of the shared space.

Addressing both SRQ5 and SRQ6, which pertain to the safety perceptions of various road users in shared spaces and conventional road environments, the image-based double stated preferences experiment that was conducted paints a detailed picture. E-scooters emerged as the mode most perceived as unsafe within the presented road scenarios. They were closely followed by e-bikes in this safety perception ranking while walking and car usage were deemed considerably safer. The survey data underscores a prevailing preference among road users for designs that lean toward traffic segregation over those that allocate extensive space to vehicles. Nevertheless, shared spaces arise as a promising compromise, providing a middle ground for all road users. Notably, there is widespread agreement on the safety advantages of shared spaces, particularly when juxtaposed with roads dominated by vehicles. It is particularly revealing that pedestrians often view non-signalized crosswalks as more dangerous than having no designated crossing areas. When it comes to navigating mixed traffic environments, e-scooters are perceived as presenting a significant risk to pedestrians. Meanwhile, the perceived safety of cyclists tends to diminish as motorized traffic volume increases, though this perception is not as influenced by the presence of pedestrians. The accessibility of micro-mobility modes like e-scooters is largely constrained to user safety concerns. Introducing the concept of VoS (Value of Safety) adds another layer to the discussion. VoS represents the extra distance a traveler is willing to cover to elevate their safety by one level. This can be achieved by following a shared space link. Yet, it becomes evident that while safety perceptions vary among road users and even individuals, the influence of these concerns on mode choice also diverges. This results in a complex reality, best tackled using simulation tools. Ultimately, the influence of shared spaces as the middle yet safer ground on the accessibility of each transport mode may be negligible at the end.

Addressing the sub-question (SRQ7) of whether a shared space road network can enhance the efficiency of the urban transport system, the study findings offer insightful revelations. Firstly, the data highlights a direct correlation between reduced speed limits and an uptick in the utilization of public transport. In metropolitan contexts, public transport has consistently emerged as the primary contender to the private car. This shift towards public transit, driven by reduced speed limits, has led to a marked decrease in passenger car kilometers. This reduction has, in turn, alleviated congestion, especially at peak hours. Contrary to initial expectations, the actual travel speed in private cars did not decrease significantly despite the lowered speed limits in urban zones. Further, there is a cascading positive impact in terms of environmental sustainability, as the private car was used for longer trips. A significant reduction in vehicle kilometers traveled by private modes will result in decreased energy consumption and emissions, as is expected. However, the key factor for the success of lowering speed limits is drivers' compliance. Experimental results emphasize this, showing that in scenarios where compliance rates are low, there is negligible difference from baseline scenarios, impacting the policy's effectiveness. Shared space emerges as a potential catalyst to ensure speed compliance rates close to one.

Exploring the potential of shared space road networks in promoting sustainable mobility and ensuring transport equity provides a multifaceted perspective. Primarily, shared space networks embody the principle of inclusivity, as was shown. They pave the way for a more equitable transport ecosystem, where each traveler, irrespective of their chosen mode, can anticipate a consistent trip characterized by fewer unsafe interruptions or discontinuities. Contrastingly, the approach of segregation, often manifested in the form of dedicated cycling lanes or tracks, brings a nuanced set of outcomes. While such infrastructure can enhance modal share and reinforce road users' accessibility, they also inadvertently give rise to greater inequities. This situation poses a peculiar balance of benefits and drawbacks, resulting in a dichotomy of winners and losers in the urban areas. In essence, the decision between shared and segregated spaces boils down to the broader objective. If the aim is to ensure an egalitarian and inclusive road network, shared spaces stand out as the ideal option. However, if the primary focus is on optimizing specific conditions, such as improving accessibility for a particular transport mode, then segregated solutions merit stronger consideration.

6.2 Practical recommendations

The advent of autonomous vehicles has propelled cities into a new era of urban planning, necessitating a reconceptualization of road design. Rather than configuring streets to accommodate these vehicles, transport and urban planners should set requirements that the vehicles should adapt to. Shared space and in general mixed traffic can be one. Indeed, previous experience suggests that modifying the urban environment exclusively for vehicles led to congested, inefficient transport systems with negative economic and social impacts in the long term. This perspective demands that vehicles, both autonomous and traditional, align with an urban fabric that prioritizes communal spaces and human-centric design. This means that an autonomous vehicle should be capable enough to cope with any interaction occurring in these complicated humanized road environments.

Shared space emerges as an essential solution in the evolving complexity of urban road networks, particularly in space-constrained locales. As opposed to laying dense networks of cycle lanes or pedestrianized zones, which might be unrealistic given spatial constraints that appear in many cities around the world, shared spaces offer a versatile alternative. It is a smart and cost-effective way to transform urban environments into areas that are less dominated by vehicles, emphasizing human orientation. Moreover, shared spaces' dynamic nature allows some adjustments – whether by temporarily closing roads to certain transport modes or by modifying speed limits. Shared space areas do not have to stand in isolation either; they can be seamlessly integrated with segregated cycle networks, thereby developing a new hierarchy in road infrastructure that considers active mobility. This facilitates bridging any discontinuities existing in the urban road networks. In other words, shared space can be interpreted as a measure to complete cycling and pedestrian networks. Nevertheless, shared space implementation necessitates a nuanced approach.

A successful shared space is more than merely instituting a 30 km/h speed limit. It is about designing environments that intuitively guide users towards compliance. Heterogeneity in driving behavior and unsafe traffic interactions should be minimized, ensuring the harmonious coexistence of all road users. While the demarcation in such spaces should be abstract, striking a balance based on demand and traffic flow conditions is paramount, as was shown. Instead of clear-cut separations, other "soft" design elements can be incorporated to subtly guide user behavior, fostering a sense of safety and community. Overall, design practices that lean towards shared spaces over unprotected pedestrian crossings should be preferred. A comprehensive road design approach should ensure that shared spaces become the mainstay of urban life, balancing both vehicular and human needs. It requires both the a-priori and ex-post assessment of the effectiveness of the selected shared space design at the link level. This study presented some techniques to achieve this.

6.3 Study limitations

This study possesses certain limitations that should be acknowledged for a comprehensive understanding of its findings. Firstly, it did not employ a qualitative approach through interviews, which would have provided deeper insights into the experts' perspectives. Instead, a more structured method (i.e., Q-method) was adopted whereby experts were asked to rank specific statements. These statements were meticulously formulated by the author to encompass the array of contradictions observed in existing literature. However, the intricate nature of composing such statements that fully capture the breadth and nuances of the contradictions is inherently challenging. As a result, this endeavor may not have been entirely exhaustive. Furthermore, the study's scope is limited to the viewpoints of European experts. Consequently, it might not enclose the unique challenges faced in North American cities or in cities within developing nations, where urban road design, transport modes, road users, and their interactions can differ markedly from the European context. This divergence underscores the need for broader studies, exploring a plethora of mobility cultures that shape urban roads. Tellingly, the future urban road research was conducted under the effect of COVID-19, meaning that some of the literature studied, the approaches undertaken, and the respondents participating in the survey were (even slightly) influenced by prevailing conditions. Also, the rapid technological advances that can be a game-changer related to a series of urban road issues may force a change of direction and cause re-prioritization. For instance, AVs are expected to emerge in cities in the very near future, but 20 years ago, they were considered an almost “fictitious” solution. Hence, a significant constraint lies in the unpredictable nature of the future; while informed projections can be made, unforeseen disruptions always loom on the horizon.

Another dimension of this study’s limitations pivots around the exploration of public acceptance concerning shared space. While the models developed yield predictive insights, the acceptance of shared space was not examined empirically in actual, on-the-ground situations—both pre- and post-implementation. In this context, this study only leans on a stated preferences model, which, although useful, lacks the validity of revealed preferences ones. Furthermore, the public acceptance model is anchored to a singular case scenario where shared space is considered a very radical solution. People did not express opinions about shared space networks, which was the main topic of this study. Nevertheless, it is questionable how citizens without scientific knowledge can balance microscopic (link level) with macroscopic (road network level) impacts, that sometimes are unpredictable in the long term. This study did not probe this aspect, leaving a potential gap in understanding the temporal changes of social acceptance, which, however, may be proven to be a determinant factor in understanding whether the implementation of shared space schemes will be fast or slow in different urban areas. Additionally. the relationship between social acceptance and socio-demographic characteristics was not examined. Individuals were divided into road user groups and not into age or other relevant groups.

Empirical data served as the backbone for the analysis of road user interactions conducted. Coexistence was particularly investigated. However, certain inherent limitations became evident during the study. Fully congested shared spaces with vehicles were not found; instead, near-free-flow conditions predominated in all cases. While the study did capture some disruptions caused by pedestrian crossings, leading to minor congestion, this sample was insufficient to develop robust models that could accurately describe car-following behavior under congested conditions. As such, modeling the dynamics in a shared space scenario that might be colloquially termed the "law of the jungle" was elusive. Hence, it was not feasible to formulate relevant fundamental diagrams, as was initially intended. Moreover, it is crucial to highlight that road user behavior is not insular – it is often significantly influenced by surrounding land uses. This variable, unfortunately, was not integrated into the analysis. Although all examined streets were centrally located, segments within these streets might naturally attract a higher volume of pedestrians, leading to an increased frequency of crossings. To face this limitation, a strategy of using relative indicators was employed. These indicators were designed to correlate with the average conditions prevailing on each specific street, providing a more standardized format through which the findings could be interpreted. Moreover, shared space design parameters (e.g., lane width, sidewalk width, visual or level segregation) were not considered in this study, since this requires the use of more cases of various designs to investigate the impact of each design feature on pedestrian and driver behavior. Last, the estimated models presented a considerably low goodness of fit showing the unpredictable nature of road user behavior in mixed traffic. For example, in the Greek case, the larger deviations in speed and pedestrian crossing rates created several outliers in the modeling process.

The limitations of the image-based double stated preference experiment primarily stem from the sample distribution. The experiment engaged participants predominantly from Athens, Greece—a city where residents primarily walk for access/egress trips to/from metro stations, and which has limited cycling infrastructure and features extensive pedestrianized zones in the center. Perceived safety is meaningful as a factor in heterogeneous road environments, in which safety perceptions fluctuate spatially. Perceived safety in car driving or walking seems to operate in a dichotomous safe-or-not-safe framework; this leads to binary logit models and the inclusion/exclusion of road links. In pedestrian settings, the notion of perceived safety can become entangled with subjective factors like comfort or personal security. These subjective factors might better explain the unseen downsides of walking than the mere safety perceptions. Notably absent from this study was the consideration of road gradient—a factor present in studies analyzing cyclist route choices. While road gradient may be more aligned with discomfort than with perceived safety, its presence can significantly influence path choices. Additionally, traffic congestion, which restricts travel speed and consequently decreases the value of safety, could inadvertently promote flexible micro-mobility modes that can maintain consistent speeds regardless of car traffic congestion. This study only gathered third-person evaluations of perceived safety, bypassing real-time, first-hand experiences of depicted traffic scenarios. Lastly, this survey was filled mainly by young people who can be considered potential micro-mobility service users. The proposed data collection technique and modeling framework can be applied in different cities also focusing on different social groups.

In the first simulation experiment, there was a deliberate reduction in the level of detail to facilitate the simulation of expansive shared space networks in the metropolitan area of Berlin. While speed compliance was pinpointed as the pivotal factor, it remains debatable whether the multifaceted impact of interactions can be condensed into a singular factor. This was a major assumption of this study. Indeed, the intricacies inherent in road user interactions make them a complex subject to capture. In general, MATSim considers initial plans, which are exported from an activity-based model, to define a new equilibrium point, where agents cannot further increase the utility of their plans. Yet, the creation of a traffic-calming network may cause significant modifications in the spatiotemporal travel patterns after some weeks, months, or years; this leads to new initial plans and new simulation inputs. MATSim cannot be considered as the most appropriate tool to evaluate the consequences of extensive traffic calming in the mid- or long- term. Nevertheless, as it has been expressed, the starting phase concerns mostly policy makers when implementing these measures; thus, the proposed approach, despite its limitations, can be deemed very useful in reality. It should also be considered that the Open-Berlin simulation assumes complete reliability of public transport services, strictly respecting the transit schedules. However, in real-world scenarios, reliability issues impact the use of public transport against private cars. Notably, Open-Berlin does not incorporate penalties related to transit shifts—from one mode or line to another. When shifting focus to active modes of transportation, a notable shortfall in MATSim is its oversight of certain urban road environment attributes that profoundly affect travel behaviors, especially in the realm of active transit modes. This limitation was overcome in the second simulation experiment.

In the second simulation experiment, several limitations emerged that warrant attention. Foremost, the area (i.e., the city center of Athens) was rather small, facilitating specific trips with low distances. A toy population and an experimental network were used; therefore, the model predictions are not sometimes realistic. Additionally, the influence of minor road network discontinuities among some agents was not analyzed. Such nuances may significantly impact travel behavior. In MATSim, the heterogeneity of safety perceptions among individuals causes noticeable fluctuations in the average score of all plans. Further complicating matters is the variability of perceptions across individuals. Ideally, a Monte-Carlo approach would have been beneficial to model the influence of perceived safety in trip choice. This inclusion, however, would potentially introduce extra instability in some simulation scenarios. Yet, it is vital to acknowledge the linkage between simulation output instability and the overall structure of cycling and waking road networks. Land uses were not considered as a factor of accessibility hypothesizing that agents will not change their initial plans and activities due to accessibility restrictions. From an environmental standpoint, the second simulation experiment did not provide explicit estimates for sustainability indicators at the end. Instead, it focused on the reduction in vehicle kilometers by private cars as a proxy for indicators like CO_2 emissions, energy consumption, air pollution, and noise—an approach consistently applied across both experiments. Additionally, the study’s primary emphasis was on economic and societal facets within the sustainability framework.

6.4 Future work

Continuing the investigation of the shared space concept offers a multitude of avenues demanding thorough research. The ambition of future research should be to answer many of the posed dilemmas, potentially revealing new contradictions regarding the future of urban roads. A meaningful pursuit involves probing into individuals' favorable and adverse perceptions of specific concepts about the future urban road while discerning the conditions that foster social acceptance. As these uncharted territories are navigated, newer (more modern) dilemmas might emerge, either adding layers to existing literature or paving the way for groundbreaking studies in the future. Hence, in transportation research, shared space will always be a concept that generates new questions for further research.

An interdisciplinary approach, which perceives roads, vehicles, operating systems, and humans as a holistic entity, holds the promise of fostering a comprehensive understanding. Besides, the conclusions about shared space are incomplete without recognizing the cultural factors influencing mobility habits and the suitability of this concept in different cities. Undertaking rating experiments across major arterials in other European cities could be instrumental. The model findings can be compared exporting more valid conclusions. The synergy of acceptance models with traffic simulations, especially when spread across short-, mid-, and long-term phases, can offer deep insights. As social acceptance dynamically changes over time, its temporal fluctuation would be also an interesting fact indicator for the decision-making process.

Further research is essential to understand how to configure harmonious coexistence within shared spaces. A particular emphasis should be placed on understanding the dynamics of the "crosswalk anywhere" scenario, especially when considering extreme situations involving traffic congestion. While real-world shared space scenarios might not always be dominated by motorized traffic, microscopic traffic microsimulations would serve as invaluable tools to replicate and evaluate such conditions. Despite the complex dynamics introduced by shared spaces, their advancement should press forward. New datasets and theories will facilitate this process. Besides, the essence of shared space is shaped by the interplay of its users; it is a game about which user group will dominate an urban environment that is informally created by road designers. While road designers have the potential to equilibrate this game, the strategy to achieve this equilibrium requires further research. Thus, shared space traffic operations can be interpreted as a mathematical problem applying some of the basic principles of game theory. Additionally, the identification of design parameters or "smart" interventions that significantly guide road users' behavior toward coexistence is another topic that should be further investigated. In other words, the challenge lies in pinpointing the optimal measures to facilitate the informal segregation of flows.

Exploring the intricacies of perceived safety necessitates a multifaceted approach. Multiple determinants, not just limited to direct safety metrics, play into individuals' perception of road spaces. Factors such as road gradient, which primarily induces discomfort, lead to the following research question: What exactly is the relationship between perceived safety, road gradient, and comfort? Various micro-mobility modes (battery-assisted or not) can be considered to provide different evidence for this general question. This becomes even more critical when various social groups are considered, offering a new opportunity to map the non-systematic variations in perceived utility across demographics. The intricate connection between acceptance of policy measures and perceived safety presents another realm of exploration. For instance, understanding how much time in traffic congestion individuals are willing to sacrifice for improved infrastructure and, by extension, enhanced perceived safety, is critical. Field evaluations, as well as experiments utilizing virtual reality (VR), could be used to calibrate and improve the validity of existing perceived safety models. Indeed, the impact of traffic interactions that will be presented in the videos can be investigated better compared to the use of live images. Notably, elements such as security and personal safety intertwine and deserve thorough research. It is posited that the relationship between perceived safety and comfort may not be as strong as expected, suggesting that safety is not the sole determinant of comfort during walking, which, in turn, can shape choices. Further research in this direction could yield insights pivotal to designing human-oriented road environments.

The advancement of simulation tools, and particularly hybrid models that allow microscopic simulations with a high level of detail for individual segments, will contribute to accurately predicting link travel times. However, it is essential to strike a balance; this issue remains unsolved until today. While there is a temptation to dive deep into microsimulation, incorporating all elements at this detailed level could significantly increase the complexity of agent-based models. This increased intricacy not only demands more computational resources but also adds to the time required for simulations. In the mental simulation part, one could consider parallel Monte Carlo simulations to estimate perception weights, given the known distributions. Such an approach can maintain the subjective nature of perceptions within the agent-based simulation process without increasing the computation time. Understanding that perceptions are closely tied to traffic flows adds another layer to the equation. By gauging the current flow, one can recalculate the perceived safety scores of all links, leading to a more informed execution and scoring process. Moreover, perceived safety could be a pivotal factor when scoring multimodal trips, enabling travelers to select the ideal combination of modes based on safety perceptions. On the sustainability front, more indicators can be derived from MATSim simulation data, such as energy consumption, CO2 emissions, and air pollution metrics. Incorporating these measures offers a holistic view, enabling a comprehensive assessment of the shared space concept's environmental implications. Lastly, the potential transformation of densely populated areas into shared space networks poses intriguing questions and new simulation loops that need to be considered. Establishing such networks could catalyze shifts in mobility patterns as it was shown, possibly leading to reduced car ownership. This will result in a considerably lower demand for parking space.

References

Aceves-González, C., Ekambaram, K., Rey-Galindo, J., Rizo-Corona, L., 2020. The role of perceived pedestrian safety on designing safer built environments. Traffic Inj Prev 21, S84–S89. https://doi.org/10.1080/15389588.2020.1812062

Adhvaryu, B., Chopde, A., Dashora, L., 2019. Mapping public transport accessibility levels (PTAL) in India and its applications: A case study of Surat. Case Stud Transp Policy 7, 293–300. https://doi.org/10.1016/j.cstp.2019.03.004

Adnan, M., Pereira, F.C., Azevedo, C.L., 2016. SimMobility : A Multi-Scale Integrated Agent-based Simulation Platform, in: 95th Annual Meeting of the Transportation Research Board. Washington D.C.

Agarwal, A., Lämmel, G., 2016. Modeling Seepage Behavior of Smaller Vehicles in Mixed Traffic Conditions Using an Agent Based Simulation. Transportation in Developing Economies. https://doi.org/10.1007/s40890-016-0014-9

Akgün-Tanbay, N., Campisi, T., Tanbay, T., Tesoriere, G., Dissanayake, D., 2022. Modelling Road User Perceptions towards Safety, Comfort, and Chaos at Shared Space: The via Maqueda Case Study, Italy. J Adv Transp 2022. https://doi.org/10.1155/2022/4979496

Alonso-González, M.J., van Oort, N., Cats, O., Hoogendoorn-Lanser, S., Hoogendoorn, S., 2020. Value of time and reliability for urban pooled on-demand services. Transp Res Part C Emerg Technol 115, 102621. https://doi.org/10.1016/j.trc.2020.102621

Aman, J.J.C., Smith-Colin, J., Zhang, W., 2021. Listen to E-scooter riders: Mining rider satisfaction factors from app store reviews. Transp Res D Transp Environ 95, 102856. https://doi.org/10.1016/j.trd.2021.102856

Anvari, B., Bell, M.G.H., Angeloudis, P., Ochieng, W.Y., 2016. Calibration and validation of a shared space model: Case Study. Transp Res Rec 2588, 43–52. https://doi.org/10.3141/2588-05

Anvari, B., Bell, M.G.H., Sivakumar, A., Ochieng, W.Y., 2015. Modelling shared space users via rule-based social force model. Transp Res Part C Emerg Technol 51, 83–103. https://doi.org/10.1016/j.trc.2014.10.012

Aral, E.A., Demirbaş, Ö.O., 2015. Pedestrians' perception of sub-spaces along urban roads as public spaces-case of Eskişehir road in Ankara. Metu Journal of the Faculty of Architecture 32, 45–64. https://doi.org/10.4305/METU.JFA.2015.1.3

Auld, J., Hope, M., Ley, H., Sokolov, V., Xu, B., Zhang, K., 2016. POLARIS: Agent-based modeling framework development and implementation for integrated travel demand and network and operations simulations. Transp Res Part C Emerg Technol 64, 101–116. https://doi.org/10.1016/j.trc.2015.07.017

Axhausen, K.W., Horni, A., Nagel, K., Axhausen, K.W., 2016. Introducing MATSim, in: Horni, A., Nagel, K., Axhausen, K.W. (Eds.), The Multi-Agent Transport Simulation MATSim. Ubiquity Press, London, pp. 3–8. https://doi.org/http://dx.doi.org/10.5334/baw.1

Azevedo, C.L., Deshmukh, N.M., Marimuthu, B., Oh, S., Marczuk, K., Soh, H., Basak, K., Toledo, T., Peh, L.S., Ben-Akiva, M.E., 2017. Simmobility short-term: An integrated microscopic mobility simulator. Transp Res Rec 2622, 13–23. https://doi.org/10.3141/2622-02

Azimian, A., Catalina Ortega, C.A., Espinosa, J.M., Mariscal, M.Á., García-Herrero, S., 2021. Analysis of drivers' eye movements on roundabouts: A driving simulator study. Sustainability (Switzerland) 13. https://doi.org/10.3390/su13137463

Bai, L., Liu, P., Chan, C.Y., Li, Z., 2017a. Estimating level of service of mid-block bicycle lanes considering mixed traffic flow. Transp Res Part A Policy Pract 101, 203–217. https://doi.org/10.1016/j.tra.2017.04.031

Bai, L., Liu, P., Chan, C.Y., Li, Z., 2017b. Estimating level of service of mid-block bicycle lanes considering mixed traffic flow. Transp Res Part A Policy Pract 101, 203–217. https://doi.org/10.1016/j.tra.2017.04.031

Bask, A., Rajahonka, M., 2017. The role of environmental sustainability in the freight transport mode choice. International Journal of Physical Distribution & Logistics Management. https://doi.org/10.1108/ijpdlm-03-2017-0127

Batista, M., Friedrich, B., 2022. Investigating spatial behaviour in different types of shared space. Transportation Research Procedia 60, 44–51. https://doi.org/10.1016/j.trpro.2021.12.007

Batista, M., Friedrich, B., Friedrich, B., 2022. Analysing the influence of a farmers ' market on spatial behaviour in shared spaces. J Urban Des (Abingdon) 00, 1–18. https://doi.org/10.1080/13574809.2022.2042228

Ben-Akiva, M., Bierlaire, M., 1999. Discrete Choice Methods and their Applications to Short Term Travel Decisions, in: Hall, R.W. (Ed.), Handbook of Transportation Science. International Series in Operations Research & Management Science. Springer US, Boston. https://doi.org/https://doi.org/10.1007/978-1-4615-5203-1_2

Bhagat-Conway, M.W., Mirtich, L., Salon, D., Harness, N., Consalvo, A., Hong, S., 2022. Subjective variables in travel behavior models: a critical review and Standardized Transport Attitude Measurement Protocol (STAMP), Transportation. Springer US. https://doi.org/10.1007/s11116-022-10323-7

Bhat, C.R., Guo, J.Y., Srinivasan, S., Sivakumar, A., 2004. Comprehensive econometric microsimulator for daily activity-travel patterns. Transp Res Rec 57–66. https://doi.org/10.3141/1894-07

Bibri, S.E., Krogstie, J., 2019. Generating a vision for smart sustainable cities of the future: a scholarly backcasting approach. European Journal of Futures Research 7. https://doi.org/10.1186/s40309-019-0157-0

Bierlaire, M., 2019. Monte-Carlo integration with PandasBiogeme. Lausanne, Switzerland.

Biswas, S., Chandra, S., Ghosh, I., 2020. Side friction parameters and their influences on capacity of Indian undivided urban streets. International Journal of Transportation Science and Technology. https://doi.org/10.1016/j.ijtst.2020.03.007

Booth, A., Sutton, A., Papaioannou, D., 2016. Systematic approaches to a successful literature review. SAGE Publications Ltd, London, UK.

Borshchev, A., 2014. Multi-method modelling: AnyLogic, in: Brailsford, S., Churilov, L., Dangerfield, B. (Eds.), Discrete-Event Simulation and System Dynamics for Management Decision Making. Wiley, pp. 248–279. https://doi.org/10.1002/9781118762745.ch12

Branion-Calles, M., Nelson, T., Fuller, D., Gauvin, L., Winters, M., 2019. Associations between individual characteristics, availability of bicycle infrastructure, and city-wide safety perceptions of bicycling: A cross-sectional survey of bicyclists in 6 Canadian and U.S. cities. Transp Res Part A Policy Pract 123, 229–239. https://doi.org/10.1016/j.tra.2018.10.024

Brown, H.C., Tarko, A.P., 1999. Effects of access control on safety on urban arterial streets. Transp Res Rec 68–74. https://doi.org/10.3141/1665-10

Calvey, J.C., Shackleton, J.P., Taylor, M.D., Llewellyn, R., 2015. Engineering condition assessment of cycling infrastructure: Cyclists' perceptions of satisfaction and comfort. Transp Res Part A Policy Pract 78, 134–143. https://doi.org/10.1016/j.tra.2015.04.031

Cao, J., Menendez, M., Waraich, R., 2019. Impacts of the urban parking system on cruising traffic and policy development: the case of Zurich downtown area, Switzerland. Transportation (Amst) 46, 883–908. https://doi.org/10.1007/s11116-017-9832-9

Cao, Z., Zhang, X., Chua, K., Yu, H., Zhao, J., 2021. E-scooter sharing to serve short-distance transit trips: A Singapore case. Transp Res Part A Policy Pract 147, 177–196. https://doi.org/10.1016/j.tra.2021.03.004

Charlton, S.G., Mackie, H.W., Baas, P.H., Hay, K., Menezes, M., Dixon, C., 2010. Using endemic road features to create self-explaining roads and reduce vehicle speeds. Accid Anal Prev 42, 1989–1998. https://doi.org/10.1016/j.aap.2010.06.006

Charypar, D., 2008. Efficient algorithms for the microsimulation of travel behavior in very large scenarios. ETH Zurich.

Charypar, D., Balmer, M., Axhausen, K.W., 2009a. A High-Performance Traffic Flow Microsimulation for Large Problems, Working paper. Zurich. https://doi.org/10.3929/ethz-a-005652298

Charypar, D., Balmer, M., Axhausen, K.W., 2009b. A High-Performance Traffic Flow Microsimulation for Large Problems, Working paper. Zurich. https://doi.org/10.3929/ethz-a-005652298

Chataway, E.S., Kaplan, S., Nielsen, T.A.S., Prato, C.G., 2014. Safety perceptions and reported behavior related to cycling in mixed traffic: A comparison between Brisbane and Copenhagen. Transp Res Part F Traffic Psychol Behav 23, 32–43. https://doi.org/10.1016/j.trf.2013.12.021

Cheng, H., Johora, F.T., Sester, M., Müller, J.P., 2021. Trajectory Modelling in Shared Spaces: Expert-Based vs. Deep Learning Approach?, in: Swarup, S., Savarimuthu, B.T.R. (Eds.), Multi-Agent-Based Simulation XXI. MABS 2020. Lecture Notes in Computer Science. Springer, Cham, Switzerland, pp. 15–27. https://doi.org/https://doi.org/10.1007/978-3-030-66888-4_2

Cheng, Y.H., Chen, S.Y., 2015. Perceived accessibility, mobility, and connectivity of public transportation systems. Transp Res Part A Policy Pract 77, 386–403. https://doi.org/10.1016/j.tra.2015.05.003

Cho, G., Rodríguez, D.A., Khattak, A.J., 2009. The role of the built environment in explaining relationships between perceived and actual pedestrian and bicyclist safety. Accid Anal Prev 41, 692–702. https://doi.org/10.1016/j.aap.2009.03.008

Chorus, C.G., Walker, J.L., Ben-Akiva, M., 2013. A joint model of travel information acquisition and response to received messages. Transp Res Part C Emerg Technol 26, 61–77. https://doi.org/10.1016/j.trc.2012.07.002

Clarke, E., 2006. Shared Space - the Alternative Approach to Calming Traffic. Traffic Engineering & Control 47, 290–292.

Colonna, P., Intini, P., Berloco, N., Fedele, V., Masi, G., Ranieri, V., 2019. An Integrated Design Framework for Safety Interventions on Existing Urban Roads—Development and Case Study Application. Safety 5, 13. https://doi.org/10.3390/safety5010013

Curl, A., Ward Thompson, C., Aspinall, P., 2015. The effectiveness of “shared space” residential street interventions on self-reported activity levels and quality of life for older people. Landsc Urban Plan 139, 117–125. https://doi.org/10.1016/j.landurbplan.2015.02.019

Curry, R., Barry, J., McClenaghan, A., 2013. Northern Visions? Applying Q methodology to understand stakeholder views on the environmental and resource dimensions of sustainability. Journal of Environmental Planning and Management 56, 624–649. https://doi.org/10.1080/09640568.2012.693453

Daly, A., Dekker, T., Hess, S., 2016. Dummy coding vs effects coding for categorical variables: Clarifications and extensions. Journal of Choice Modelling 21, 36–41. https://doi.org/10.1016/j.jocm.2016.09.005

Davies, B.B., Hodge, I.D., 2006. Farmers’ preferences for new environmental policy instruments: Determining the acceptability of cross compliance for biodiversity benefits. J Agric Econ 57, 393–414. https://doi.org/10.1111/j.1477-9552.2006.00057.x

Davis, J., Mengersen, K., Bennett, S., Mazerolle, L., 2014. Viewing systematic reviews and meta-analysis in social research through different lenses. Springerplus 3, 1–9. https://doi.org/10.1186/2193-1801-3-511 de Groot, J.I.M., Schuitema, G., 2012. How to make the unpopular popular? Policy characteristics, social norms and the acceptability of environmental policies. Environ Sci Policy 19–20, 100–107. https://doi.org/10.1016/j.envsci.2012.03.004

Dekker, R., Bekkers, V., 2015. The contingency of governments' responsiveness to the virtual public sphere: A systematic literature review and meta-synthesis. Gov Inf Q 32, 496–505. https://doi.org/10.1016/j.giq.2015.09.007

Delbosc, A., Currie, G., 2011. Using Lorenz curves to assess public transport equity. J Transp Geogr 19, 1252–1259. https://doi.org/10.1016/j.jtrangeo.2011.02.008

Demasi, F., Loprencipe, G., Moretti, L., 2018. Road Safety Analysis of Urban Roads: Case Study of an Italian Municipality. Safety 4, 58. https://doi.org/10.3390/safety4040058

Department for Transport, 2011. Shared Space, Local Transport Note 1/11. London, UK. https://doi.org/10.4324/9781315397108-4

Dill, J., McNeil, N., 2013. Four Types of Cyclists? Examination of Typology for Better Understanding of Bicycling Behavior and Potential. Transp Res Rec 129–138. https://doi.org/10.3141/2387-15

Domenichini, L., Branzi, V., Meocci, M., 2018. Virtual testing of speed reduction schemes on urban collector roads. Accid Anal Prev 110, 38–51. https://doi.org/10.1016/j.aap.2017.09.020

Eccarius, T., Lu, C.C., 2020. Adoption intentions for micro-mobility – Insights from electric scooter sharing in Taiwan. Transp Res D Transp Environ 84. https://doi.org/10.1016/j.trd.2020.102327

Elvik, R., 2010a. A restatement of the case for speed limits. Transp Policy (Oxf) 17, 196–204. https://doi.org/10.1016/j.tranpol.2009.12.006

Elvik, R., 2010b. A restatement of the case for speed limits. Transp Policy (Oxf) 17, 196–204. https://doi.org/10.1016/j.tranpol.2009.12.006

Ershova, S., Smirnov, E., 2017. Conceptual Justification of Town-Planning Design Standards for Streets and Roads in Large Cities for Ensuring Traffic Safety. Transportation Research Procedia 20, 180–184. https://doi.org/10.1016/j.trpro.2017.01.047

Falzanaro, S., 2009. Regionwide congestion pricing study in Chicago:Stated preference survey purpose, approach, and outcomes, in: 88th Annual Meeting of the Transportation Research Board. Washington, DC.

Fitch, D.T., Carlen, J., Handy, S.L., 2022a. What makes bicyclists comfortable? Insights from a visual preference survey of casual and prospective bicyclists. Transp Res Part A Policy Pract 155, 434–449. https://doi.org/10.1016/j.tra.2021.11.008

Fitch, D.T., Carlen, J., Handy, S.L., 2022b. What makes bicyclists comfortable? Insights from a visual preference survey of casual and prospective bicyclists. Transp Res Part A Policy Pract 155, 434–449. https://doi.org/10.1016/j.tra.2021.11.008

Flötteröd, G., 2016. Queueing Representation of Kinematic Waves. The Multi-Agent Transport Simulation MATSim 347–352. https://doi.org/10.5334/baw.50

Frosch, C., 2017. Evaluation of Shared Space to Reduce Traffic Congestion : A case study on West Virginia University ' s Downtown Campus. West Virginia University.

Frosch, C., Martinelli, D., Unnikrishnan, A., 2019a. Evaluation of Shared Space to Reduce Traffic Congestion. J Adv Transp 2019. https://doi.org/10.1155/2019/6510396

Frosch, C., Martinelli, D., Unnikrishnan, A., 2019b. Evaluation of Shared Space to Reduce Traffic Congestion. J Adv Transp 2019. https://doi.org/10.1155/2019/6510396

Galland, S., Knapen, L., Yasar, A.U.H., Gaud, N., Janssens, D., Lamotte, O., Koukam, A., Wets, G., 2014. Multi-agent simulation of individual mobility behavior in carpooling. Transp Res Part C Emerg Technol 45, 83–98. https://doi.org/10.1016/j.trc.2013.12.012

García, A., Torres, A.J., Romero, M.A., Moreno, A.T., 2011. Traffic microsimulation study to evaluate the effect of type and spacing of traffic calming devices on capacity. Procedia Soc Behav Sci 16, 270–281. https://doi.org/10.1016/j.sbspro.2011.04.449

García-Vázquez, C.A., Llorens-Iborra, F., Fernández-Ramírez, L.M., Sánchez-Sainz, H., Jurado, F., 2017. Comparative study of dynamic wireless charging of electric vehicles in motorway, highway and urban stretches. Energy 137, 42–57. https://doi.org/10.1016/j.energy.2017.07.016

Gargoum, S.A., El-Basyouny, K., Kim, A., 2016a. Towards setting credible speed limits: Identifying factors that affect driver compliance on urban roads. Accid Anal Prev 95, 138–148. https://doi.org/10.1016/j.aap.2016.07.001

Gargoum, S.A., El-Basyouny, K., Kim, A., 2016b. Towards setting credible speed limits: Identifying factors that affect driver compliance on urban roads. Accid Anal Prev 95, 138–148. https://doi.org/10.1016/j.aap.2016.07.001

Gerlach, J., Methorst, R., 2009. Sense and nonsense about Shared Space-For an objective view of a popular planning concept. Routes/Roads 342, 36–45.

Geurs, K.T., van Wee, B., 2004. Accessibility evaluation of land-use and transport strategies: Review and research directions. J Transp Geogr 12, 127–140. https://doi.org/10.1016/j.jtrangeo.2003.10.005

Gibb, S., 2015. Simulating The Streets of Tomorrow - An Innovative Approach to Modelling Shared Space.

Gill, G., Bigazzi, A., Winters, M., 2022. Investigating relationships among perceptions of yielding, safety, and comfort for pedestrians in unsignalized crosswalks. Transp Res Part F Traffic Psychol Behav 85, 179–194. https://doi.org/10.1016/j.trf.2022.01.007

Gitelman, V., Korchatov, A., Elias, W., 2020. An Examination of the Safety Impacts of Bus Priority Routes in Major Israeli Cities. Sustainability 12, 8617. https://doi.org/10.3390/su12208617

Gkekas, F., Bigazzi, A., Gill, G., 2020. Perceived safety and experienced incidents between pedestrians and cyclists in a high-volume non-motorized shared space. Transp Res Interdiscip Perspect 4, 100094. https://doi.org/10.1016/j.trip.2020.100094

Gonzalez-Feliu, J., Salanova Grau, J.M., Beziat, A., 2014. A location-based accessibility analysis to estimate the suitability of urban consolidation facilities. International Journal of Urban Sciences 18, 166–185. https://doi.org/10.1080/12265934.2014.930673

González-González, E., Nogués, S., Stead, D., 2019. Automated vehicles and the city of tomorrow: A backcasting approach. Cities 94, 153–160. https://doi.org/10.1016/j.cities.2019.05.034

Guo, L., Huang, S., Sadek, A.W., 2013. A novel agent-based transportation model of a university campus with application to quantifying the environmental cost of parking search. Transp Res Part A Policy Pract 50, 86–104. https://doi.org/10.1016/j.tra.2013.01.045

Gurumurthy, K.M., de Souza, F., Enam, A., Auld, J., 2020. Integrating Supply and Demand Perspectives for a Large-Scale Simulation of Shared Autonomous Vehicles. Transp Res Rec 2674, 181–192. https://doi.org/10.1177/0361198120921157

Guzman, L.A., Arellana, J., Alvarez, V., 2020. Confronting congestion in urban areas: Developing Sustainable Mobility Plans for public and private organizations in Bogotá. Transp Res Part A Policy Pract 134, 321–335. https://doi.org/10.1016/j.tra.2020.02.019

Guzman, L.A., Oviedo, D., Rivera, C., 2017. Assessing equity in transport accessibility to work and study: The Bogotá region. J Transp Geogr 58, 236–246. https://doi.org/10.1016/j.jtrangeo.2016.12.016

Hadas, Y., Nahum, O.E., 2016. Urban bus network of priority lanes: A combined multi-objective, multi-criteria and group decision-making approach. Transp Policy (Oxf) 52, 186–196. https://doi.org/10.1016/j.tranpol.2016.08.006

Hamilton-Baillie, B., 2008a. Towards shared space. Urban Design International 13, 130–138. https://doi.org/10.1057/udi.2008.13

Hamilton-Baillie, B., 2008b. Shared Space: Reconciling People, Places and Traffic. Built Environ 34, 161–181.

Hammond, V., Musselwhite, C., 2013. The Attitudes, Perceptions and Concerns of Pedestrians and Vulnerable Road Users to Shared Space: A Case Study from the UK. J Urban Des (Abingdon) 18, 78–97. https://doi.org/10.1080/13574809.2012.739549

Han, Z., Zhang, K., Yin, H., Zhu, Y., 2015. An urban traffic simulation system based on multi-agent modeling. Proceedings of the 2015 27th Chinese Control and Decision Conference, CCDC 2015 6378–6383. https://doi.org/10.1109/CCDC.2015.7161966

Hansen, W.G., 1959. How Accessibility Shapes Land Use. Journal of the American Planning Association 25, 73–76. https://doi.org/10.1080/01944365908978307

Hayatnagarkar, H.G., Murali Krishna, G., 2016. A controlled natural language based knowledge representation approach for agent based simulation results. European Simulation and Modelling Conference 2016, ESM 2016 133–139.

Hellenic Ministry of Infrastructure and Transport, 2015. Technical Guidelines for Cycling Infrastructure.

Hellenic Ministry of Infrastructure and Transport, 2001. Road Design Guidelines Manual - Main Urban Roads.

Hidayati, I., Tan, W., Yamu, C., 2020. How gender differences and perceptions of safety shape urban mobility in Southeast Asia. Transp Res Part F Traffic Psychol Behav 73, 155–173. https://doi.org/10.1016/j.trf.2020.06.014

Hill, J.D., Boyle, L.N., 2007. Driver stress as influenced by driving maneuvers and roadway conditions. Transp Res Part F Traffic Psychol Behav 10, 177–186. https://doi.org/10.1016/j.trf.2006.09.002

Horl, S., Balac, M., Axhausen, K.W., 2019. Dynamic demand estimation for an AMoD system in Paris. IEEE Intelligent Vehicles Symposium, Proceedings 2019-June, 260–266. https://doi.org/10.1109/IVS.2019.8814051

Hosseinzadeh, A., Algomaiah, M., Kluger, R., Li, Z., 2021. E-scooters and sustainability: Investigating the relationship between the density of E-scooter trips and characteristics of sustainable urban development. Sustain Cities Soc 66. https://doi.org/10.1016/j.scs.2020.102624

Imrie, R., 2012. Universalism, universal design and equitable access to the built environment. Disabil Rehabil 34, 873–882. https://doi.org/10.3109/09638288.2011.624250

Jaredson, S., 2002. Utvärdering av Skvallertorget i Norrköping/Evaluation of Skvallertorget in Norrköping. Norrköping.

Jeihani, M., Sherali, H.D., Hobeika, A.G., 2006. Computing dynamic user equilibria for large-scale transportation networks. Transportation (Amst) 589–604. https://doi.org/10.1007/s11116-006-8473-1

Johansson, R., 2009. Vision Zero - Implementing a policy for traffic safety. Saf Sci. https://doi.org/10.1016/j.ssci.2008.10.023

Joseph, E. Ben, 1995. Changing the residential street scene- adapting the shared street (Woonerf) concept to the suburban environment. Journal of the American Planning Association 61, 504–515. https://doi.org/10.1080/01944369508975661

Joshi, A., Kale, S., Chandel, S., Pal, D., 2015. Likert Scale: Explored and Explained. Br J Appl Sci Technol 7, 396–403. https://doi.org/10.9734/bjast/2015/14975

Kagho, G.O., Balac, M., Axhausen, K.W., 2020. Agent-Based Models in Transport Planning: Current State, Issues, Expectations. Procedia Comput Sci 170, 726–732. https://doi.org/10.1016/j.procs.2020.03.164

Kaparias, I., Bell, M.G.H., Dong, W., Sastrawinata, A., Singh, A., Wang, X., Mount, B., 2014. Analysis of Pedestrian–Vehicle Traffic Conflicts in Street Designs with Elements of Shared Space. Transportation Research Record: Journal of the Transportation Research Board 2393, 21–30. https://doi.org/10.3141/2393-03

Kaparias, I., Bell, M.G.H., Miri, A., Chan, C., Mount, B., 2012. Analysing the perceptions of pedestrians and drivers to shared space. Transp Res Part F Traffic Psychol Behav 15, 297–310. https://doi.org/10.1016/j.trf.2012.02.001

Kaparias, I., Hirani, J., Bell, M.G.H., Mount, B., 2016. Pedestrian gap acceptance behavior in street designs with elements of shared space. Transp Res Rec 2586, 17–27. https://doi.org/10.3141/2586-03

Kaparias, I., Li, P., 2021. Behaviour and perceptions of powered two-wheeler users in street designs with elements of shared space. Transp Res Part F Traffic Psychol Behav 80, 368–380. https://doi.org/10.1016/j.trf.2021.05.007

Kaparias, I., Wang, R., 2020a. Vehicle and pedestrian level of service in street designs with elements of shared space. Transp Res Rec 2674, 1–13. https://doi.org/10.1177/0361198120933627

Kaparias, I., Wang, R., 2020b. Vehicle and Pedestrian Level of Service in Street Designs with Elements of Shared Space. Transp Res Rec July 2020. https://doi.org/10.1177/0361198120933627

Karndacharuk, A., Wilson, D.J., Dunn, R., 2014a. A Review of the Evolution of Shared (Street) Space Concepts in Urban Environments. Transp Rev 34, 190–220. https://doi.org/10.1080/01441647.2014.893038

Karndacharuk, A., Wilson, D.J., Dunn, R.C.M., 2014b. Analysis of Pedestrian Performance in Shared-Space Environments. Transportation Research Record: Journal of the Transportation Research Board 2393, 1–11. https://doi.org/10.3141/2393-01

Karndacharuk, A., Wilson, D.J., Dunn, R.C.M., 2014c. Analysis of Pedestrian Performance in Shared-Space Environments. Transportation Research Record: Journal of the Transportation Research Board 2393, 1–11. https://doi.org/10.3141/2393-01

Karolemeas, C., Tsigdinos, S., Tzouras, P.G., Nikitas, A., Bakogiannis, E., 2021. Determining Electric Vehicle Charging Station Location Suitability: A Qualitative Study of Greek Stakeholders Employing Thematic Analysis and Analytical Hierarchy Process. Sustainability (Switzerland) 13, 2298. https://doi.org/10.3390/su13042298

Kepaptsoglou, K., Karlaftis, M.G., Gkotsis, I., Vlahogianni, E., Stathopoulos, A., 2015. Urban Regeneration in Historic Downtown Areas: An Ex-Ante Evaluation of Traffic Impacts in Athens, Greece. Int J Sustain Transp 9, 478–489. https://doi.org/10.1080/15568318.2013.811331

Kepaptsoglou, K., Milioti, C., Spyropoulou, D., Haider, F., Karlaftis, A.G., 2020. Comparing traveler preferences for BRT and LRT systems in developing countries: Evidence from Multan, Pakistan. Journal of Traffic and Transportation Engineering (English Edition) 7, 384–393. https://doi.org/10.1016/j.jtte.2018.10.013

Keseru, I., Coosemans, T., Macharis, C., 2019. Building Scenarios for the Future of Transport in Europe: The Mobility4EU Approach, in: Muller, B., Meyer, G. (Eds.), Towards User-Centric Transport in

Europe Lectures Notes in Mobility. Springer, pp. 15–30. https://doi.org/10.1007/978-3-319-99756-8_2

Khondaker, B., Kattan, L., 2015. Variable speed limit: A microscopic analysis in a connected vehicle environment. Transp Res Part C Emerg Technol 58, 146–159. https://doi.org/10.1016/j.trc.2015.07.014

Kladeftiras, M., Antoniou, C., 2013. Simulation-based assessment of double-parking impacts on traffic and environmental conditions. Transp Res Rec 121–130. https://doi.org/10.3141/2390-13

Klinger, T., 2017. Moving from monomodality to multimodality? Changes in mode choice of new residents. Transp Res Part A Policy Pract 104, 221–237. https://doi.org/10.1016/j.tra.2017.01.008

Knoop, V.L., Daganzo, C.F., 2018a. The effect of crosswalks on traffic flow. European Journal of Transport and Infrastructure Research 18, 145–157. https://doi.org/10.18757/ejtir.2018.18.2.3227

Knoop, V.L., Daganzo, C.F., 2018b. The effect of crosswalks on traffic flow. European Journal of Transport and Infrastructure Research 18, 145–157. https://doi.org/10.18757/ejtir.2018.18.2.3227

Kopplin, C.S., Brand, B.M., Reichenberger, Y., 2021. Consumer acceptance of shared e-scooters for urban and short-distance mobility. Transp Res D Transp Environ 91, 102680. https://doi.org/10.1016/j.trd.2020.102680

Kopsidas, A., Kepaptsoglou, K., Vlahogianni, E., Iliopoulou, C., 2019. Modeling transit user travel time perception in a post-economic recession era: The case of Athens, Greece. Advances in Intelligent Systems and Computing 879, 504–511. https://doi.org/10.1007/978-3-030-02305-8_61

Kougias, I., Nikitas, A., Thiel, C., Szabó, S., 2020a. Clean energy and transport pathways for islands: A stakeholder analysis using Q method. Transp Res D Transp Environ 78, 102180. https://doi.org/10.1016/j.trd.2019.11.009

Kougias, I., Nikitas, A., Thiel, C., Szabó, S., 2020b. Clean energy and transport pathways for islands: A stakeholder analysis using Q method. Transp Res D Transp Environ 78, 102180. https://doi.org/10.1016/j.trd.2019.11.009

Kroes, E.P., Sheldon, R.J., 1988. Stated Preference Methods. Journal of Transport Economics and Policy 11–25.

Kwan, M.P., 1998. Space-time and integral measures of individual accessibility: a comparative analysis using a point-based framework. Geogr Anal 30, 191–216. https://doi.org/10.1111/j.1538-4632.1998.tb00396.x

Kyriakidis, C., Chatziioannou, I., Iliadis, F., Nikitas, A., Bakogiannis, E., 2022. Evaluating the public acceptance of sustainable mobility interventions responding to Covid-19: The case of the Great Walk of Athens and the importance of citizen engagement. Cities 132, 103966. https://doi.org/10.1016/j.cities.2022.103966

Lee, K.S., Eom, J.K., Moon, D.S., 2014. Applications of TRANSIMS in transportation: A literature review. Procedia Comput Sci 32, 769–773. https://doi.org/10.1016/j.procs.2014.05.489

Li, J., Rombaut, E., Vanhaverbeke, L., 2021. A systematic review of agent-based models for autonomous vehicles in urban mobility and logistics: Possibilities for integrated simulation models. Comput Environ Urban Syst 89, 101686. https://doi.org/10.1016/j.compenvurbsys.2021.101686

Li, Y., 2012. Enhancing the Image of Urban Space, Promoting Urban History and Culture: A Case Study of the Urban Design of Wangjiang Avenue. Nature Environment and Pollution Technology 11, 601–606.

Liddell, T.M., Kruschke, J.K., 2018. Analyzing ordinal data with metric models: What could possibly go wrong? J Exp Soc Psychol 79, 328–348. https://doi.org/10.1016/j.jesp.2018.08.009

Liu, Z., Yang, A., Gao, M., Jiang, H., Kang, Y., Zhang, F., Fei, T., 2019. Towards feasibility of photovoltaic road for urban traffic-solar energy estimation using street view image. J Clean Prod 228, 303–318. https://doi.org/10.1016/j.jclepro.2019.04.262

Livingston, C., Beyer Bartana, I., Ziemke, D., Bahamonde-Birke, F., 2018. The influence of the route environment on the route choice of bicyclists: A preliminary study. hEART 2019 - 8th Symposium of the European Association for Research in Transportation. https://doi.org/10.3929/ethz-b-000376513

Loorbach, D., Shiroyama, H., 2016. The Challenge of Sustainable Urban Development and Transforming Cities. pp. 3–12. https://doi.org/10.1007/978-4-431-55426-4_1

López, I., Ortega, J., Pardo, M., 2020. Mobility infrastructures in cities and climate change: An analysis through the superblocks in Barcelona. Atmosphere (Basel) 11. https://doi.org/10.3390/ATMOS11040410

Lucas, K., 2012. Transport and social exclusion: Where are we now? Transp Policy (Oxf) 20, 105–113. https://doi.org/10.1016/j.tranpol.2012.01.013

Lyons, G., Rohr, C., Smith, A., Rothnie, A., Curry, A., 2021. Scenario planning for transport practitioners. Transp Res Interdiscip Perspect 11. https://doi.org/10.1016/j.trip.2021.100438

Ma, Q., Yang, H., Mayhue, A., Sun, Y., Huang, Z., Ma, Y., 2021. E-Scooter safety: The riding risk analysis based on mobile sensing data. Accid Anal Prev 151, 105954. https://doi.org/10.1016/j.aap.2020.105954

Macmillan, A., Connor, J., Witten, K., Kearns, R., Rees, D., Woodward, A., 2014. The Societal Costs and Benefits of Commuter Bicycling: Simulating the Effects of Specific Policies Using System Dynamics Modeling. Environ Health Perspect 122, 335–344. https://doi.org/10.1289/ehp.1307250

McAndrews, C., Marshall, W., 2018. Livable Streets, Livable Arterials? Characteristics of Commercial Arterial Roads Associated With Neighborhood Livability. Journal of the American Planning Association 84, 33–44. https://doi.org/10.1080/01944363.2017.1405737

Meister, A., Axhausen, K.W., Felder, M., Schmid, B., 2022. Route Choice Modelling for Cyclists on Dense Urban Networks. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.4267767

Meng, Z., Le, D.T., Zegras, P.C., Ferreira, J., 2019. Impacts of Automated Mobility on Demand on Long-term Mobility Choices: a Case Study of Singapore. 2019 IEEE Intelligent Transportation Systems Conference, ITSC 2019 1908–1913. https://doi.org/10.1109/ITSC.2019.8917172

Merlin, L.A., Yan, X., Xu, Y., Zhao, X., 2021. A segment-level model of shared, electric scooter origins and destinations. Transp Res D Transp Environ 92, 102709. https://doi.org/10.1016/j.trd.2021.102709

Methorst, R., Gerlach, J., Boenke, D., Leven, J., 2007. Shared Space: safe or dangerous? A contribution to objectification of a popular design philosophy, in: Proceedings Walk21 Conference. Toronto, pp. 1–17.

Milakis, D., Kroesen, M., van Wee, B., 2018. Implications of automated vehicles for accessibility and location choices: Evidence from an expert-based experiment. J Transp Geogr 68, 142–148. https://doi.org/10.1016/j.jtrangeo.2018.03.010

Milakis, D., Vlastos, T., Barbopoulos, N., 2008. Relationships between urban form and travel behaviour in Athens, Greece. A comparison with Western European and North American results. European Journal of Transport and Infrastructure Research 8, 201–215. https://doi.org/10.18757/ejtir.2008.8.3.3346

Molin, E., Blangé, J., Cats, O., Chorus, C., 2017. Willingness to pay for safety improvements in passenger air travel. J Air Transp Manag 62, 165–175. https://doi.org/10.1016/j.jairtraman.2017.04.002

Molin, E., Chorus, C., van Sloten, R., 2009. The need for advanced public transport information services when making transfers. European Journal of Transport and Infrastructure Research 9, 397–410.

Moody, S., Melia, S., 2014. Shared space – research, policy and problems. Proceedings of the Institution of Civil Engineers - Transport 167, 384–392. https://doi.org/10.1680/tran.12.00047

Mora, R., Truffello, R., Oyarzún, G., 2021. Equity and accessibility of cycling infrastructure: An analysis of Santiago de Chile. J Transp Geogr 91. https://doi.org/10.1016/j.jtrangeo.2021.102964

Nagel, K., Kickhofer, B., Horni, A., Charypar, D., 2016. A Closer Look at Scoring, in: Horni, A., Nagel, K., Axhausen, K.W. (Eds.), The Multi-Agent Transport Simulation MATSim. Ubiquity Press, London, UK, pp. 23–34. https://doi.org/10.5334/baw.3

Nieuwenhuijsen, M.J., Khreis, H., 2016. Car free cities: Pathway to healthy urban living. Environ Int 94, 251–262. https://doi.org/10.1016/j.envint.2016.05.032

Nigro, M., Castiglione, M., Maria Colasanti, F., De Vincentis, R., Valenti, G., Liberto, C., Comi, A., 2022. Exploiting floating car data to derive the shifting potential to electric micromobility. Transp Res Part A Policy Pract 157, 78–93. https://doi.org/10.1016/j.tra.2022.01.008

Nikiforiadis, A., Paschalidis, E., Stamatiadis, N., Raptopoulou, A., Kostareli, A., Basbas, S., 2021. Analysis of attitudes and engagement of shared e-scooter users. Transp Res D Transp Environ 94, 102790. https://doi.org/10.1016/j.trd.2021.102790

Nikitas, A., Avineri, E., Parkhurst, G., 2011. Older people's attitudes to road charging: Are they distinctive and what are the implications for policy? Transportation Planning and Technology 34, 87–108. https://doi.org/10.1080/03081060.2011.530831

Nikitas, A., Kougias, I., Alyavina, E., Njoya Tchouamou, E., 2017. How Can Autonomous and Connected Vehicles, Electromobility, BRT, Hyperloop, Shared Use Mobility and Mobility-As-A-Service Shape Transport Futures for the Context of Smart Cities? Urban Science 1, 36. https://doi.org/10.3390/urbansci1040036

Nikitas, A., Tsigdinos, S., Karolemeas, C., Kourmpa, E., Bakogiannis, E., 2021. Cycling in the era of covid-19: Lessons learnt and best practice policy recommendations for a more bike-centric future. Sustainability (Switzerland) 13. https://doi.org/10.3390/su13094620

Novosel, T., Perković, L., Ban, M., Keko, H., Pukšec, T., Krajačić, G., Duić, N., 2015. Agent based modelling and energy planning - Utilization of MATSim for transport energy demand modelling. Energy 92, 466–475. https://doi.org/10.1016/j.energy.2015.05.091

Novotný, V., Kočárková, D., Havlena, O., Jacura, M., 2016. Detailed analysis of public bus vehicle ride on urban roads. Transport Problems 11, 43–55. https://doi.org/10.20858/tp.2016.11.4.5

Odioso, M., Smith, M., 2009. Perception of congestion charging:Lessons for U.S. cities from London and Stockholm, in: 88th Annual Meeting of the Transportation Research Board. Washington, DC.

Oh, S., Seshadri, R., Azevedo, C.L., Kumar, N., Basak, K., Ben-Akiva, M., 2020. Assessing the impacts of automated mobility-on-demand through agent-based simulation: A study of Singapore. Transp Res Part A Policy Pract 138, 367–388. https://doi.org/10.1016/j.tra.2020.06.004

O'Hern, S., Stephan, K., Qiu, J., Oxley, J., 2019. A simulator study of driving behavior and mental workload in mixed-use arterial road environments. Traffic Inj Prev 20, 648–654. https://doi.org/10.1080/15389588.2019.1632443

Oliveira, C., Albergaria De Mello Bandeira, R., Vasconcelos Goes, G., Schmitz Gonçalves, D., D'Agosto, M., 2017. Sustainable Vehicles-Based Alternatives in Last Mile Distribution of Urban Freight Transport: A Systematic Literature Review. Sustainability 9, 1324. https://doi.org/10.3390/su9081324

Oxley, J., Langford, J., Charlton, J., 2010. The safe mobility of older drivers: a challenge for urban road designers. J Transp Geogr 18, 642–648. https://doi.org/10.1016/j.jtrangeo.2010.04.005

Papaioannou, P., 2007. Driver behaviour, dilemma zone and safety effects at urban signalised intersections in Greece. Accid Anal Prev 39, 147–158. https://doi.org/10.1016/j.aap.2006.06.014

Park, D.E., Park, S.E., 2021. Factors affecting perceived safety and enjoyment based on driver experience. Transp Res Part F Traffic Psychol Behav 83, 148–163. https://doi.org/10.1016/j.trf.2021.10.006

Parkin, J., Ricci, M., Parkhurst, G., Clark, B., Clayton, W., 2018. Autonomous vehicle interactions in the urban street environment: a research agenda. Proceedings of the Institution of Civil Engineers: Municipal Engineer 171, 15–25. https://doi.org/10.1680/jmuen.16.00062

Pascucci, F., Rinke, N., Schiermeyer, C., Friedrich, B., Berkhahn, V., 2015a. Modeling of shared space with multi-modal traffic using a multi-layer social force approach. Transportation Research Procedia 10, 316–326. https://doi.org/10.1016/j.trpro.2015.09.081

Pascucci, F., Rinke, N., Schiermeyer, C., Friedrich, B., Berkhahn, V., 2015b. Modeling of shared space with multi-modal traffic using a multi-layer social force approach. Transportation Research Procedia 10, 316–326. https://doi.org/10.1016/j.trpro.2015.09.081

Pastia, V., Tzouras, P.G., Kaparias, I., Kepaptsoglou, K., 2022. Modeling the impact of the urban road environment on the perceived safety of different road users in Greece . SSRN Electronic Journal.

Peters, S., 2019. Sharing space or meaning? A geosemiotic perspective on shared space design. Applied Mobilities 4, 66–86. https://doi.org/10.1080/23800127.2017.1386850

Pnevmatikou, A.M., Karlaftis, M.G., Kepaptsoglou, K., 2015. Metro service disruptions: how do people choose to travel? Transportation (Amst) 42, 933–949. https://doi.org/10.1007/s11116-015-9656-4

Politis, I., Papaioannou, P., Basbas, S., 2012. Integrated choice and latent variable models for evaluating flexible transport mode choice. Research in Transportation Business and Management 3, 24–38. https://doi.org/10.1016/j.rtbm.2012.06.007

Pritchard, J.P., Tomasiello, D.B., Giannotti, M., Geurs, K., 2019. Potential impacts of bike-and-ride on job accessibility and spatial equity in São Paulo, Brazil. Transp Res Part A Policy Pract 121, 386–400. https://doi.org/10.1016/j.tra.2019.01.022

Ramirez, R., Wilkinson, A., 2014. Rethinking the 2×2 scenario method: Grid or frames? Technol Forecast Soc Change 86, 254–264. https://doi.org/10.1016/j.techfore.2013.10.020

Raney, B., Cetin, N., Völlmy, A., Vrtic, M., Axhausen, K., Nagel, K., 2003. An Agent-Based Microsimulation Model of Swiss Travel: First Results. Netw Spat Econ 3, 23–41. https://doi.org/10.1023/A:1022096916806

Reggiani, G., van Oijen, T., Hamedmoghadam, H., Daamen, W., Vu, H.L., Hoogendoorn, S., 2022. Understanding bikeability: a methodology to assess urban networks. Transportation (Amst) 49, 897–925. https://doi.org/10.1007/s11116-021-10198-0

Rentziou, A., Milioti, C., Gkritza, K., Karlaftis, M.G., 2011. Urban Road Pricing: Modeling Public Acceptance. J Urban Plan Dev 137, 56–64. https://doi.org/10.1061/(asce)up.1943-5444.0000041

Rieser, M., Dobler, C., Dubernet, T., Grether, D., Horni, A., Lämmel, G., Waraich, R., Zilske, M., Axhausen, K.W., Nagel, K., 2014. MATSim User Guide.

Rinke, N., Schiermeyer, C., Pascucci, F., Berkhahn, V., Friedrich, B., 2017a. A multi-layer social force approach to model interactions in shared spaces using collision prediction. Transportation Research Procedia 25, 1249–1267. https://doi.org/10.1016/j.trpro.2017.05.144

Rinke, N., Schiermeyer, C., Pascucci, F., Berkhahn, V., Friedrich, B., 2017b. A multi-layer social force approach to model interactions in shared spaces using collision prediction. Transportation Research Procedia 25, 1249–1267. https://doi.org/10.1016/j.trpro.2017.05.144

Rossetti, T., Daziano, R., 2022. How does self-assessed health status relate to preferences for cycling infrastructure? A latent class and latent variable approach. Transportation (Amst). https://doi.org/10.1007/s11116-022-10266-z

Rowley, J., Slack, F., 2004. Conducting a literature review. Management Research News 27, 31–39. https://doi.org/10.1108/01409170410784185

Rudloff, C., Schönauer, R., Fellendorf, M., 2014. Comparing Calibrated Shared Space Simulation Model with Real-Life Data. Transportation Research Record: Journal of the Transportation Research Board 2390, 44–52. https://doi.org/10.3141/2390-05

Ruiz-Apilánez, B., Karimi, K., García-Camacha, I., Martín, R., 2017. Shared space streets: Design, user perception and performance. Urban Design International 22, 267–284. https://doi.org/10.1057/s41289-016-0036-2

Salini, S., Ashalatha, R., 2020. Analysis of traffic characteristics of urban roads under the influence of roadside frictions. Case Stud Transp Policy 8, 94–100. https://doi.org/10.1016/j.cstp.2018.06.008

Sanders, R.L., Branion-Calles, M., Nelson, T.A., 2020. To scoot or not to scoot: Findings from a recent survey about the benefits and barriers of using E-scooters for riders and non-riders. Transp Res Part A Policy Pract 139, 217–227. https://doi.org/10.1016/j.tra.2020.07.009

Saplıoğlu, M., Aydın, M.M., 2018. Choosing safe and suitable bicycle routes to integrate cycling and public transport systems. J Transp Health 10. https://doi.org/10.1016/j.jth.2018.05.011

Säumel, I., Weber, F., Kowarik, I., 2016. Toward livable and healthy urban streets: Roadside vegetation provides ecosystem services where people live and move. Environ Sci Policy 62, 24–33. https://doi.org/10.1016/j.envsci.2015.11.012

Schmid, T., 2018a. Microscopic simulation of shared space on traffic-oriented streets in city centers.

Schmid, T., 2018b. Microscopic simulation of shared space on traffic-oriented streets in city centers. ETH Zurich.

Schonauer, R., 2017. A Microscopic Traffic Flow Model for Shared Space. Graz University of Technology.

Schönauer, R., Stubenschrott, M., Huang, W., Rudloff, C., Fellendorf, M., 2012a. Modeling concepts for mixed traffic. Transp Res Rec 114–121. https://doi.org/10.3141/2316-13

Schönauer, R., Stubenschrott, M., Huang, W., Rudloff, C., Fellendorf, M., 2012b. Modeling concepts for mixed traffic: Steps towards a microscopic simulation tool for shared space zones. Transportation Research Record: Journal of Transportation Research Board 2316, 114–121.

Scott Long, J., 2015. Regression models for nominal and ordinal outcomes, in: Best, H., Wolf, C. (Eds.), The SAGE Handbook of Regression Analysis and Causal Inference. SAGE Publications Ltd, pp. 173–204.

Simon, P.M., Esser, J., Nagel, K., 1999. Simple queueing model applied to the city of Portland. International Journal of Modern Physics C 10, 941–960. https://doi.org/10.1142/S0129183199000747

Snyder, H., 2019. Literature review as a research methodology: An overview and guidelines. J Bus Res 104, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Soret, A., Jimenez-Guerrero, P., Baldasano, J.M., 2011. Comprehensive air quality planning for the Barcelona Metropolitan Area through traffic management. Atmos Pollut Res 2, 255–266. https://doi.org/10.5094/APR.2011.032

Sorkou, T., Tzouras, P.G., Koliou, K., Mitropoulos, L., Karolemeas, C., Kepaptsoglou, K., 2022. An Approach to Model the Willingness to Use of E-Scooter Sharing Services in Different Urban Road Environments. Sustainability (Switzerland) 14, 15680. https://doi.org/10.3390/ su142315680

Stead, D., Vaddadi, B., 2019. Automated vehicles and how they may affect urban form: A review of recent scenario studies. Cities 92, 125–133. https://doi.org/10.1016/j.cities.2019.03.020

Steck, F., Kolarova, V., Bahamonde-Birke, F., Trommer, S., Lenz, B., 2018. How Autonomous Driving May Affect the Value of Travel Time Savings for Commuting. Transp Res Rec 2672, 11–20. https://doi.org/10.1177/0361198118757980

Sunitiyoso, Y., Wicaksono, A., Pambudi, N.F., Rahayu, W.A., Nurdayat, I.F., Hadiansyah, F., Nuraeni, S., Muhammad, A.A., 2023. Future of mobility in Jakarta Metropolitan Area: A Multi-Stakeholder scenario planning. Transp Res Interdiscip Perspect 19. https://doi.org/10.1016/j.trip.2023.100810

SWOV, 2013. Sustainable Safety: principles, misconceptions, and relations with other visions. The Hague.

Szele, A., Kisgyorgy, L., 2018. Autonomous vehicles in sustainable cities: more questions than answers. Sustainable Development and Planning 217, 725–734. https://doi.org/10.2495/SDP180611

Tisue, S., Wilensky, U., 2004. Netlogo: A simple environment for modeling complexity. Conference on Complex Systems 1–10.

Trifunović, A., Timmermann, C., Friedrich, B., Berkhahn, V., 2021. Implications of Converting Low Capacity Intersection Adjacent to Park Into a Shared Space, in: 100th Annual Meeting of Transportation Research Board. Washington D.C., USA.

Tsigdinos, S., Nikitas, A., Bakogiannis, E., 2020. Multimodal Corridor Development As A Way Of Supporting Sustainable Mobility In Athens. Case Stud Transp Policy. https://doi.org/10.1016/j.cstp.2020.11.004

Tsigdinos, S., Vlastos, T., 2020. Exploring ways to determine an alternative strategic road network in a metropolitan city: A multi-criteria analysis approach. IATSS Research. https://doi.org/10.1016/j.iatssr.2020.06.002

Tuncer, S., Laurier, E., Brown, B., Licoppe, C., 2020. Notes on the practices and appearances of e-scooter users in public space. J Transp Geogr 85, 102702. https://doi.org/10.1016/j.jtrangeo.2020.102702

Tzamourani, E., Tzouras, P.G., Tsigdinos, S., Kepaptsoglou, K., 2022. Exploring the social acceptance of transforming urban arterials to multimodal corridors . The case of Panepistimiou Avenue in Athens. Int J Sustain Transp 17, 333–347. https://doi.org/10.1080/15568318.2022.2037793

Tzouras, P.G., Farah, H., Papadimitriou, E., Oort, N. Van, Hagenzieker, M., 2020. Tram drivers' perceived safety and driving stress evaluation. A stated preference experiment. Transp Res Interdiscip Perspect 7, 100205. https://doi.org/10.1016/j.trip.2020.100205

Tzouras, P.G., Karolemeas, C., Bakogiannis, E., Kepaptsoglou, K., 2021. A Concept Agent-Based Simulation Model to Evaluate the Impacts of a Shared Space Network. Procedia Comput Sci 184, 680–685.

Tzouras, P.G., Karolemeas, C., Kepaptsoglou, K., Vlahogianni, E.I., 2022a. Towards the Estimation of Macroscopic Traffic Parameters in Shared Space Network Links: An Empirical Study, in: 101st Annual Meeting of the Transportation Research Board (TRB). Washington D.C.

Tzouras, P.G., Mitropoulos, L., Koliou, K., Stavropoulou, E., Karolemeas, C., Antoniou, E., Karaloulis, A., Mitropoulos, K., Vlahogianni, E.I., 2023. Describing Micro-Mobility First / Last-Mile Routing Behavior in Urban Road Networks through a Novel Modeling Approach. Sustainability (Switzerland) 15, 3095. https://doi.org/10.3390/su15043095

Tzouras, P.G., Mitropoulos, L., Stavropoulou, E., Antoniou, E., Koliou, K., Karolemeas, C., Karaloulis, A., Mitropoulos, K., Tarousi, M., Vlahogianni, E.I., Kepaptsoglou, K., 2022b. Agent-based models for simulating e-scooter sharing services: A review and a qualitative assessment. International Journal of Transportation Science and Technology. https://doi.org/10.1016/j.ijtst.2022.02.001

Useche, S.A., Gene-Morales, J., Siebert, F.W., Alonso, F., Montoro, L., 2021. "Not as safe as i believed": Differences in perceived and self-reported cycling behavior between riders and non-riders. Sustainability (Switzerland) 13, 1–14. https://doi.org/10.3390/su13041614

Useche, S.A., Gonzalez-Marin, A., Faus, M., Alonso, F., 2022. Environmentally friendly, but behaviorally complex? A systematic review of e-scooter riders' psychosocial risk features. PLoS One 17, 1–20. https://doi.org/10.1371/journal.pone.0268960

Uttley, J., Lee, Y.M., Madigan, R., Merat, N., 2020. Road user interactions in a shared space setting: Priority and communication in a UK car park. Transp Res Part F Traffic Psychol Behav 72, 32–46. https://doi.org/10.1016/j.trf.2020.05.004

van der Veen, A.S., Annema, J.A., Martens, K., van Arem, B., Correia, G.H. de A., 2020. Operationalizing an indicator of sufficient accessibility – a case study for the city of Rotterdam. Case Stud Transp Policy 8, 1360–1370. https://doi.org/10.1016/j.cstp.2020.09.007

van Wee, B., 2012. How suitable is CBA for the ex-ante evaluation of transport projects and policies? A discussion from the perspective of ethics. Transp Policy (Oxf) 19, 1–7. https://doi.org/10.1016/j.tranpol.2011.07.001

Van Wee, B., Geurs, K., 2011. Discussing Equity and Social Exclusion in Accessibility Evaluations. EJTIR Issue 11, 350–367.

Villegas Flores, N., Cruz Salvador, L.C., Parapinski dos Santos, A.C., Madero, Y.S., 2021. A proposal to compare urban infrastructure using multi-criteria analysis. Land use policy 101, 105173. https://doi.org/10.1016/j.landusepol.2020.105173

Vitale Brovarone, E., Scudellari, J., Staricco, L., 2021a. Planning the transition to autonomous driving: A policy pathway towards urban liveability. Cities 108, 102996. https://doi.org/10.1016/j.cities.2020.102996

Vitale Brovarone, E., Scudellari, J., Staricco, L., 2021b. Planning the transition to autonomous driving: A policy pathway towards urban liveability. Cities 108, 102996. https://doi.org/10.1016/j.cities.2020.102996

Vlek, C.A.J., 1997. The role of problem awareness in willingness-to-change car use and in evaluating relevant policy measures, in: Rothengatter, J.A., Carbonell Vaya, E. (Eds.), Traffic and Transport Psychology. Pergamon Press, Oxford, UK, pp. 465–475.

von Schönfeld, K.C., Bertolini, L., 2017. Urban streets: Epitomes of planning challenges and opportunities at the interface of public space and mobility. Cities 68, 48–55. https://doi.org/10.1016/j.cities.2017.04.012

Waraich, R.A., Charypar, D., Balmer, M., Axhausen, K.W., 2015a. Performance Improvements for Large-Scale Traffic Simulation in MATSim, in: M., H., J., J.A., M., L. (Eds.), Computational Approaches for Urban Environments, Geotechnologies and the Environment. Springer, Cham, pp. 211–233. https://doi.org/10.1007/978-3-319-11469-9

Waraich, R.A., Charypar, D., Balmer, M., Axhausen, K.W., 2015b. Performance Improvements for Large-Scale Traffic Simulation in MATSim, in: M., H., J., J.A., M., L. (Eds.), Computational Approaches for Urban Environments, Geotechnologies and the Environment. Springer, Cham, pp. 211–233. https://doi.org/10.1007/978-3-319-11469-9

Watts, S., Stenner, P., 2005. Doing Q methodology: Theory, method and interpretation. Qual Res Psychol 2, 67–91. https://doi.org/10.1191/1478088705qp022oa

Webster DC, M.A., 1996. Review of Traffic Calming Schemes in 20 mph Zones. Transportation Research Laboratory Report 215.

Wolbertus, R., Jansen, S., Kroesen, M., 2020a. Stakeholders' perspectives on future electric vehicle charging infrastructure developments. Futures 123, 102610. https://doi.org/10.1016/j.futures.2020.102610

Wolbertus, R., Jansen, S., Kroesen, M., 2020b. Stakeholders' perspectives on future electric vehicle charging infrastructure developments. Futures 123, 102610. https://doi.org/10.1016/j.futures.2020.102610

Woodman, R., Lu, K., Higgins, M.D., Brewerton, S., Jennings, P.A., Birrell, S., 2019. Gap acceptance study of pedestrians crossing between platooning autonomous vehicles in a virtual environment. Transp Res Part F Traffic Psychol Behav 67, 1–14. https://doi.org/10.1016/j.trf.2019.09.017

Xia, T., Zheng, Y., Braunack-Mayer, A., Crabb, S., 2017. Public Attitudes towards Encouraging Sustainable Transportation: an Australian case study. International Journal of Sustainable Transportation ISSN: 11, 593–601. https://doi.org/10.1080/15568318.2017.1287316

Xia, Y., 2020. Correlation and association analyses in microbiome study integrating multiomics in health and disease, 1st ed, Progress in Molecular Biology and Translational Science. Elsevier Inc. https://doi.org/10.1016/bs.pmbts.2020.04.003

Yannis, G., Kondyli, A., Georgopoulou, X., 2014. Investigation of the impact of low cost traffic engineering measures on road safety in urban areas. Int J Inj Contr Saf Promot 21. https://doi.org/10.1080/17457300.2013.796387

Yannis, G., Nikolaou, D., Laiou, A., Stürmer, Y.A., Buttler, I., Jankowska-Karpa, D., 2020. Vulnerable road users: Cross-cultural perspectives on performance and attitudes. IATSS Research 44, 220–229. https://doi.org/10.1016/j.iatssr.2020.08.006

Yigitcanlar, T., Cugurullo, F., 2020. The sustainability of artificial intelligence: an urbanistic viewpoint from the lens of smart and sustainable cities. Sustainability (Switzerland) 12, 1–24. https://doi.org/10.3390/su12208548

Younes, H., Baiocchi, G., 2022. Analyzing the spatial determinants of dockless E-Scooter & E-Bike trips across four U.S. Cities. Int J Sustain Transp 0, 1–13. https://doi.org/10.1080/15568318.2022.2119623

Zabala, A., 2014. Qmethod: A package to explore human perspectives using Q methodology. R Journal 6, 163–173. https://doi.org/10.32614/rj-2014-032

Zabala, A., Pascual, U., 2016. Bootstrapping Q Methodology to Improve the Understanding of Human Perspectives. PLoS One 11, 1–19. https://doi.org/10.1371/journal.pone.0148087

Zhang, F., Zheng, N., Yang, H., Geroliminis, N., 2018. A systematic analysis of multimodal transport systems with road space distribution and responsive bus service. Transp Res Part C Emerg Technol 96, 208–230. https://doi.org/10.1016/j.trc.2018.09.009

Zheng, N., Geroliminis, N., 2013. On the distribution of urban road space for multimodal congested networks. Transportation Research Part B: Methodological 57, 326–341. https://doi.org/10.1016/j.trb.2013.06.003

Zheng, N., Waraich, R.A., Axhausen, K.W., Geroliminis, N., 2012. A dynamic cordon pricing scheme combining the Macroscopic Fundamental Diagram and an agent-based traffic model. Transp Res Part A Policy Pract 46, 1291–1303. https://doi.org/10.1016/j.tra.2012.05.006

Ziemke, D., Kaddoura, I., Nagel, K., 2019a. The MATSim open Berlin scenario: A multimodal agent-based transport simulation scenario based on synthetic demand modeling and open data. Procedia Comput Sci 151, 870–877. https://doi.org/10.1016/j.procs.2019.04.120

Ziemke, D., Metzler, S., Nagel, K., 2019b. Bicycle traffic and its interaction with motorized traffic in an agent-based transport simulation framework. Future Generation Computer Systems 97, 30–40. https://doi.org/10.1016/j.future.2018.11.005

Ziemke, D., Metzler, S., Nagel, K., 2019c. Bicycle traffic and its interaction with motorized traffic in an agent-based transport simulation framework. Future Generation Computer Systems 97, 30–40. https://doi.org/10.1016/j.future.2018.11.005

Ziemke, D., Metzler, S., Nagel, K., 2017. Modeling bicycle traffic in an agent-based transport simulation. Procedia Comput Sci 109, 923–928. https://doi.org/10.1016/j.procs.2017.05.424

Zilske, M., Neumann, A., Nagel, K., 2011. OpenStreetMap For Traffic Simulation.