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Mathematical Models for Dynamic Eco-driving in Signalized Intersections in the Context of Cooperative Intelligent Transportation Systems

Dissertation for the Degree of Doctor of Philosophy prepared by

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[3] Know the Self as lord of the chariot,
The body as the chariot itself,
The discriminating intellect as
The charioteer, and the mind as reins.
[4] The senses, say the wise, are the horses;
Selfish desires are the roads they travel.
When the Self is confused with the body,
Mind, and senses, they point out, he seems
To enjoy pleasure and suffer sorrow.

The Katha Upanishad, Part [3], Verses 3-4

[38] Just as a fire is covered by smoke and a mirror is
obscured by dust, just as the embryo rests deep within
the womb, knowledge is hidden by selfish desire
– [39] hidden, Arjuna, by this unquenchable fire for
self-satisfaction, the inveterate enemy of the wise.

The Bhagavad Gita, Chapter 3: Selfless Service, Verses 38-39

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The realization of a doctoral dissertation constitutes a strenuous and demanding journey but also a major leap towards personal growth and self-realization. It requires creativity, critical thinking, collaboration, adaptability, dedication, endurance, and firmness from the knowledge aspirant side, but it cannot be accomplished without illumined guidance of experienced teachers, and collective effort that encompasses many more people. Thus, I would like to express my deepest gratitude to all the people who have contributed directly or indirectly to the completion of this work.

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Diogenes Laertius in his Lives of the Eminent Philosophers attributes the following quote to Aristotle:

"The root of education is bitter but the fruit is sweet."

I hope that we get the chance to taste the fruit together and that it will enable us to become helpful and useful to those who need it the most.

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Any errors in the text are the sole responsibility of the author.

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List of Acronyms

ADAS	Advanced Driving Alert System
AERIS	Applications for the Environment: Real-Time Information Synthesis
AKTIV	Adaptive and Cooperative Technologies for Intelligent Transport
API	Application Programming Interface
ATIS	Advanced Traveler Information Systems
ATMS	Advanced Traffic Management Systems
CAD	Connected and Automated Driving
CAM	Cooperative Awareness Message
CAV	Connected and Automated Vehicle
CBD	Central Business District
CFS	Correlation-based Feature Selection
CICAS	Cooperative Intersection Collision Avoidance Systems
CMEM	Comprehensive Modal Emissions Model
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COOPERS	Co-Operative Systems for Intelligent Road Safety
CVIS	Cooperative Vehicle-Infrastructure system
CV	Connected Vehicle
C2X	Car-to-Everything
C-ITS	Cooperative Intelligent Transportation Systems
C-MobILE	Accelerating C-ITS Mobility Innovation and Deployment in Europe
DLL	Dynamic-link Library
DSRC	Dedicated Short Range Communications
DT	Decision Tree
EAD	Eco-Approach and Departure
ECACC	Eco-Cooperative Adaptive Cruise Control
eCoMove	Cooperative Mobility Systems and Services for Energy Efficiency
EEI	Energy Efficient Intersection

EV	Electric Vehicle
EVPA	Enhanced Velocity Planning Algorithm
EVPA-DT	Enhanced Velocity Planning Algorithm – Decision Tree
FHWA	Federal Highway Administration
FOT	Field Operational Test
GHG	Greenhouse Gas
GLOSA	Green Light Optimized Speed Advisory
GUI	Graphical User Interface
HDV	Heavy Duty Vehicle
HMI	Human-Machine Interface
IA	Intersection Approach
ICE	Internal Combustion Engine
IDM	Intelligent Driver Model
IEA	International Energy Agency
InterCor	Interoperable Corridors
ISA	Intelligent Speed Adaptation
ITS	Intelligent Transportation Systems
I2V	Infrastructure-to-Vehicle
KOLINE	Cooperative and Optimized Traffic Signal Control in Urban Networks
KPI	Key Performance Indicator
LV	Legacy Vehicle
MPC	Model Predictive Control
NO_x	Oxides of Nitrogen
NO_2	Nitrogen Dioxide
OBU	Onboard Unit
PCC	Predictive Cruise Control
PHEM	Passenger Car and Heavy Duty Emission Model
PM_{10}	Particulate Matter
POC	Proof-of-Concept

POMS	Pilot Operation Management System
PSAT	Powertrain System Analysis Toolkit
RHW	Road Hazard Warning
RLVW	Red Light Violation Warning
RSU	Road-side Unit
sim^{TD}	Safe and Intelligent Mobility
SO_2	Sulphur Dioxide
SPaT	Signal Phase and Timing
SSAM	Surrogate Safety Assessment Model
TMC	Traffic Management Centre
TrajAIM	Trajectory Analysis for Microsimulation
TranLIVE	Transportation for Livability by Integrating Vehicles and the Environment
TTC	Time-to-Collision
USDOT	United States Department of Transportation
VII	Vehicle Infrastructure Integration
VMS	Variable Message Sign
VOT	Volatile Organic Compounds
VPA	Velocity Planning Algorithm
VSL	Variable Speed Limits
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything

Abstract

This PhD dissertation enhances the human-centered design of existing dynamic eco-driving systems, and models driver adaptation to energy-efficient speed advice upstream of signalized intersections with the use of decision trees and empirical evidence generated via the pilot operation of an advisory dynamic eco-driving system along an urban arterial corridor, quantifies the relevant impacts on emissions, and compares them with the case of automated execution of dynamic eco-driving advice. Moreover, it proposes a simulation framework that is comprised of a microscopic traffic simulator, an external test-bed for emulating dynamic eco-driving, multiple tools for the analysis of simulation output, and a comprehensive set of simulation scenarios for evaluating the performance of different variants of dynamic eco-driving technology.

Results indicate that despite rendering advised deceleration strategies more conservative for enhancing user acceptance and safety, traffic and energy efficiency of dynamic eco-driving are not undermined. Moreover, advisory dynamic eco-driving can yield significant emissions reduction compared to unequipped manually driven vehicles for increased market penetration rate of the relevant technology. However, for multi-vehicle and multi-lane traffic simulation experiments environmental, traffic and safety benefits are maximized when dynamic eco-driving is automated and market penetration rate is maximum. Finally, the implications of this PhD dissertation's results with respect to system design, operational, technological and policy aspects of dynamic eco-driving are discussed.

Keywords: dynamic eco-driving, speed advice, traffic simulation, AIMSUN, emissions, connected vehicle, signalized intersection

Περίληψη

Η παρούσα διδακτορική διατριβή αναπτύσσει μεθόδους που βελτιώνουν τον ανθρωποκεντρικό σχεδιασμό των συστημάτων περιβαλλοντικά φιλικής οδήγησης, προτυποποιούν την προσαρμογή των οδηγών σε ενεργειακά αποδοτικές στρατηγικές οδήγησης ανάντη σηματοδοτημένων διασταυρώσεων με τη χρήση δένδρων αποφάσεων και εμπειρικών δεδομένων που συλλέχθηκαν κατά την πιλοτική εφαρμογή ενός συστήματος περιβαλλοντικά φιλικής οδήγησης κατά μήκος μιας αστικής οδικής αρτηρίας, ποσοτικοποιούν τις συναφείς περιβαλλοντικές και κυκλοφοριακές επιπτώσεις, καθώς και καθιστούν εφικτή τη σύγκριση επιδόσεων με αυτοματοποιημένα συστήματα περιβαλλοντικά φιλικής οδήγησης, όπου το όχημα είναι ταυτοχρόνως εξοπλισμένο με συστήματα αυτοματοποιημένης οδήγησης που επιτρέπουν την ακριβή προσαρμογή σε ενεργειακά αποδοτικά προφίλ ταχυτήτων. Επιπλέον, η αξιολόγηση επιπτώσεων των συστημάτων περιβαλλοντικά φιλικής οδήγησης γίνεται μέσω της ανάπτυξης λογισμικού που προσομοιώνει τη λειτουργία τους στα πλαίσια μοντέλου μικροσκοπικής προσομοίωσης της κυκλοφορίας για διαφορετικές συνθήκες ζήτησης μετακινήσεων αλλά και διείσδυσης της συγκεκριμένης τεχνολογίας στο συνολικό στόλο των οχημάτων.

Τα αποτελέσματα των αναλύσεων της μικροσκοπικής προσομοίωσης της κυκλοφορίας κατέδειξαν ότι οι προσαρμογές στη δομή των υφιστάμενων μοντέλων περιβαλλοντικά φιλικής οδήγησης που αποσκοπούν στην βελτίωση της αποδοχής τους από τους χρήστες αλλά και στην βελτίωση της οδικής ασφάλειας δεν επηρεάζουν αρνητικά την απόδοσή τους αναφορικά με τη μείωση της ενεργειακής κατανάλωσης και των εκπομπών αέριων ρύπων. Επίσης, το περιβαλλοντικό αποτύπωμα διασυνδεδεμένων οχημάτων που είναι εξοπλισμένα με συμβουλευτικού τύπου συστήματα περιβαλλοντικά φιλικής οδήγησης είναι σημαντικά μικρότερο σε σχέση με συμβατικά οχήματα όταν το ποσοστό διείσδυσης στο στόλο των παραπάνω συστημάτων είναι υψηλό. Είναι όμως αξιοσημείωτο, ότι σε οδικές αρτηρίες πολλαπλών λωρίδων η μεγιστοποίηση των περιβαλλοντικών και κυκλοφοριακών πλεονεκτημάτων των συστημάτων περιβαλλοντικά φιλικής οδήγησης συμβαίνει όταν αυτά είναι αυτοματοποιημένου τύπου και η διείσδυσή τους στο στόλο είναι μέγιστη. Τελικώς, αναλύονται οι επιπτώσεις των ευρημάτων της συγκεκριμένης διδακτορικής διατριβής αναφορικά με τον ανθρωποκεντρικό σχεδιασμό των συστημάτων περιβαλλοντικής οδήγησης συμβουλευτικού τύπου και τη ορθή εφαρμογή τους σε πραγματικές κυκλοφοριακές συνθήκες.

Εκτενής Περίληψη

Η συνεχώς αυξανόμενη ζήτηση για οδικές μετακινήσεις δύναται να επιδεινώσει σε σημαντικό βαθμό τις επιπτώσεις της οδικής κυκλοφορίας στο περιβάλλον. Από την άλλη πλευρά, οι πρόσφατες τεχνολογικές εξελίξεις στον τομέα των τηλεπικοινωνιών έχουν καταστήσει εφικτή την ανάπτυξη και εφαρμογή συστημάτων διασυνδεδεμένης οδήγησης (Συνεργατικά Ευφυή Συστήματα Μεταφορών) που δίνουν τη δυνατότητα βελτίωσης των κυκλοφοριακών συνθηκών, της οδικής ασφάλειας, καθώς και την βιωσιμότητας του συστήματος οδικών μεταφορών. Για παράδειγμα, η διασύνδεση υποδομής-οχήματος μέσω εξειδικευμένου εξοπλισμού και κατάλληλων τηλεπικοινωνιακών πρωτοκόλλων επιτρέπει σε διασυνδεδεμένα οχήματα (ΔΟ) να πληροφορηθούν μελλοντικές μεταβολές των υφιστάμενων προγραμμάτων σηματοδότησης και να σχεδιάσουν και υλοποιήσουν περιβαλλοντικά φιλικές τροχιές κίνησης πέριξ σηματοδοτημένων διασταυρώσεων. Επιπλέον, ο σχεδιασμός του τρόπου κίνησης των ΔΟ για την επίτευξη στόχων σχετιζόμενων με την βελτίωση της ενεργειακής κατανάλωσης και του περιορισμού των αέριων ρύπων τους (περιβαλλοντικά φιλική οδήγηση) δύναται να λάβει υπόψη τις ενέργειες και τις προθέσεις παρακείμενων ΔΟ μέσω κατάλληλων τηλεπικοινωνιακών πρωτοκόλλων διασύνδεσης οχήματος-οχήματος σε ένα οδικό περιβάλλον εξοπλισμένο με σύγχρονες τεχνολογίες διασύνδεσης και τηλεπικοινωνιών.

Κατά την περασμένη δεκαετία, πλήθος μαθηματικών μοντέλων και συστημάτων περιβαλλοντικά φιλικής οδήγησης πέριξ σηματοδοτημένων διασταυρώσεων προτάθηκαν και διερευνήθηκαν. Η παρούσα διδακτορική διατριβή σκιαγραφεί την ερευνητική δραστηριότητα γύρω από τις παραπάνω τεχνολογίες, αναδεικνύει τα πλεονεκτήματά και τους περιορισμούς τους, αλλά και καταδεικνύει πτυχές τους που δεν έχουν διερευνηθεί με συστηματικό τρόπο ακόμα. Ειδικότερα, πραγματοποιήθηκε ενδελεχής βιβλιογραφική ανασκόπηση βάσει της οποίας προέκυψε ότι τα υφιστάμενα συστήματα περιβαλλοντικής οδήγησης διαφέρουν σε σημαντικό βαθμό ως προς τις δομές ελέγχου που παρουσιάζουν, τους δείκτες βελτιστοποίησης που χρησιμοποιούν, τα ενεργειακά και συγκοινωνιακά μοντέλα που λαμβάνουν υπόψη, καθώς και το χωρικό εύρος εφαρμογής τους. Επίσης, προσδιορίστηκε ένα σύνολο επιθυμητών χαρακτηριστικών για τα συστήματα περιβαλλοντικά φιλικής οδήγησης τα οποία αναμένεται ότι θα επαυξήσουν την αποτελεσματικότητά τους και παρουσιάζονται αναλυτικώς παρακάτω:

- οι αλγόριθμοι των συστημάτων περιβαλλοντικά φιλικής οδήγησης θα πρέπει να λαμβάνουν υπόψη πληροφορία σχετικά με τη μελλοντική κατάσταση των φωτεινών σηματοδοτών (τόσο πλήρη όσο και μερική), τα δυναμικά χαρακτηριστικά του ΔΟ, τη διαδικασία δημιουργίας και απόσβεσης ουρών ανάντη φωτεινών σηματοδοτών, καθώς και την κατάσταση του προπορευόμενου οχήματος μέσω τηλεπικοινωνιών διασύνδεσης οχήματος-οχήματος,
- οι αλγόριθμοι των συστημάτων περιβαλλοντικά φιλικής οδήγησης θα πρέπει να βελτιστοποιούν ταυτοχρόνως την κατανάλωση ενέργειας, μικροσκοπικά κυκλοφοριακά μεγέθη, καθώς και δείκτες οδικής ασφάλειας για τον υπολογισμό ενεργειακά αποδοτικών στρατηγικών οδήγησης,
- οι συναρτήσεις βελτιστοποίησης των αλγορίθμων προτείνεται να ενσωματώνουν μη γραμμικά μοντέλα ισχύος των ΔΟ ή μικροσκοπικά μοντέλα κατανάλωσης ενέργειας που χρησιμοποιούν ως εισαγόμενα δεδομένα τιμές ταχυτήτων και επιταχύνσεων,
- η επίλυση των προαναφερθέντων προγραμμάτων μαθηματικής βελτιστοποίησης θα πρέπει να είναι αποδοτική και γρήγορη σε βαθμό που να επιτρέπει τη λειτουργία των συστημάτων περιβαλλοντικά φιλικής οδήγησης σε επιχειρησιακές συνθήκες,
- ο υπολογισμός των ενεργειακά αποδοτικών τροχιών κίνησης των ΔΟ συνίσταται να λαμβάνει υπόψη γραμμικά μοντέλα επιβράδυνσης ανάντη των φωτεινών σηματοδοτών, και μη γραμμικά μοντέλα επιτάχυνσης κατάντη των φωτεινών σηματοδοτών,
- η επίδραση της εναλλαγής σχέσεων του ΔΟ στην υλοποίηση ενεργειακά αποδοτικών στρατηγικών κίνησης προτείνεται να συνεκτιμάται,
- τα συστήματα περιβαλλοντικά φιλικής οδήγησης θα πρέπει να συνεργάζονται με διαφορετικά προγράμματα σηματοδότησης (π.χ. σταθερού χρόνου, επενεργούμενα, δυναμικά προσαρμοζόμενα στις επικρατούσες κυκλοφοριακές συνθήκες, συντονισμένα), αλλά και λαμβάνουν υπόψη τη μελλοντική μεταβολή της κατάστασης πλήθους φωτεινών σηματοδοτών που βρίσκονται κατάντη του ΔΟ, ώστε να επιτυγχάνονται υψηλότερα οφέλη σε κατανάλωση ενέργειας και εκπομπές αέριων ρύπων σε επίπεδο οδικής αρτηρίας ή και δικτύου.

Πέραν του προσδιορισμού ενός συνόλου επιθυμητών χαρακτηριστικών που επιτρέπουν μια πιο ολιστική μαθηματική έκφραση του προβλήματος της περιβαλλοντικά φιλικής οδήγησης ανάντη φωτεινών σηματοδοτών, η κριτική επισκόπηση της υφιστάμενης βιβλιογραφίας κατέδειξε και ορισμένους τομείς στην έρευνα των συγκεκριμένων συστημάτων που δεν έχουν διερευνηθεί διεξοδικά και εκθέτονται παρακάτω:

- ανθρωποκεντρικός σχεδιασμός συστημάτων περιβαλλοντικά φιλικής οδήγησης,
- προτυποποίηση συστημάτων περιβαλλοντικά φιλικής οδήγησης συμβουλευτικού τύπου, όπου ο οδηγός του ΔΟ είναι επιφορτισμένος με την εκτέλεση της προτεινόμενης ενεργειακά αποδοτικής στρατηγικής οδήγησης,
- αξιολόγηση τεχνολογιών περιβαλλοντικά φιλικής οδήγησης βάσει πιλοτικών εφαρμογών που έχουν πραγματοποιηθεί σε πραγματικά οδικά δίκτυα και υπό ρεαλιστικές κυκλοφοριακές συνθήκες.

Συγκεκριμένα, τα υφιστάμενα συστήματα περιβαλλοντικά φιλικής οδήγησης δίνουν περιορισμένη έμφαση στην υπολογισμό ενεργειακά αποδοτικών στρατηγικών οδήγησης που συνεκτιμούν παράγοντες όπως η άνεση των επιβατών, η αποδοχή των συστημάτων από τους οδηγούς, και η οδική ασφάλεια. Δηλαδή, δίνεται προτεραιότητα στην επίτευξη ενεργειακών και περιβαλλοντικών στόχων, ενώ επίσης οι περισσότερες ερευνητικές εργασίες υποθέτουν ότι τα ΔΟ διαθέτουν και συστήματα αυτοματοποιημένης οδήγησης που επιτρέπουν την επακριβή εφαρμογή των ενεργειακά αποδοτικών στρατηγικών κίνησης.

Λαμβάνοντος υπόψη ότι η μετάβαση προς ένα πλήρως διασυνδεδεμένο και αυτοματοποιημένο οδικό περιβάλλον θα διαρκέσει δεκαετίες, αλλά και ότι η ενσωμάτωση εξοπλισμού διασύνδεσης σε εμπορικά διαθέσιμα οχήματα υπολείπεται των συστημάτων αυτοματοποιημένης οδήγησης, καθίσταται σαφές ότι ο ανθρωποκεντρικός σχεδιασμός συστημάτων περιβαλλοντικά φιλικής οδήγησης είναι απαραίτητος για την επίτευξη περιβαλλοντικών στόχων. Επιπλέον η διερεύνηση της προσαρμογής των οδηγών σε οδηγίες συστημάτων περιβαλλοντικά φιλικής οδήγησης συμβουλευτικού χαρακτήρα θα δώσει τη δυνατότητα αξιολόγησης των επιπτώσεων περισσότερων σχετικών τεχνολογιών και για διαφορετικά επίπεδα διείσδυσής τους στο συνολικό στόλο των οχημάτων. Παρόλα αυτά, είναι αξιοσημείωτο ότι η ανάπτυξη και διερεύνηση των παραπάνω τεχνολογιών θα πρέπει να βασίζεται σε επαρκή δεδομένα από αντίστοιχες πιλοτικές εφαρμογές ευρείας κλίμακας που λαμβάνουν υπόψη τη μεταβλητότητα της οδικής συμπεριφοράς των οδηγών, των κυκλοφοριακών συνθηκών, αλλά και των χαρακτηριστικών των οχημάτων. Προς το παρόν, η συντριπτική πλειοψηφία των υφιστάμενων ερευνητικών έργων αξιολογεί τις άνωθεν τεχνολογίες με τη χρήση μεθόδων αριθμητικής ανάλυσης και μικροσκοπικής προσομοίωσης της κυκλοφορίας.

Δεδομένων των ευρημάτων της βιβλιογραφικής ανασκόπησης, αναπτύχθηκαν μεθοδολογίες που ενσωματώνουν ανθρωπογενείς παράγοντες σχετιζόμενους με την οδική συμπεριφορά στο σχεδιασμό, λειτουργία και αξιολόγηση συστημάτων περιβαλλοντικά φιλικής οδήγησης ανάντη φωτεινών σηματοδοτών. Ειδικότερα, προτάθηκαν γενικευμένες τροποποιήσεις στη δομή των αλγόριθμων περιβαλλοντικά φιλικής οδήγησης, ώστε να βελτιωθεί η άνεση των οδηγών κατά την εκτέλεση ενεργειακά αποδοτικών στρατηγικών οδήγησης αλλά και η ασφάλεια του συστήματος κατά την εφαρμογή στρατηγικών επιβράδυνσης. Οι προτεινόμενες τροποποιήσεις παρουσιάζονται παρακάτω:

- αποφυγή υπολογισμού στρατηγικών επιβράδυνσης που συμπεριλαμβάνουν πολύ χαμηλές ταχύτητες κίνησης και οι οποίες θα τυγχάνουν χαμηλής αποδοχής από τους οδηγούς/μετακινούμενους και θα επιτυγχάνουν χαμηλή ενεργειακή αποδοτικότητα,
- υπολογισμός στρατηγικών επιβράδυνσης που ολοκληρώνονται πρωθύστερα της μεταβολής της ένδειξης του φωτεινού σηματοδότη από κόκκινο σε πράσινο και δε συνεπάγονται την άφιξη του ΔΟ στη διασταύρωση ταυτόχρονα με την παραπάνω μεταβολή.

Η δεύτερη προτεινόμενη τροποποίηση εξασφαλίζει ότι οι οδηγοί δε θα είναι υποχρεωμένοι να οδηγούν το ΔΟ σε υψηλή ταχύτητα πολύ κοντά στον φωτεινό σηματοδότη ενώ αυτός παραμένει σε κόκκινη ένδειξη, ενώ επίσης θα παρέχει περιθώριο ασφαλούς τροποποίησης της τροχιάς κίνησης του ΔΟ σε περίπτωση παραβίασης του φωτεινού σηματοδότη από διασταυρούμενη κατεύθυνση που λαμβάνει πράσινη ένδειξη κατά τη διάρκεια υλοποίησης της στρατηγικής επιβράδυνσης από το ΔΟ.

Επιπλέον, διερευνήθηκε και προτυποποιήθηκε μαθηματικά η προσαρμογή των οδηγών σε ενεργειακά αποδοτικές στρατηγικές οδήγησης ανάντη φωτεινών σηματοδοτών με τη χρήση εμπειρικών δεδομένων που συλλέχθηκαν κατά την πιλοτική εφαρμογή ενός συστήματος περιβαλλοντικά φιλικής οδήγησης συμβουλευτικού χαρακτήρα κατά μήκος μιας αστικής οδικής αρτηρίας. Αρχικά, πραγματοποιήθηκε ανάλυση των εμπειρικών δεδομένων με αλγόριθμους CFS οι οποίοι αναγνώρισαν τους κάτωθι παράγοντες ως επιδραστικότερους στο βαθμό προσαρμογής των οδηγών σε ενεργειακά αποδοτικές στρατηγικές οδήγησης ανάντη φωτεινών σηματοδοτών:

- τύπος προτεινόμενης ενεργειακά αποδοτικής στρατηγικής οδήγησης (επιτάχυνση, επιβράδυνση, διατήρηση ταχύτητας),
- απόσταση ΔΟ από το φωτεινό σηματοδότη,

- υπολειπόμενος χρόνος της τρέχουσας φωτεινής ένδειξης.

Ακολούθως, αναπτύχθηκε δένδρο αποφάσεων το οποίο εκτιμά τον βαθμό προσαρμογής των οδηγών σε ενεργειακά αποδοτικές στρατηγικές οδήγησης ανάντη φωτεινών σηματοδοτών βάσει των παραπάνω παραγόντων. Συγκεκριμένα, το δένδρο αποφάσεων προσδιορίζει ένα εύρος πιθανών αποκλίσεων από το ιδεατό προφίλ ταχύτητας μιας υπολογισθείσας ενεργειακά αποδοτικής στρατηγικής οδήγησης βάσει των τιμών των παραπάνω παραγόντων. Η τελική τιμή της απόκλισης που μετασχηματίζει το ιδεατό προφίλ ταχύτητας καθορίζεται με τη χρήση στατιστικών μεθόδων. Η ανάπτυξη του δένδρου αποφάσεων δίνει τη δυνατότητα αξιολόγησης συστημάτων περιβαλλοντικής οδήγησης συμβουλευτικού τύπου αλλά τη σύγκρισή τους με αντίστοιχα συστήματα αυτοματοποιημένου τύπου, όπου το όχημα είναι ταυτοχρόνως εξοπλισμένο με συστήματα αυτοματοποιημένης οδήγησης που επιτρέπουν την ακριβή προσαρμογή σε ενεργειακά αποδοτικά προφίλ ταχυτήτων.

Η αξιοποίηση εμπειρικών δεδομένων από την πιλοτική εφαρμογή ενός συστήματος περιβαλλοντικά φιλικής οδήγησης συμβουλευτικού χαρακτήρα κατά μήκος μιας αστικής οδικής αρτηρίας για την ανάπτυξη των προαναφερθέντων μαθηματικών προτύπων αποτελεί μια από τις βασικές καινοτομίες της παρούσας διδακτορικής διατριβής, καθώς η βιβλιογραφική ανασκόπηση δεν εντόπισε προηγούμενο αντίστοιχο ερευνητικό έργο. Για την υλοποίηση της πιλοτικής εφαρμογής εγκαταστάθηκε τεχνολογικός εξοπλισμός σε 200 ταξί και 12 φωτεινούς σηματοδότες, ώστε να καταστεί εφικτή η διασύνδεση υποδομής-οχήματος και η ενημέρωση των οδηγών σχετικά με τις ενεργειακά αποδοτικές στρατηγικές οδήγησης. Κατά τη διάρκεια της πιλοτικής εφαρμογής, ΔΟ που εισέρχονταν σε προκαθορισμένες ζώνες της αστικής οδικής αρτηρίας (οδικά τμήματα ανάντη φωτεινών σηματοδοτών) λάμβαναν πληροφόρηση μέσω κατάλληλου τηλεπικοινωνιακού πρωτοκόλλου σχετικά με τις μελλοντικές μεταβολές των αντίστοιχων προγραμμάτων σηματοδότησης, ενώ λογισμικό εγκατεστημένο στον εξοπλισμό του ΔΟ αξιοποιούσε την παρεχόμενη πληροφόρηση προκειμένου να υπολογίσει και μεταβιβάσει στον οδηγό μέσω κατάλληλης απεικόνισης τις ενεργειακά αποδοτικές στρατηγικές οδήγησης (υπό τη μορφή συνιστώμενης ταχύτητας κίνησης) και τον υπολειπόμενο χρόνο της τρέχουσας φωτεινής ένδειξης. Παράλληλα, λειτουργούσε σύστημα επισκόπησης και καταγραφής της λειτουργίας της εφαρμογής περιβαλλοντικά φιλικής οδήγησης, μέσω του οποίου αποθηκεύονταν σε κατάλληλη βάση δεδομένων τα ακόλουθα λεπτομερή στοιχεία που χρησιμοποιήθηκαν στα πλαίσια της παρούσης διδακτορικής διατριβής:

- μοναδικός αριθμός κάθε διασυνδεδεμένου ταξί που λάμβανε πληροφόρηση σχετικά με ενεργειακά αποδοτικές στρατηγικές οδήγησης,
- χρονικές στιγμές κατά τις οποίες κάθε διασυνδεδεμένο ταξί λάμβανε πληροφόρηση,
- κωδικός προκαθορισμένης ζώνης στην οποία εισερχόταν κάθε διασυνδεδεμένο ταξί που λάμβανε οδηγίες σχετικά με περιβαλλοντικά φιλική οδήγηση,
- τύπος προτεινόμενης ενεργειακά αποδοτικής στρατηγικής οδήγησης (επιτάχυνση, επιβράδυνση, διατήρηση ταχύτητας),
- τιμή ενεργειακά αποδοτικής ταχύτητας κίνησης που παρέχονταν ως συμβουλή στον οδηγό μέσω κατάλληλης οθόνης απεικόνισης της σχετικής πληροφορίας,
- στιγμιαία ταχύτητα κίνησης του διασυνδεδεμένου ταξί,
- απόσταση του διασυνδεδεμένου ταξί από τον φωτεινό σηματοδότη,
- φάση του προγράμματος σηματοδότησης για την οποία πραγματοποιούνταν ο υπολογισμός της εκάστοτε ενεργειακά αποδοτικής στρατηγικής οδήγησης,
- υπολειπόμενη χρονική διάρκεια της τρέχουσας ένδειξης του φωτεινού σηματοδότη,
- τύπος ένδειξης του φωτεινού σηματοδότης (πράσινη ή κόκκινη).

Τα παραπάνω δεδομένα ανανεώνονταν και καταγράφονταν στη βάση δεδομένων κάθε 3 δευτερόλεπτα.

Η παρούσα διδακτορική διατριβή ανέπτυξε επίσης ένα μεθοδολογικό πλαίσιο για την αξιολόγηση των επιπτώσεων διαφορετικών τεχνολογιών περιβαλλοντικά φιλικής οδήγησης ανάντη φωτεινών σηματοδοτών, το οποίο βασίζεται στη χρήση εργαλείων μικροσκοπικής προσομοίωσης της κυκλοφορίας. Για τις ανάγκες του συγκεκριμένου ερευνητικού έργου, προσομοιώθηκε στο λογισμικό μικροσκοπικής προσομοίωσης της κυκλοφορίας Aimsun το δίκτυο της αστικής οδικής αρτηρίας επί της οποίας πραγματοποιήθηκε η πιλοτική εφαρμογή του συστήματος περιβαλλοντικά φιλικής οδήγησης συμβουλευτικού τύπου. Το μοντέλο μικροσκοπικής προσομοίωσης της κυκλοφορίας του παραπάνω δικτύου βαθμονομήθηκε σχολαστικά με τη χρήση κυκλοφοριακών μετρήσεων (κυκλοφορικοί φόρτοι και χρόνοι διαδρομής) και κατάλληλων στατιστικών ελέγχων προκειμένου να εξασφαλιστεί η ρεαλιστική αναπαράσταση των πραγματικών κυκλοφοριακών συνθηκών που επικρατούν επί της συγκεκριμένης οδικής αρτηρίας.

Για την προσομοίωση συστημάτων περιβαλλοντικά φιλικής οδήγησης στο Aimsun αναπτύχθηκε εξειδικευμένη Διεπαφή Προγραμματισμού Εφαρμογών (ΔΠΕ). Η ΔΠΕ δίνει τη δυνατότητα προσομοίωσης συστημάτων περιβαλλοντικά φιλικής οδήγησης ανάντη φωτεινών σηματοδοτών τόσο συμβουλευτικού όσο και αυτοματοποιημένου τύπου, ενώ επίσης διαθέτει μια απλοποιημένη και ευέλικτη δομή που επιτρέπει την εύκολη ενσωμάτωση μελλοντικών αλγόριθμων αντίστοιχων συστημάτων. Μέσω του σχεδιασμού και της υλοποίησης ενός εύχρηστου γραφικού περιβάλλοντος στα πλαίσια ανάπτυξης της ΔΠΕ, διευκολύνεται η παραμετροποίηση της λειτουργίας των συστημάτων περιβαλλοντικά φιλικής οδήγησης πριν την αξιολόγηση των αντίστοιχων πειραμάτων μικροσκοπικής προσομοίωσης της κυκλοφορίας. Συγκεκριμένα, δύναται να οριστούν:

- τα οδικά τμήματα επί των οποίων τα συστήματα περιβαλλοντικά φιλικής οδήγησης επηρεάζουν τη συμπεριφορά των ΔΟ,
- οι φάσεις των επιμέρους προγραμμάτων σηματοδότησης για τις οποίες πραγματοποιείται υπολογισμός ενεργειακά αποδοτικών στρατηγικών οδήγησης,
- τιμές παραμέτρων που σχετίζονται αποκλειστικά με τους αλγόριθμους υπολογισμού ενεργειακά αποδοτικών στρατηγικών οδήγησης,
- τύποι οχημάτων που θεωρούνται εξοπλισμένα με συστήματα περιβαλλοντικά φιλικής οδήγησης στα πλαίσια της προσομοίωσης,
- αριθμός στοχαστικών προσομοιώσεων για τις οποίες επαναληπτικά και αυτοματοποιημένα θα αξιολογούνται οι επιπτώσεις των συστημάτων περιβαλλοντικά φιλικής οδήγησης.

Κατά τη διάρκεια της προσομοίωσης, κάθε ΔΟ που εισέρχεται σε κάποιο οδικό τμήμα όπου έχει οριστεί ως ενεργό το σύστημα περιβαλλοντικά φιλικής οδήγησης λαμβάνει και υλοποιεί μέσω της ΔΠΕ μια ενεργειακά αποδοτική στρατηγική οδήγησης (υπό τη μορφή ενός διανύσματος ταχυτήτων) η οποία ενδέχεται να αναιρεθεί δυναμικά εφόσον η κίνηση του ΔΟ παρακωλυθεί από προπορευόμενο όχημα στην ίδια λωρίδα κυκλοφορίας. Όταν το ΔΟ εφαρμόσει πλήρως την ενεργειακά αποδοτική στρατηγική οδήγησης και διασχίσει την κατάντη σηματοδοτημένη διασταύρωση δίχως να σταματήσει, τότε η συμπεριφορά του υποδεικνύεται εν συνεχεία από τα μαθηματικά υποδείγματα του Aimsun.

Η αξιολόγηση των επιπτώσεων των συστημάτων περιβαλλοντικά φιλικής οδήγησης πραγματοποιήθηκε μέσω της κατάρτισης δύο υποομάδων πειραμάτων μικροσκοπικής προσομοίωσης. Η πρώτη υποομάδα πειραμάτων καταρτίστηκε με στόχο την αξιολόγηση των προτεινόμενων τροποποιήσεων στους αλγόριθμους περιβαλλοντικά φιλικής οδήγησης που αποσκοπούν στη βελτίωση της άνεσης του οδηγού κατά την εφαρμογή ενεργειακά αποδοτικών στρατηγικών οδήγησης αλλά και της ασφαλούς λειτουργίας των σχετικών συστημάτων. Η συγκεκριμένη υποομάδα πειραμάτων έλαβε υπόψη διαφορετικές κυκλοφοριακές συνθήκες (μη συμφορημένες, σχεδόν συμφορημένες, συμφορημένες) και πολλαπλά επίπεδα διείσδυσης της συγκεκριμένης τεχνολογίας στο σύνολο του στόλου οχημάτων. Η δεύτερη υποομάδα πειραμάτων σχεδιάστηκε με στόχο τη σύγκριση επιδόσεων ανάμεσα σε συστήματα περιβαλλοντικά φιλικής οδήγησης συμβουλευτικού και αυτοματοποιημένου τύπου, αλλά και κυκλοφοριακών ροών που απαρτίζονται αποκλειστικά από συμβατικά οχήματα που δεν έχουν δυνατότητες διασύνδεσης με τα στοιχεία της οδικής υποδομής. Η συγκεκριμένη υποομάδα πειραμάτων έλαβε υπόψη μη συμφορημένες κυκλοφοριακές συνθήκες και διαφορετικά επίπεδα διείσδυσης των διαφορετικών τεχνολογιών περιβαλλοντικά φιλικής οδήγησης στο σύνολο του στόλου οχημάτων.

Για την αξιολόγηση των επιπτώσεων των συστημάτων περιβαλλοντικά φιλικής οδήγησης έγινε ανάλυση των αποτελεσμάτων των πειραμάτων προσομοίωσης σε επίπεδο μεμονωμένων οχημάτων, οδικών τμημάτων αλλά και του συνόλου της αστικής οδικής αρτηρίας. Τα αποτελέσματα των προσομοιώσεων χρησιμοποιήθηκαν για τον υπολογισμό των παρακάτω δεικτών κυκλοφοριακής αποδοτικότητας, περιβαλλοντικών επιπτώσεων και οδικής ασφάλειας:

- σχέση ταχύτητας-διανυθείσας απόστασης μεμονωμένου οχήματος,
- σχέση ταχύτητας-επιτάχυνσης μεμονωμένου οχήματος,
- χρονοσειρά ταχύτητας μεμονωμένου οχήματος,
- σχέση εκπομπών διοξειδίου του άνθρακα-διανυθείσας απόστασης μεμονωμένου οχήματος,
- εκπομπές διοξειδίου του άνθρακα ανά διανυθέν χιλιόμετρο,
- αριθμός στάσεων ανά όχημα,
- μέσος χρόνος διαδρομής ανά οδικό τμήμα,
- μέσος χρόνος στάσης ανά διανυθέν χιλιόμερτο,
- μέση ταχύτητα δικτύου,
- αριθμός ενδεχόμενων συγκρούσεων ανά τύπο σύγκρουσης,
- υπολειπόμενος χρόνος έως την σύγκρουση δύο οχημάτων σε περίπτωση που οι τροχιές τους παραμείνουν αμετάβλητες,
- σχετική ταχύτητα οχημάτων εμπλεκόμενων σε δυνητική σύγκρουση.

Ο υπολογισμός των δεικτών κυκλοφοριακής απόδοσης πραγματοποιήθηκε με την χρήση του MS Excel, ενώ για την ανάλυση και απεικόνιση των χαρακτηριστικών των τροχιών κίνησης μεμονωμένων οχημάτων αναπτύχθηκε εξειδικευμένη διαδικτυακή εφαρμογή. Ο υπολογισμός των δεικτών που ποσοτικοποιούν τις επιπτώσεις των συστημάτων περιβαλλοντικά φιλικής οδήγησης στην οδική ασφάλεια πραγματοποιήθηκε με το Surrogate Safety Assessment Model (SSAM) το οποίο έχει τη δυνατότητα να συσχετίζει στατιστικώς με αξιοπιστία δυνητικές συγκρούσεις οχημάτων με πραγματικά δεδομένα ατυχημάτων. Αξίζει επίσης να σημειωθεί ότι το πολύπλευρο μεθοδολογικό πλαίσιο αξιολόγησης των επιπτώσεων των συστημάτων περιβαλλοντικά φιλικής οδήγησης ανάντη φωτεινών σηματοδοτών δύναται να προσαρμοστεί εύκολα στις ανάγκες μελλοντικών ερευνητικών δραστηριοτήτων μέσω της προσθήκης νέων εργαλείων ή την τροποποίηση των υφιστάμενων.

Η ανάλυση των αποτελεσμάτων της πρώτης υποομάδας πειραμάτων μικροσκοπικής προσομοίωσης της κυκλοφορίας κατέδειξαν ότι οι προσαρμογές στη δομή των υφιστάμενων μοντέλων περιβαλλοντικά φιλικής οδήγησης που αποσκοπούν στην βελτίωση της αποδοχής τους από τους χρήστες αλλά και στην βελτίωση της ασφαλούς λειτουργίας τους δεν επηρεάζουν αρνητικά την απόδοσή τους αναφορικά με τη μείωση της ενεργειακής κατανάλωσης και των εκπομπών αέριων ρύπων. Ειδικότερα, δύνανται να μειώσουν τις εκπομπές διοξειδίου του άνθρακα έως και 13% επί μεμονωμένων οδικών τμημάτων και 2.5% σε επίπεδο οδικής αρτηρίας, δίχως να επηρεάζουν αρνητικά του δείκτες κυκλοφοριακής αποδοτικότητας. Επίσης, αναγνωρίστηκε ότι τα οφέλη των συστημάτων περιβαλλοντικά φιλικής οδήγησης εξαρτώνται σε σημαντικό βαθμό από τους παρακάτω παράγοντες:

- γεωμετρικά χαρακτηριστικά της οδού,
- μήκος του οδικού τμήματος επί του οποίου είναι ενεργό το σύστημα,
- χαρακτηριστικά του προγράμματος σηματοδότησης,
- πλήθος κατάντη φωτεινών σηματοδοτών για τους οποίους υφίσταται συνεχής πληροφόρηση σχετικά με τον υπολειπόμενο χρόνο της τρέχουσας φωτεινής ένδειξης αλλά και την διάρκεια της επόμενης,
- επικρατούσες κυκλοφοριακές συνθήκες.

Αξιοσημείωτο εύρημα το οποίο δεν έχει αποτυπωθεί με σαφήνεια σε προηγούμενα ερευνητικά έργα, είναι και το γεγονός ότι τα συστήματα περιβαλλοντικά φιλικής οδήγησης μεταβάλλουν χαρακτηριστικά της κυκλοφοριακής ροής και σε περιοχές του οδικού δικτύου πέραν αυτών που εφαρμόζονται. Συνεπώς, το πλαίσιο υλοποίησης ενός συστήματος περιβαλλοντικά φιλικής οδήγησης ανάντη φωτεινών σηματοδοτών θα πρέπει να διερευνάται επαρκώς κατά περίπτωση και σε συνάρτηση με τους προαναφερθέντες παράγοντες, ώστε να διασφαλίζονται τα μέγιστα εφικτά περιβαλλοντικά και κυκλοφοριακά οφέλη.

Η ανάλυση των αποτελεσμάτων της δεύτερης υποομάδας πειραμάτων μικροσκοπικής προσομοίωσης της κυκλοφορίας κατέδειξε ότι το περιβαλλοντικό αποτύπωμα συνδεδεμένων οχημάτων που είναι εξοπλισμένα με συμβουλευτικού τύπου συστήματα περιβαλλοντικής οδήγησης είναι σημαντικά μικρότερο σε σχέση με μη συμβατικά οχήματα όταν το ποσοστό διείσδυσης στο στόλο των παραπάνω συστημάτων είναι υψηλό. Αντιθέτως, τα περιβαλλοντικά οφέλη των συστημάτων περιβαλλοντικά φιλικής οδήγησης συμβουλευτικού τύπου είναι μικρότερα των αντίστοιχων αυτοματοποιημένου τύπου, ενώ ο βαθμός προσαρμογής των οδηγών σε ενεργειακά αποδοτικές στρατηγικές οδήγησης εξαρτάται από τα γεωμετρικά και λειτουργικά χαρακτηριστικά του οδικού τμήματος όπου εφαρμόζεται το σύστημα περιβαλλοντικά φιλικής οδήγησης. Είναι επίσης αξιοσημείωτο, ότι σε οδικές αρτηρίες πολλαπλών λωρίδων η μεγιστοποίηση των περιβαλλοντικών και κυκλοφοριακών πλεονεκτημάτων των συστημάτων περιβαλλοντικής οδήγησης παρατηρείται όταν αυτά είναι αυτοματοποιημένου τύπου και η διείσδυσή τους στο στόλο είναι μέγιστη.

Τα ευρήματα της παρούσης διδακτορικής διατριβής αναφορικά με τον ανθρωποκεντρικό σχεδιασμό συστημάτων περιβαλλοντικά φιλικής οδήγησης, την ορθή εφαρμογή τους σε πραγματικές κυκλοφοριακές συνθήκες, καθώς και τις περιβαλλοντικές και κυκλοφοριακές τους επιπτώσεις είναι πολυσήμαντα για τις εταιρείες και τους φορείς που εμπλέκονται στο οδικό σύστημα μεταφορών. Η αυτοκινητοβιομηχανία και οι πάροχοι υπηρεσιών που σχετίζονται με τα Συνεργατικά Ευφυή Συστήματα Μεταφορών μπορούν να αναπτύξουν ενεργειακά αποδοτικές στρατηγικές οδήγησης που είναι φιλικότερες προς τον χρήστη και πιο ασφαλείς, δίχως να απομειώνονται οι θετικές επιπτώσεις τους στο περιβάλλον και στην κυκλοφορία. Οι φορείς διαχείρισης των οδικών δικτύων μπορούν να προβλέψουν τις επιπτώσεις διαφορετικών τεχνολογιών περιβαλλοντικά φιλικής οδήγησης ανάντη φωτεινών σηματοδοτών τόσο τοπικά όσο και σε επίπεδο συνολικού δικτύου, ενώ επίσης μπορούν να εξετάσουν το ενδεχόμενο υλοποίησης των παραπάνω τεχνολογιών σε διαφορετικά σημεία των οδικών δικτύων βάσει των γεωμετρικών και λειτουργικών χαρακτηριστικών τους, αλλά και των προγραμμάτων σηματοδότησης που ρυθμίζουν την κυκλοφορία σ’ αυτά. Επίσης, οι φορείς διαμόρφωσης πολιτικών σχετικά με τα Συνεργατικά Ευφυή Συστήματα Μεταφορών μπορούν να προωθήσουν την εφαρμογή συστημάτων περιβαλλοντικά φιλικής οδήγησης συμβουλευτικού τύπου ανάντη φωτεινών σηματοδοτών, καθώς βάσει εμπειρικών δεδομένων αποδεικνύεται ότι τα συγκεκριμένα συστήματα μπορούν να παρέχουν σημαντικά περιβαλλοντικά οφέλη υπό ευνοϊκές συνθήκες υλοποίησής τους στο πεδίο.

Σημαντική πτυχή της παρούσης διδακτορικής διατριβής αποτελεί και η αναγνώριση προοπτικών για πραγματοποίηση περαιτέρω έρευνας επί των συστημάτων περιβαλλοντικά φιλικής οδήγησης ανάντη φωτεινών σηματοδοτών. Ειδικότερα, οι τροποποιήσεις που προτάθηκαν για τη βελτίωση της άνεσης και ασφάλειας των ενεργειακά αποδοτικών στρατηγικών οδήγησης πραγματοποιούνται μεταγενέστερα του αρχικού υπολογισμού τους. Μελλοντικά, δύναται να ενσωματωθούν περιορισμοί άνεσης και οδικής ασφάλειας στα μοντέλα μαθηματικής βελτιστοποίησης τα οποία αναπτύσσονται για τον υπολογισμό ενεργειακά αποδοτικών στρατηγικών οδήγησης. Μέσω της παραπάνω προσέγγισης, δύναται να βελτιωθεί η αποδοτικότητα των παραπάνω στρατηγικών, αλλά και να επιταχυνθεί η διαδικασία υπολογισμού τους ώστε να εφαρμόζονται πιο αποτελεσματικά σε πραγματικό χρόνο και υπό ρεαλιστικές κυκλοφοριακές συνθήκες.

Επιπλέον, η συλλογή λεπτομερέστερων και περισσότερων εμπειρικών δεδομένων κατά την πιλοτική εφαρμογή συστημάτων περιβαλλοντικά φιλικής οδήγησης συμβουλευτικού τύπου θα δώσει τη δυνατότητα ανάπτυξης βελτιωμένων αντίστοιχων αλγόριθμων. Για παράδειγμα, η συλλογή κυκλοφοριακών δεδομένων κατά την πιλοτική εφαρμογή των παραπάνω συστημάτων θα επιτρέψει τη δημιουργία δένδρων αποφάσεων που εκτιμούν την προσαρμογή των οδηγών σε ενεργειακά αποδοτικές στρατηγικές οδήγησης σε συνάρτηση με τις επικρατούσες κυκλοφοριακές συνθήκες (μη συμφορημένες, σχεδόν συμφορημένες, συμφορημένες). Η συγκέντρωση πληροφορίας σχετικά με τη λωρίδα κίνησης των ΔΟ κατά την εφαρμογή ενεργειακά αποδοτικών στρατηγικών οδήγησης δύναται να αξιοποιηθεί προκειμένου ο βαθμός προσαρμογή των οδηγών να προβλέπεται σε επίπεδο λωρίδας. Η παραπάνω δυνατότητα θα είχε μεγάλη χρησιμότητα για οδικά τμήματα που εμπεριέχουν λωρίδες αποκλειστικής χρήσης από συγκεκριμένα οχήματα. Επίσης, θα μπορούσε μελλοντικά να προτυποποιηθεί μαθηματικά η μεταβολή του βαθμού προσαρμογής του οδηγού κατά την εκτέλεση μιας ενεργειακά αποδοτικής στρατηγικής οδήγησης σε συνάρτηση του χρόνου και της συμπεριφοράς του οδηγού κατά τα παρελθόντα βήματα εφαρμογής της άνωθεν στρατηγικής. Στην περίπτωση αυτή, ενδεχομένως να καταστεί εφικτή η προσομοίωση ενεργειακά αποδοτικών στρατηγικών οδήγησης που καταλήγουν να έχουν μεγαλύτερο περιβαλλοντικό αποτύπωμα από τη συμβατική οδήγηση ακόμα και σε περιπτώσεις που ο βαθμός προσαρμογής των οδηγών δε θα είναι ιδιαίτερα χαμηλός.

Προηγούμενα ερευνητικά έργα έχουν αποδείξει ότι η συνεργασία διασυνδεδεμένων και αυτοματοποιημένων οχημάτων (ΔΑΟ) μέσω διασύνδεσης οχήματος-οχήματος μπορεί να επαυξήσει σημαντικά τις επιδόσεις των συστημάτων περιβαλλοντικά φιλικής οδήγησης αυτοματοποιημένου τύπου σε μεικτές κυκλοφοριακές ροές. Τα υφιστάμενα ερευνητικά έργα επικεντρώνονται όμως στην συνεργασία των προαναφερθέντων οχημάτων σε επίπεδο διαμήκους κίνησης προκειμένου να μειώσουν την κατανάλωση ενέργειας και τις εκπομπές ρύπων. Η ενσωμάτωση δυνατοτήτων συνεργατικής αλλαγής λωρίδας σε προγράμματα μαθηματικής βελτιστοποίησης που αναπτύσσονται με στόχο την περιβαλλοντικά φιλική οδήγηση ανάντη φωτεινών σηματοδοτών μπορεί να μειώσει ακόμα περισσότερο το περιβαλλοντικό αποτύπωμα των ΔΑΟ. Τα δυνητικά περιβαλλοντικά οφέλη μπορεί να αυξηθούν έτι περαιτέρω μέσω της διασύνδεση οχήματος-υποδομής όπου η υποδομή δύναται να αναλάβει ένα κεντρικό ρόλο διευκόλυνσης των συνεργασιών μεταξύ ΔΑΟ ώστε να μεγιστοποιηθεί η μείωση της κατανάλωσης ενέργειας και εκπομπών ρύπων σε επίπεδο δικτύου.

Εν τέλει, συνίσταται η ανάπτυξη τεχνικών οδηγιών βάσει των οποίων θα δύναται να αποφασιστεί η υλοποίηση διαφορετικών τεχνολογιών περιβαλλοντικά φιλικής οδήγησης σε συνάρτηση με τις υπολογιστικές τους επιδόσεις, τα γεωμετρικά και λειτουργικά χαρακτηριστικά των οδών, τον τύπο και τη δομή των προγραμμάτων σηματοδότησης, καθώς και των επικρατουσών κυκλοφοριακών συνθηκών. Στην περίπτωση των συστημάτων περιβαλλοντικά φιλικής οδήγησης συμβουλευτικού τύπου τα παραπάνω στοιχεία δύναται να συνδυαστούν με τα χαρακτηριστικά του εκάστοτε οδηγού αλλά και τα δυναμικά χαρακτηριστικά του ΔΟ κατά την είσοδο σε ένα οδικό τμήμα όπου υποστηρίζεται η παραπάνω τεχνολογία, ώστε να αποφασιστεί η αξία ενημέρωσης ενός οδηγού σχετικά με τη δυνατότητα εκτέλεσης μιας ενεργειακά αποδοτικής στρατηγικής οδήγησης.

1 Introduction

1.1 Environmental Impacts of Road Traffic

Road traffic is currently one of the main contributors to energy consumption, climate change and atmospheric pollution. Road traffic in the US produces 59.6% of the total carbon monoxide (CO) emissions, 33.1% of the oxides of nitrogen (NO_x), and 26% of the volatile organic compounds (VOT) (Chen et al. 2014). In the International Energy Agency (IEA) countries road traffic accounts for the biggest share of total energy consumption in the transport sector (89%), while passenger cars and freight trucks rank highest (28%) among the top ten carbon dioxide (CO_2) emitting end uses (IEA 2020). Moreover, urban road traffic is responsible for 40% of CO_2 emissions and 70% of emissions of other pollutants (EC 2007).

Statistics indicate that demand for travel has significantly increased in the past 30 years (FHWA 2021). Due to continued population and economic growth, urban sprawl, road user centric mobility services, and periods of low fuel prices the latter trend is expected to further escalate (EPA 2021; Leard et al. 2016). Therefore, it is also expected that the total energy needs of surface transportation will be increasing constantly in the near future. Thus, the adoption of innovative policies, measures, and technologies for mitigating the adverse environmental impacts of road traffic constitutes key element for attaining long-term sustainability goals (EC 2019).

1.2 Mitigating the Environmental Imprint of Urban Road Traffic

A US driver wastes on the average 40 hrs annually in standstill traffic. The cost of fuel consumed during this time frame amounts to 78 billion dollars per year (Schrank et al. 2013). Policy makers strongly advocate for more fuel-efficient vehicles (encompassing broader use of alternative fuels) (CEC 2005) and comprehensive legislation relating to stricter emission performance standards for new passenger cars (EU Parliament 2009). Moreover, the Council of the EU has published directives with respect to limiting values of sulphur dioxide (SO_2), nitrogen dioxide (NO_2), NO_x and particulate matter (PM_{10}) (EU Council 1999). Nowadays, sustainable transportation programs place significant focus on strategies that minimize fuel consumption and gas emissions (especially CO_2 emissions) from motor vehicles.

Freeway traffic is free-flowing under light-to-moderate traffic conditions and experiences high delays during congestion (stop-and-go traffic) due to increased travel demand (which induces high traffic density along with the randomness of individual driver's behavior). On the contrary, arterial traffic can be subject to increased delays even during uncongested conditions due to the presence of intersections controlled by traffic signals. By definition an intersection is a distribution node of traffic flow in urban networks, and is also a bottleneck node of road capacity affecting mobility, safety and the environment.

Vehicles approaching signalized intersections frequently have to decelerate to a complete stop, idle till they receive green signal status, and subsequently accelerate to their desired speed. Thus, surface street traffic in the proximity of signalized intersections is subject to high delays. Moreover, several field studies identified a strong positive correlation between delay time at signalized intersections and vehicle fuel consumption and emissions (Saint Pierre & Ehrlich 2008; Myhrberg 2008). Therefore, vehicles that stop at traffic signals are also subject to wasted fuel and increased emissions.

It has been estimated that 22% of all wasted fuel is caused by inefficient deceleration and/or lack of anticipation (Vreeswijk et al. 2010). The relationship between fuel consumption/emissions and vehicle speed has been thoroughly studied at a microscopic level and a comprehensive review has been presented in (Barth and Boriboonsomsin 2009). Vehicles traveling at low speeds exhibit a high fuel/distance value, since they travel for longer time periods. At high speeds, vehicles require excessive engine tractive force to overcome aerodynamic resistance, thus producing higher emissions. It was estimated that fuel consumption and emissions are minimized around 60 km/h depending on the vehicle type. Therefore, it is best for vehicles to travel at a steady-state velocity around these mid-range speeds, in order to minimize fuel consumption and emissions.

Prior to the development of communication capabilities between connected vehicles (CVs) and the infrastructure, innovations in vehicles' powertrain (Bandivadekar et al. 2008), infrastructure, road geometry design and traffic signal operation (Bazzan 2005; Li et al. 2004; Midenet et al. 2004; Yin et al. 2007) enhanced fuel efficiency by more than 83% over the past 35 years. Moreover, the introduction of Intelligent Transportation Systems (ITS) in the surface transportation sector in the mid-1990s provided new capabilities to mitigate the adverse traffic, energy and environmental impacts of vehicular traffic (Khondaker and Kattan 2015b; Papageorgiou and Kotsialos 2002).

When vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication was rendered technologically feasible researchers focused on the development of CV technologies to further enhance traffic safety and efficiency. Initially developed speed advice systems provided speed advice to equipped vehicles according to external conditions (weather, traffic, road grade, etc.) in order to promote safety (Spyropoulou & Karlaftis 2008). Currently, connected vehicle applications can utilize the signal phase and timing (SPaT) message for the estimation of energy optimal speed advice.

1.2.1 Advancements on the Vehicle Side

The automobile industry is constantly investing on the production of more energy efficient and environmentally friendly vehicles (Johnson 2015). The efficiency of drive train (use of lighter and stronger materials without compromising safety characteristics) and power train of modern vehicles has increased significantly. These advancements improved the average passenger car fuel efficiency from 18.4 l/100km in 1975 to 10.1 l/100km in 2005 (Bandivadekar et al. 2008). Moreover, new technologies were introduced such as hybrid and fuel-cell vehicles. Concurrently, the list of available in market vehicles that utilize carbon-neutral alternative fuels is gradually growing. Regardless of the technological advancements on the vehicle-side, drivers can also save fuel and reduce emissions from their vehicles via proper maintenance. Normal maintenance practices are tire pressure checks, regular air filters replacements, removal of excess weight from the vehicle, performance of periodic engine tune-ups and use of manufacturer-recommended oil.

1.2.2 Advancements on the Infrastructure Side

Significant advancements have also taken place on the infrastructure-side. Past studies identified increased vehicle energy waste, emissions, and delays incurred due to inefficient traffic signal control plans (Coelho et al. 2005; Unal et al. 2003). Therefore, research activities focused on the development of advanced signal timing plans (Li et al. 2004), actuated signal control systems (Midenet et al. 2004), adaptive signal control (Yin et al. 2007), and coordination of traffic signals (Bazaan 2005). Few researchers focused on the development of advanced signal timing plans that seek to minimize explicitly motor vehicle fuel consumption and gas emissions (Nishuichi & Yoshii

2005; Stevanovic et al. 2009), while others formulated mathematical programs for the optimization of signal time design that concurrently minimized fuel consumption, emissions and delays (Li et al. 2004).

However, the annual maintenance and update of advanced traffic signal control systems is a significant expenditure. It was estimated that in the US only, the update of traffic signal plans costs annually 217 million dollars. Some studies proposed that the substitution of conventional traffic lights with intelligent ones in fully connected and automated road environments could address the aforementioned limitation (Dresner & Stone 2008). In this case fully connected and automated vehicles (CAVs) approaching an intersection equipped with intelligent lights will request in advance the reservation of a time-space slot in order to pass safely the intersection without stopping (Vanmiddlesworth et al. 2008; Zohdy & Rakha 2016).

1.2.3 Intelligent Transportation Systems (ITS)

The deployment of ITS renders traffic management more robust and as a result improves traffic operations significantly. Increased traffic efficiency yields substantial fuel consumption and gas emissions savings. It was identified that ITS technologies which homogenize and smooth traffic flow can generate profound energy and environmental benefits. Thus, the EU has incorporated ITS deployment in its strategic planning, in order to accomplish the goal set in the White Paper for a 60% reduction of CO_2 emissions in the 1990-2050 period (EC 2011).

Initial ITS technologies encompassed Advanced Traffic Management Systems (ATMS) and Advanced Traveler Information Systems (ATIS). Example ATMS applications for uninterrupted traffic flow facilities that increase energy efficiency of vehicular traffic are ramp metering and variable speed limits (VSL). In the US, ITS technology was introduced in the surface transportation sector through the Federal Highway Administration (FHWA) ITS Program that began in the mid-1990s (Rakha et al. 2012). During the ITS Program, the US road infrastructure was equipped with sensors that monitored prevailing traffic conditions and provided congestion information to drivers so as to assist them with route-guidance. However, interest was soon shifted towards communications and vehicle connectivity due to the rapid evolution of telematics.

1.2.4 Connected Vehicle (CV) Technologies

Advancements in the field of digital technologies have enabled the development and deployment of CV applications which utilize vehicle-to-everything (V2X) communications (exchange of real-time information: a) between road-side infrastructure and vehicles, and b) among vehicles) to provide smart advice to CVs for the realization of mobility, safety and environmental benefits (Grace et al. 2012; Lu et al. 2018b; Monteil et al. 2011; Rakha et al. 2012; Zeng et al. 2012). Development of CV technologies is growing constantly, and several research works have been conducted to date in order to enhance their operation and evaluate their efficiency **Table 1.1**.

The SAFESPOT cooperative system harnessed both infrastructure and vehicles as sources and destinations of safety-related information (Brignolo et al. 2006). The Cooperative Intersection Collision Avoidance system placed focus on the use of the SPaT message for improving intersection safety (Sengupta et al. 2007). The EU-co-funded Cooperative Vehicle-Infrastructure system (CVIS) allowed vehicles to communicate – and cooperate – directly with each other and with the roadside infrastructure through a unified technical solution that utilized a variety of media and exhibited enhanced localization (Koenders & Vreeswijk 2008). The CO-OPerative SystEms for Intelligent Road Safety innovation activity (COOPERS) placed emphasis on the reduction of the self-opening gap of the development of telematics applications between car industry and infrastructure operators (Frotscher & Schneider 2008). BMW and Volkswagen developed a wide range of traffic safety related cooperative applications within the context of the German project AKTIV (Giebel et al. 2008).

The sim^{TD} project focused on the technical implementation of a hybrid communication system, based on the well-known WLAN standard, to facilitate the testing of the effectiveness of car-to-x (C2X) functions (Stübing et al. 2010). The European research project eCoMove used V2V and V2I communication to develop and integrate three strategies that provide efficient route choice, improved driving performance and robust traffic management and control, with an aim of reducing total fuel consumption by 20% (Vreeswijk et al. 2010). Within the context of the German project "Cooperative and Optimized Traffic Signal Control in Urban Networks" (KOLINE), V2I data were used in addition to ordinary loop detector traffic data for the optimization of the adaptive traffic signal control systems signalization (Niebel et al. 2012). During the EU co-funded Compass4D project three Cooperative-ITS (C-ITS) services (Energy Efficient Intersection, Road Hazard

Warning, and Red Light Violation Warning) were piloted for one year in seven EU cities (Mitsakis et al. 2014). The Local4Global Mobility Tool combines the number of petrol litters filled in the vehicle's fuel tank with data of the GPS-navigator and information regarding the current weather conditions in order to provide speed profiling commands to drivers that assist them in significantly reducing fuel consumption and travel time (Michailidis et al. 2015).

In the US, the Vehicle Infrastructure Integration (VII) Program was initiated by the US Department of Transportation (DOT) in 2005 to develop standardized wireless V2V and V2I communications (Andrews & Cops 2009). The VII Program, which was a joint government-industry effort, tested a 5.9GHz-based VII Proof-of-Concept (POC) in a real-world uncontrolled environment in Detroit, Michigan. The VII Program managed to demonstrate the technical feasibility and functionality of the VII architecture, and the effective implementation of safety, mobility and commercial applications. This initial initiative evolved subsequently into the CV Program which became part of the USDOT's 2010-2014 ITS Strategic Plan (Grace et al. 2012). The USDOT's future plans with respect to CVs focus on the adoption and eventual deployment of CV systems based on the 2015-2019 ITS Strategic Plan (Barbaresso et al. 2014). USDOT will place attention on research activities pertaining to the development of V2V communications based on dedicated short-range communications (DSRC) technology and other CV technologies and communications that are enabled by either DSRC or other networks, such as cellular, Wi-Fi, or satellite.

CV technologies have been also widely adopted for increasing energy efficiency and diminishing greenhouse gas (GHG) emissions via eco-routing (Djavadian et al. 2020; J. Wang et al. 2019) and eco-driving assistance on highways (Barth & Boriboonsomsin 2009; Shen et al. 2018), rolling terrains (Hu et al. 2016), transit routes (Xu et al. 2017) and signalized traffic (Chen et al. 2014; Kamalanathsharma et al. 2015). Previous research has identified that inefficient vehicle acceleration/deceleration, stop-and-go events, queuing time in idle mode and lack of driver anticipation can incur significant vehicle delay, fuel consumption and exhaust emissions at signalized intersections (Adamidis et al. 2020; Li et al. 2011; Pandian et al. 2009). Thus, the provision of dynamic eco-driving advice (robust and real-time speed and/or countdown advice) to CVs in the proximity of signalized intersections with the use of I2V communication has shown notable potential for achieving energy savings and GHG emissions reduction by preventing CVs from unnecessarily cruising/accelerating while approaching a signalized intersection and suddenly breaking just upstream of the stop line (Barth et al. 2011; Mitsakis et al. 2014; Rakha &

Kamalanathsharma 2011) and has received significant attention from funding agencies, vehicle manufacturers, road authorities, technology providers, and the research community.

Table 1.1. Research projects in the field of CV technologies and applications

Project Name	Duration	Location	Application	Outputs
C-MobILE (Accelerating C-ITS Mobility Innovation and depLoyment in Europe) (Lu et al. 2018b)	2017 – 2020	EU	Safety, Traffic and Energy Efficiency	Fully integrated C-ITS technologies in real-world conditions
InterCor (Interoperable Corridors) (Lu et al. 2018a)	2016 - 2019	EU	Connectivity, Energy Efficiency	A Test Bed for beyond Day-One C-ITS services development and deployment
2015-2019 ITS Strategic Plan (Barbaresso et al. 2014)	2015 – 2019	USA	Safety, Mobility and Commercial	Research activities pertaining to the development of V2V communications
Connected Vehicle Pilot Deployment Program (ITS JPO 2019)	2014 – 2020	USA	Connectivity, Safety, Traffic and Energy Efficiency	Integrate CV research concepts enhancing existing operational capabilities
Local4Global (Kosmatopoulos et al. 2015)	2013 – 2016	EU	Traffic and Energy Efficiency	Speed profiling commands for fuel consumption and travel time savings.
Compass4D (Mitsakis et al. 2014)	2013 – 2015	EU	Safety, Energy Efficiency	Energy Efficient Intersection (EEI), Road Hazard Warning (RHW), and Red Light Violation Warning (RLW) Applications
Transportation for Livability by Integrating Vehicles and the Environment (TranLIVE) (Rakha et al. 2016; Tang et al. 2016)	2012 – 2016	USA	Energy Efficiency	Integration of real-time data and advanced transportation applications to minimize environmental impacts; Development of modeling, simulation, and visualization tools to assess energy, environmental, and emission impacts
DRIVE C2X (Stahlmann et al. 2011)	2011 – 2014	EU	Safety	Assessment of cooperative Systems through FOTs.

Table 1.1. (*Continued*)

Project Name	Duration	Location	Application	Outputs
Connected Vehicle Program (2010-2014 ITS Strategic Plan) (Grace et al. 2012)	2010 – 2014	USA	Safety, Mobility and Commercial	More than three dozen connected vehicle applications concepts through prototyping and demonstration.
eCoMove (Cooperative Mobility Systems and Services for Energy Efficiency) (Vreeswijk et al. 2010)	2010 – 2014	EU	Traffic and Energy Efficiency	Strategies that provide efficient route choice, improved driving performance and robust traffic management and control.
Applications for the Environment: Real-Time Information Synthesis (AERIS) Program (Rakha et al. 2012)	2009 – 2014	USA	Energy Efficiency	Models for the analysis of the environmental impacts of CV applications; Prototype development of CV applications.
Cooperative and Optimized Traffic Signal Control in Urban Networks (KOLINE) (Saust et al. 2010)	2009 – 2012	DE	Traffic Monitoring	V2I and loop detector data for the optimization of the adaptive traffic signal control systems signalization.
Safe and Intelligent Mobility (sim^{TD}) (Stübing et al. 2010)	2008 – 2014	DE	Safety, Traffic Efficiency, Integrated Value-Added Services	Technical implementation of a hybrid communication system, based on the well-known WLAN standard.
PRE-DRIVE C2X (Bechler et al. 2009)	2008 – 2014	EU	Connectivity	Common European C2X communication system.
SAFESPOT (Vivo 2007)	2006 – 2010	EU	Safety	V2X safety-related information.
Cooperative Intersection Collision Avoidance Systems (CICAS) (Misener 2010)	2006 – 2010	USA	Safety	SPaT message for improving intersection safety.

Table 1.1. (*Continued*)

Project Name	Duration	Location	Application	Outputs
Cooperative Vehicle-Infrastructure Systems (CVIS) (Toulminet et al. 2008)	2006 – 2010	EU	Connectivity	V2X in a continuous and transparent way using a variety of media and with enhanced localization.
CO-OPerative SystEms for Intelligent Road Safety (COOPERS) (Toulminet et al. 2008)	2006 – 2010	EU	Safety	Reduction of the gap in the development of telematics applications between car industry and infrastructure operators.
Adaptive and Cooperative Technologies for Intelligent Transport (AKTIV) (Giebel et al. 2008)	2006 – 2010	DE	Safety	Wide range of traffic safety related cooperative applications.
Vehicle Infrastructure Integration (VII) (Opiola 2006)	2005 – 2008	USA	Safety, Mobility and Commercial	Technical feasibility and functionality of the VII architecture, and the effective implementation of safety, mobility and commercial applications.

1.3 Research Scope and Objectives

Increased demand for road trips is expected to have significant implications for energy consumption and emissions in the upcoming decades. On the other hand, the evolution of CV technology, such as dynamic eco-driving systems, provides an opportunity for achieving sustainability goals and ameliorating the adverse environmental impacts of vehicular traffic. Specifically, the standardization of C-ITS messages and the development of V2I communication equipment enables the adoption of environmental friendly driving via dedicated real-time advice on interrupted traffic flow facilities.

In the past decade, several models were introduced for achieving dynamic eco-driving in the proximity of signalized intersections. Although the latter models assumed different methodologies and optimization objectives for enhancing energy efficiency, the vast majority of them were developed on the premise that CVs are equipped with automated driving functions that can accurately execute the advised energy efficient driving strategies (automated dynamic eco-driving systems). However, the transition towards a fully connected and automated road environment is expected to endure for several decades prior to fruition. Thus, there will be a significant period of time when several drivers will still have to enact upon provision of advice form the CV side or supervise lower-level vehicle automation functions that will be commissioned with the task of adopting the latter advice.

Hence, it becomes evident that human factors shall exert significant influence on the efficiency of dynamic eco-driving systems that are advisory (driver has to adopt energy efficient driving strategy) in the near future. This dissertation focuses on the human aspects of advisory dynamic eco-driving and aims to provide methodologies and tools that:

- enhance comfort and safety of dynamic eco-driving advice,
- identify factors that influence driver adaptation to dynamic eco-driving advice,
- model and predict driver adaptation to dynamic eco-driving advice as a function of the most influential factors identified in the previous step,
- incorporate dynamic eco-driving algorithms in microscopic traffic simulation software,
- conduct microscopic traffic simulation analysis to compare advisory and automated dynamic eco-driving for different penetration rates and traffic demand levels,

- process and analyze microscopic traffic simulation results to estimate traffic efficiency, safety and environmental indicators.

Specifically, this dissertation proposes new elements in the design of existing dynamic eco-driving models that are expected to bolster efficient adaptation to speed advice and evaluates their impacts on emissions and mobility. Secondly, it uses data from the deployment of an advisory dynamic eco-driving system on public roads to identify factors that affect driver's adaptation to speed advice and develop a decision tree (DT) model that can predict driver's adaptation to speed advice as a function of the latter factors. The DT model is subsequently integrated in the microscopic traffic simulator AIMSUN to assess the environmental, traffic efficiency and safety impacts of advisory dynamic eco-driving and compare its performance with automated dynamic eco-driving and manual driving.

To this end, the objectives of the specific dissertation are:

- to provide insights about human-centered design of dynamic eco-driving systems to automakers and C-ITS service providers,
- inform road authorities and operators about the expected impacts of different dynamic eco-driving systems on the environment, traffic operations and safety
- advocate the benefits and point out the limitations of different dynamic eco-driving technologies to policy makers,
- facilitate further research on the addressed topic via the set-up of a generic framework for evaluating the impacts of human factors on dynamic eco-driving and the provision of relevant and appropriate software and tools (in open-source format).

Finally, it is important to emphasize that the research scope of this dissertation explicitly encompasses dynamic eco-driving models that are tailored for internal combustion engine (ICE) vehicles.

1.4 Research Methodology

To accomplish the aforementioned objectives this dissertation adopts a multi-step methodological approach which is illustrated in **Figure 1.1** and presented in detail below:

A) A comprehensive literature review is conducted that considers multiple aspects of state-of-the-art research in the field of dynamic eco-driving for interrupted traffic flow facilities. Existing dynamic eco-driving models are analyzed in terms of their conceptual design and optimization objectives. Relevant impact assessment frameworks encompassing both simulation studies and field experiments are elaborately described, while emphasis is also placed on a limited number of research efforts that examine human factors in the context of dynamic eco-driving near signalized intersections. Finally, an overview of the limitations of existing dynamic eco-driving models is provided, which serves for the identification of knowledge gaps in the domain and the set-up of the objectives and research hypotheses of this dissertation.

B) Theoretical model formulations are introduced for incorporating human factors in advisory dynamic eco-driving models. Enhancements to the control logic of existing dynamic eco-driving models are proposed that account for driver's comfort and safety. Feature selection strategies are recommended for identifying factors that affect driver's adaptation to speed advice in the proximity of signalized intersections. Additionally, DT models are adopted for predicting driver's adaptation to speed advice according to vehicle behavior, road geometry and traffic control characteristics.

C) A microscopic traffic simulation framework is set-up for the investigation of the environmental, traffic efficiency and safety impacts of advisory dynamic eco-driving. The framework encompasses the microscopic traffic simulation software Aimsun, an Aimsun Application Programming Interface (API) that mimics the behavior of CVs equipped with dynamic eco-driving systems, an emissions models that quantifies environmental impacts, a Surrogate Safety Assessment Model (SSAM) that estimates safety proxies for safety assessment, and a web-based application that analyses vehicle trajectories generated via Aimsun. A simulation network of an actual urban arterial corridor is built and calibrated against real-world traffic counts in Aimsun. Finally, a comprehensive simulation experiment including several simulation scenarios with varying penetration rates of different dynamic eco-driving technologies is devised and conducted.

D) The pilot operation of an advisory dynamic eco-driving model along an urban arterial corridor is described. Information is provided with respect to the functional and physical architectures of the deployed dynamic eco-driving system, as well as about the algorithm that determines its operation. The management and performance of the pilot operation is presented along with technical details of the data collection process. Moreover, a description of the collected dataset that feeds the development of the DT model is given.

E) The DT model that dictates driver adaptation to speed advice in the vicinity of signalized intersections based on vehicle behavior, road geometry and traffic control characteristics is presented. Subsequently, a thorough simulative assessment of advisory and automated dynamic eco-driving models is conducted that considers environmental, traffic efficiency and safety key performance indicators (KPIs). The assessment encompasses analysis of individual vehicle behavior throughout dynamic eco-driving episodes, local impacts along specific dynamic eco-driving service zones, as well as impacts on the network scale. Eventually, assumptions and limitations of the current dissertation are discussed based on the dissertation's findings and outlooks are highlighted for future research in the field of dynamic eco-driving on urban roads.

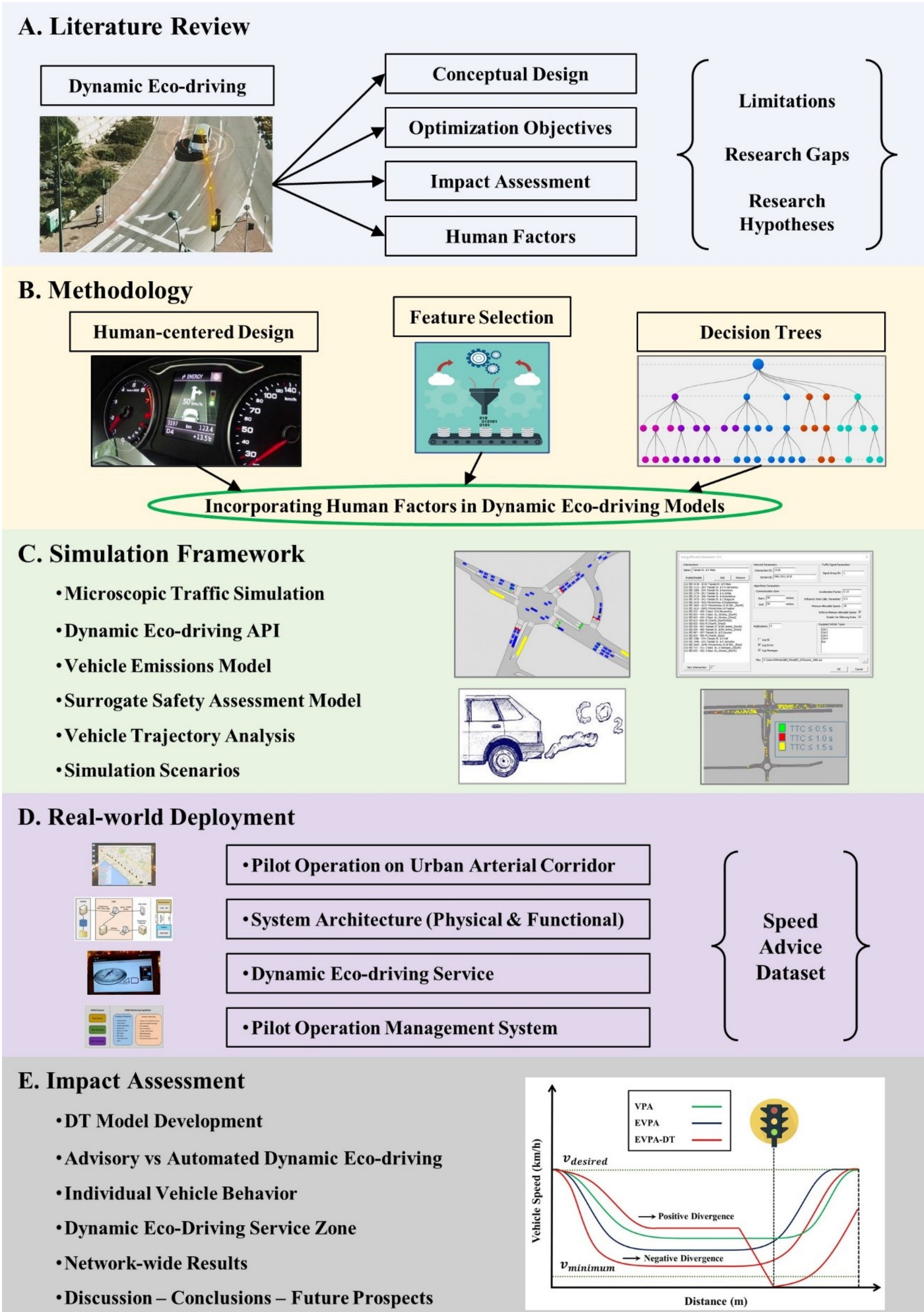


Figure 1.1. Outline of the dissertation's methodological approach

1.5 Structure of the Dissertation

An outline of the dissertation's structure is given below:

1. Chapter 2 provides a comprehensive state-of-the-art review on the core elements of dynamic eco-driving models and the impact assessment methods used to evaluate their performance.
2. Chapter 3 deals with the introduction of human factors in the modelling of dynamic eco-driving near signalized intersections and proposes a generic simulation framework for evaluating the performance of different dynamic eco-driving systems.
3. Chapter 4 describes the pilot operation of a dynamic eco-driving service along an urban arterial corridor and the relevant data used for model development in the context of this dissertation.
4. Chapter 5 presents a DT model developed for emulating driver adaptation to speed advice and a simulative analysis of the performance of different dynamic eco-driving systems.
5. Chapter 6 summarizes the findings of this dissertation and illuminates future pathways for research in the field of advisory dynamic eco-driving.
6. Appendix A provides information on an API developed for emulating dynamic eco-driving in a microscopic traffic simulator.
7. Appendix B presents a web-based application developed for the analysis of vehicle trajectories generated from microscopic traffic simulation software.

Finally, a list of related publications is provided at the end of the text.

2 State-of-the-Art Review

Among the prevailing modern strategies to achieve energy savings and ameliorate the negative environmental impacts of vehicular traffic is eco-driving. Eco-driving, constitutes a set of rules that promote energy efficiency by operating the vehicle engine at the most fuel-efficient points. Several eco-driving training programs were previously developed to establish eco-friendly driving traits (Barkenbus 2010; Zarkadoula et al. 2007), while recently, the advent of CV technology has empowered the development of dynamic eco-driving applications (offering real-time eco-driving advice to drivers) for both interrupted and uninterrupted traffic flow facilities.

Examples for uninterrupted traffic flow facilities include: a) Intelligent Speed Adaptation (ISA) systems (Servin et al. 2006; Várhelyi & Mäkinen 2001), b) cooperative variable speed limits applications (Grumert et al. 2015; Khondaker & Kattan 2015a), c) speed advisory systems in the proximity of work zones (Ramezani & Benekohal 2015), or d) at the emergence of phantom traffic jams (Suijs et al. 2015), as well as e) speed harmonization (Ma et al. 2016) and f) dynamic eco-driving systems (Barth & Boriboonsomsin 2009).

For the case of interrupted traffic flow facilities, dynamic eco-driving applications have recently attracted significant attention (Chen et al. 2015; Hao et al. 2015a; Jiang et al. 2017; Kamalanathsharma & Rakha 2016; Xia et al. 2013b). This is mainly due to advancements in the infrastructure-to-vehicle (I2V) communication technologies and the standardization of the SPaT message, which provides a consistent manner to communicate signal status changes for C-ITS applications (ETSI 2009; SAE International 2016). Research in dynamic eco-driving near signalized intersections is progressing rapidly and producing a variety of conceptual and methodological frameworks, application objectives and models to evaluate energy savings. These advancements necessitate the analysis of existing literature to enhance the understanding of research aspects, the applicability of services and their impacts to the road transport system.

A few scholars have already reviewed literature relevant to eco-driving. Policy and technology issues pertaining to eco-driving were discussed by (Alam & McNabola 2014), while the major factors affecting eco-driving were identified in (Huang et al. 2018). The energy implications of eco-driving in a connected and automated road environment were also highlighted in a number of recent studies (Guanetti et al. 2018; Taiebat et al. 2018; Vahidi & Sciarretta 2018; Wadud et al.

2016). However, the latter studies mainly emphasize on the generic principles of eco-driving and focus less on its technology and modelling related aspects. Moreover, none of the aforementioned studies reviews dynamic eco-driving in the proximity of signalized intersections in a rigorous and explicit manner although the topic is partially addressed in (Vahidi & Sciarretta 2018).

The latter gap in literature is addressed by this research, which focuses on the different aspects (conceptual, methodological, evaluation, technology, human-related) of dynamic eco-driving in the proximity of signalized intersections. To this end, a structured approach is adopted to analyze literature through the following steps: a) identify the elements of dynamic eco-driving models designed for signalized intersections and analyze literature accordingly, and b) present and evaluate the corresponding impact assessment frameworks. Dedicated attention is given to human factors and field experiments of dynamic eco-driving, which are aspects that have not been comprehensively covered by existing reviews. Finally, this dissertation provides research pathways for further enhancements of speed advice services developed for signalized intersections.

2.1 Elements of Dynamic Eco-Driving Models

The dynamic eco-driving models are analyzed according to (**Figure 2.1**): a) the elements that specify the conceptual and methodological framework of the system, and b) the impact assessment framework of the system, which can be analytical, simulated or based on real time data.

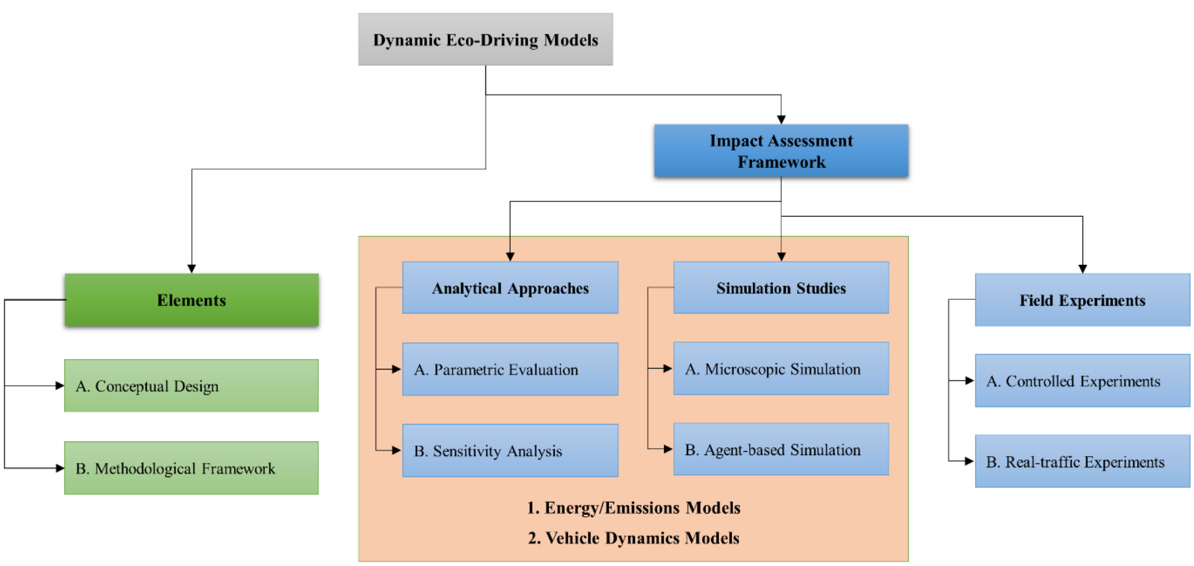


Figure 2.1. Structured approach for the state-of-the-art review of dynamic eco-driving models

A variety of different algorithms and services for dynamic eco driving can be traced in literature (**Table 2.1**). Existing dynamic eco-driving models vary in terms of conceptual design (problem statement, parameters used etc.), the formulation of the problem solution (mathematical formulation, interacting modules, input space etc.) and the energy and traffic models, which translate the eco-driving service to energy and vehicle dynamics (Mintsis et al. 2020). Through this prism, the existing literature is summarized in relation to the following features:

- specification of the input space,
- proposed methodological aspects (optimization objectives),
- fuel consumption models,
- vehicle dynamics models,
- analysis boundary (service zone of the dynamic eco-driving system), and
- traffic signal control strategy.

Furthermore, dynamic eco-driving models can be classified based on the recipient of the energy-efficient speed advice. In the case of personalized advice (**Figure 2.2**), the system objective is to generate energy and emission savings explicitly for a single vehicle. Thus, the impacts of personalized advice to the fuel efficiency of surrounding traffic are not considered. On the contrary, platoon-based speed recommendation (**Figure 2.2**) ensures that a fuel-optimal driving strategy is provided to a group of vehicles approaching a signalized intersection. In this case, the probability of adversely affecting the fuel efficiency of surrounding vehicles diminishes.

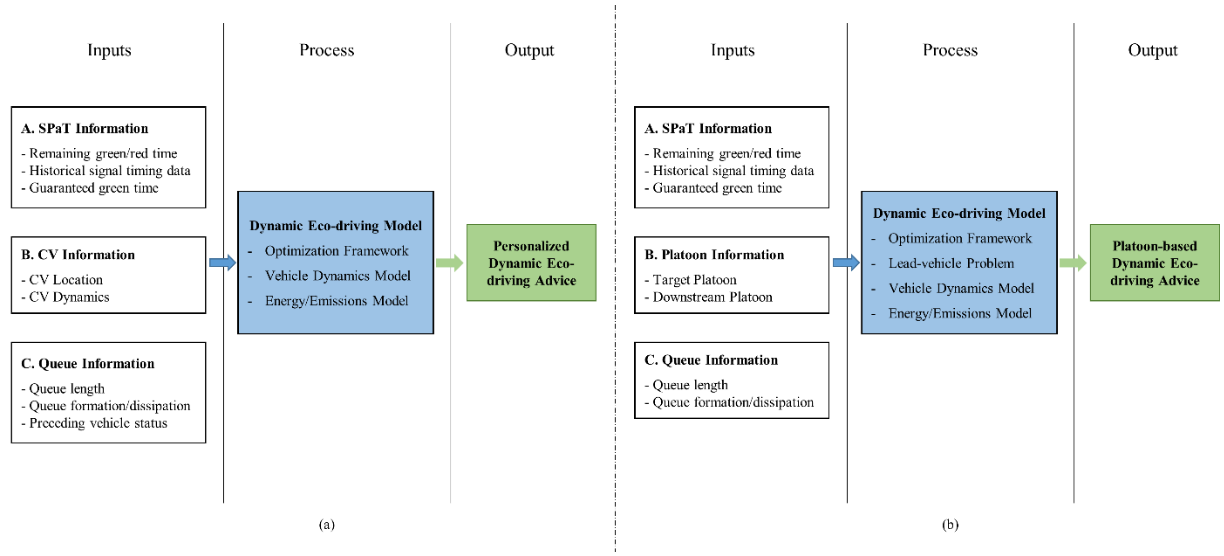


Figure 2.2. Interacting elements of dynamic eco-driving models: (a) personalized advice; and (b) platoon-based advice

2.1.1 Conceptual Design

Few dynamic eco-driving models explicitly accounted for single vehicle information (dynamic status and location) and SPaT information to estimate energy-efficient speed advice in the vicinity of isolated and pre-timed controlled signalized intersections (Li et al. 2009; Mandava et al. 2009; Wan et al. 2016; Xia et al. 2013a; Yao & Li 2020). A dynamic eco-driving system for signalized corridors that encompasses an arterial velocity planning algorithm which estimates energy-efficient (de)acceleration profiles based on remaining green/red time and distance between the vehicle and the intersection was developed by (Barth et al. 2011). Although the aforementioned models considered similar inputs for the estimation of fuel-optimal speed profiles, they used different methodologies to process these inputs. Moreover, they assumed that the space between the equipped vehicle and the signalized intersection is unoccupied, thus disregarding the impact of surrounding traffic.

Lead vehicle status and queue length at stop line were also incorporated in the mathematical formulations of dynamic eco-driving models to enhance the accuracy, feasibility and fuel-efficiency of speed advice tailored for single vehicles under denser traffic conditions (He et al. 2015; Kamalanathsharma & Rakha 2016; Xia et al. 2013b; Yang et al. 2017). The predictive cruise control (PCC) model provided energy-efficient (de)acceleration strategies, while, concurrently minimizing travel time under both free-flow and stop-and-go traffic (Asadi & Vahidi 2011), and the predictive driver assistance system was based on SPaT information, vehicle location and dynamics, and queue length information for the estimation and provision of energy-optimal advice to drivers (Schuricht et al. 2011). (Rakha et al. 2012) introduced a dynamic eco-driving model that initially estimates a suggested arrival time to the signalized intersection according to queue length information, presence of preceding vehicles and the SPaT message, and subsequently calculates a fuel-optimal driving strategy based on the previously estimated suggested arrival time to intersection, the vehicle (de)acceleration model, and roadway characteristics. (Xia et al. 2013b) incorporated an intersection delay term to the velocity planning algorithm previously developed by (Barth et al. 2011) to capture the effects of preceding vehicles on energy and emissions savings. (Chen et al. 2014) developed a dynamic eco-driving model that estimates fuel-efficient vehicle trajectories by using SPaT and queue discharge information. Furthermore, (He et al. 2015) integrated spatial and temporal constraints from traffic light queues into the formulation of an optimal control problem that estimates fuel-efficient speed advisory for CVs approaching signalized intersections.

Early dynamic eco-driving models were designed based on the assumption that the signal control plan of the equipped signalized intersection is pre-timed, and that real-time accurate acquisition of future SPaT information is always feasible and guaranteed (Barth et al. 2011; Kamalanathsharma & Rakha 2016; Mandava et al. 2009; Rakha et al. 2012; Raubitschek et al. 2011; Wan et al. 2016; Xia et al. 2013a). However, vehicular traffic is controlled by actuated and/or coordinated or adaptive traffic signal control plans at several signalized intersections and the acquisition of precise future SPaT information is a difficult task due to timing drift in pre-timed traffic signals, and fluctuating traffic conditions for actuated and adaptive lights. In these cases, the retrieval and use of accurate future SPaT information from signal controllers becomes a demanding task and, thus, may be restricted to only the red phase in actuated conditions (Vreeswijk et al. 2010).

However, few researchers developed and simulated methodologies that facilitate the implementation of dynamic eco-driving services for actuated or adaptive traffic lights (Bodenheimer et al. 2014; Hao et al. 2015a; Hao et al. 2018; Mahler & Vahidi 2012; Mousa et al. 2019; Sun et al. 2018; Weber & Winckler 2013; Xin et al. 2019). (Mahler & Vahidi 2012) utilized probabilistic signal timing information based on real-time phase data, and historically averaged timing data per signal status, while (Weber & Winckler 2013) worked with the guaranteed green and the green band for the determination of the possible green window that the CV could arrive at the intersection in the case of coordinated and actuated control. Moreover, (Hao et al. 2015a) also developed an Eco-Approach and Departure (EAD) application for actuated signals, while (Bodenheimer et al. 2014) enabled Green Light Optimized Speed Advisory (GLOSA) for adaptive traffic lights by using empirical signal and detector data. Stochastic dynamic programming techniques were adopted by (Typaldos et al. 2020a; Typaldos et al. 2021) to estimate in real time fuel-efficient velocity profiles for CVs when traffic signals operate in adaptive mode. Precise knowledge of future SPaT information is still difficult due to technological barriers and the dynamic operation of actuated coordinated and adaptive traffic signals, thus rendering dynamic eco-driving challenging for most traffic signals in the real world. However, it is expected that connected and automated driving (CAD) technology will provide new opportunities in terms of accurate prediction of future signal status for actuated, coordinated and adaptive traffic lights.

Interest in the field of dynamic eco-driving in the proximity of signalized intersections has been also oriented towards the estimation of energy and traffic efficient speed advice for platoons of vehicles (Chen et al. 2015; Stebbins et al. 2017; Wang et al. 2018; Wu et al. 2019; Zhou et al. 2017). Platoon-based energy-efficient speed control of vehicles in the proximity of signalized intersections has been considered both for mixed and fully connected and automated road traffic environments based on the following approaches. Either by explicitly identifying the optimal leaders, controlling platoon length (joining/splitting), and naturally allowing platoons to form upstream of the traffic signal (Chen et al. 2015; Stebbins et al. 2017), or by additionally enabling V2V communication based cooperative car-following CAVs to bolster platoon progression (Han et al. 2020; Jin et al. 2013; Liu & Kamel 2016; Ma et al. 2021; Wang et al. 2017; Z. Wang et al. 2019; Yang et al. 2021; Zhao et al. 2018).

(Chen et al. 2015) proposed a platoon-based speed control algorithm for eco-driving at signalized intersections, which accounts for the signal timing information, the dynamic traffic characteristics of the target platoon, as well as for the influence of the downstream platoon to estimate an optimal (de)acceleration profile for the target platoon. (Stebbins et al. 2017) adapted a GLOSA system to provide multiple acceleration advices to a CAV, irrespective of the initial conditions (remaining red time, activation zone and initial speed) based on a time looping technique to solve the lead-vehicle problem (Daganzo 2006). Finally, (Zhou et al. 2017) developed a parsimonious shooting heuristic algorithm that can estimate safe, traffic efficient and energy-efficient trajectories for a platoon of CAVs along a signalized highway taking into consideration boundary conditions, vehicle powertrain capabilities, safety constrains, and remaining red/green time to plan the vehicle trajectories. It is to note that, although dynamic eco-driving for CAV platoons has gained lesser attention so far, early evidence indicates that it provides the ground for a substantial enhancement of the energy and emission saving potentials of existing dynamic eco-driving models.

Additionally, research attention has been placed on the development of dynamic eco-driving models that utilize SPaT information from multiple signalized intersections to provide fuel efficient speed advice along signalized corridors (Asadi & Vahidi 2011; Lin et al. 2021; Liu et al. 2019; Yang et al. 2020). Other implementations have integrated CAV lane changing and overtaking capabilities in the estimation of energy-efficient speed advice along signalized corridors (Guo et al. 2021; Hu et al. 2021; Wang et al. 2017). Moreover, deceleration strategies received greater interest, since they provide higher energy savings potential, while some researchers considered the recommendation of acceleration as safety critical (Raubitschek et al. 2011). Very promising results with respect to environmental benefits at interrupted traffic flow facilities have been also identified from the joint optimization of traffic signal control and dynamic eco-driving advice (Du et al. 2021; Erdmann 2013; Liang et al. 2019; Soleimaniamiri et al. 2020; Xu et al. 2019; Yu et al. 2018).

2.1.2 Methodological Framework: Eco-driving as an Optimization Problem

Dynamic eco-driving systems mainly use mathematical programming methods to estimate energy and/or traffic optimal (de)acceleration speed profiles. Existing dynamic eco-driving models vary significantly in terms of their optimization objectives (**Table 2.1**). The formulated optimization problems of many dynamic eco-driving models minimize vehicle tractive force, vehicle (de)acceleration and/or idling time (Barth et al. 2011; Chen et al. 2015; Hao et al. 2015a; Mahler & Vahidi 2012; Mandava et al. 2009; Xia et al. 2013b). The rationale behind idling time minimization is based on the strong correlation between stop events at traffic lights and increased fuel consumption and emissions.

(Mandava et al. 2009) developed a power-constrained algorithm that minimizes the (de)acceleration rate of the equipped vehicle during the transition from the vehicle's current speed to a target speed that will allow it to pass the downstream signalized intersection on green signal status without stopping. Barth's velocity planning algorithm minimizes fuel consumption and emissions by minimizing idling time and total tractive force demanded for the complete vehicle maneuver. Concurrently, the optimal velocity must be lower than a maximum speed threshold, and ride comfort constraints should be met (Barth et al. 2011). (Mahler & Vahidi 2012) formulated an optimization problem that minimized total trip time and acceleration, thus disengaging the estimation of fuel-optimum speed from the vehicle's dynamic models and propulsion system. Finally, (Chen et al. 2015) formulated an optimization problem that minimized the target platoon's idling time by optimizing the (de)acceleration rate during the eco-driving maneuver.

Interestingly, literature emphasizes that those algorithms that focus on optimization of the standstill time could be more energy-efficient compared to those that attempt to reduce the deceleration time under specific circumstances (Raubitschek et al. 2011). Thus, researchers incorporated explicit fuel consumption models in the objective functions of the speed advice optimal controllers to ensure energy and emissions benefits under any conditions (He et al. 2015; Rakha et al. 2012).

Recent dynamic eco-driving models value energy efficiency and mobility concurrently by integrating mobility components into their optimal controllers. These models can estimate optimal speed profiles both in terms of energy and traffic efficiency. A variety of different optimization frameworks have been proposed in literature. Some prominent examples include model predictive control (MPC) approaches based on trip time and kinetic energy loss (Asadi & Vahidi 2011), fuel-optimal speed profiles estimation based on a linear combination of traffic efficiency and emissions (Chen et al. 2014), and optimal controllers based on the formation of tight and fast-moving platoons prior to the optimization of fuel efficiency (Jiang et al. 2017). In some research efforts, optimization frameworks that also encompassed safety constraints for the estimation of safe, energy and traffic efficient trajectories of vehicle streams near signalized intersections were proposed (Hao et al. 2015a; Ma et al. 2017; Stebbins et al. 2017; Zhou et al. 2017). Recently, artificial intelligence has been also used for estimating and providing dynamic eco-driving advice in the proximity of signalized intersections (Mousa et al. 2018; Yang et al. 2019).

Table 2.1. Characteristics of existing dynamic eco-driving models

Author(s)	Dynamic Eco-driving Model	Inputs	Methodology	Optimization Objectives	Fuel Consumption Model	Vehicle Dynamics Models	Analysis Boundary	Traffic Signal Control
Ma et al. (2021)	Eco-CACC	- SPaT Message - Vehicle Status - Preceding Vehicle Status	Dynamic Programming	- Electricity Consumption	Dynamic Battery Model	- Non-linear Deceleration - Non-linear Acceleration	Upstream of Traffic Signal	Pre-timed
Yang et al. (2021)	Cooperative Driving Framework	- SPaT Message - Vehicle Status - Preceding Vehicle Status - Queue information -Signal Parameters	Integrated Optimization	- Idle Time - Tractive Force - Delay - Cycle Offset	MOVES	Trigonometric Acceleration	Upstream of Traffic Signal	Coordinated Actuated
Han et al. (2020)	PTO-GFC	- SPaT Message - Vehicle Status - Preceding Vehicle Status	Mixed Integer Non-linear Program	- Fuel Consumption	Akcelik Model & VT-Micro	- Constant Deceleration - Constant Acceleration	Upstream of Traffic Signal	Pre-timed
Yao & Li (2020)	Decentralized Model for CAV Trajectory Optimization	- SPaT Message - Vehicle Status - Preceding Vehicle Status	Mathematical Optimization	- Travel Time - Fuel Consumption - Inverse Time-to-collision	VT-Micro	- Non-linear Deceleration - Non-linear Acceleration	Upstream of Traffic Signal	Pre-timed
Wang et al. (2019)	CED	- SPaT Message - Vehicle Status - Preceding Vehicle Status	Analytical Model	- Idle Time - Tractive Force	MOVES	Trigonometric Acceleration	Upstream & Downstream of Traffic Signal	Pre-timed
Wang et al. (2018)	Cluster-Wise Cooperative EAD	- SPaT Message - Vehicle Status - Preceding Vehicle Status	Analytical Model	- Idle Time - Tractive Force	MOVES	Trigonometric Acceleration	Upstream & Downstream of Traffic Signal	Pre-timed

Table 2.1. (*Continued*)

Author(s)	Dynamic Eco-driving Model	Inputs	Methodology	Optimization Objectives	Fuel Consumption Model	Vehicle Dynamics Models	Analysis Boundary	Traffic Signal Control
Jiang et al. (2017)	Dynamic Eco-driving under Partially Connected and Automated Vehicles Environment	- SPaT message - Vehicle Status - Preceding Vehicle Status - Loop Detector Data	Optimal Controller (Pontryagin Minimum Principle)	- Mobility - Fuel Consumption	Akcelik Model & VT-Micro	-	Upstream & Downstream of Traffic Signal	Pre-timed
Kamalanathsharma & Rakha (2016)	ECACC	- SPaT message - Vehicle Status - Preceding Vehicle Status - Queue information	Dynamic Programming (modified A-star pathfinding algorithm)	- Fuel Consumption	VT-CPFM-1	- Constant Deceleration - Rakha & Lucic Acceleration	Upstream & Downstream of Traffic Signal	Pre-timed
Wang et al. (2016)	Speed Guidance Model	- Full SPaT information - Vehicle Status - Environmental Characteristics of Intersection Surrounding	One-engine Simulation Architecture	-	Shi Model	Constant Acceleration	Upstream of Traffic Signal	Pre-timed
Hao et al. (2015a)	EAD	- SPaT message - Vehicle Status - Preceding Vehicle Status	Analytical Model	- Idle Time - Tractive Force	MOVES	Trigonometric Acceleration	Upstream & Downstream of Traffic Signal	Actuated
Chen et al. (2015)	Platoon-Based Dynamic Eco-driving	- SPaT message - Vehicle Status - Preceding Vehicle Status	Analytical Model	-	VT-micro	- Constant Deceleration - Constant Acceleration	Upstream of Traffic Signal	Pre-timed
Xiang et al. (2015)	CAEHV-C	- Full SPaT information - Vehicle Status	Mathematical Optimization	- Idle Time - Tractive Force	Power-based Quasi-Static Model	Trigonometric Acceleration	Upstream & Downstream of Traffic Signal	Pre-timed

Table 2.1. (*Continued*)

Author(s)	Dynamic Eco-driving Model	Inputs	Methodology	Optimization Objectives	Fuel Consumption Model	Vehicle Dynamics Models	Analysis Boundary	Traffic Signal Control
He et al. (2015)	-	- Full SPaT information - Vehicle Status - Queue information	Multi-stage Optimal Control Problem (Approximation Method)	- Fuel Consumption	Biggs & Akcelik Model	Constant Acceleration	Upstream & Downstream of Traffic Signal	Pre-timed
Chen et al. (2014)	-	- Full SPaT information - Vehicle Status - Queue information	Mathematical Optimization (Genetic Algorithm)	- Emissions (NO_x) - Travel Time	Motor Vehicle Emissions Simulator	- Constant Deceleration - Nonlinear Acceleration	Upstream & Downstream of Traffic Signal	Pre-timed
Xia et al. (2013b)	Dynamic Eco-Driving for Connected Vehicles	- Full SPaT information - Vehicle Status - Preceding Vehicle Status	Mathematical Optimization	- Idle Time - Tractive Force	CMEM	Trigonometric Acceleration	Upstream & Downstream of Traffic Signal	Pre-timed
Weber & Wrinclker (2013)	Dynamic Eco-Driving	- Full SPaT information - Vehicle Status	Mathematical Optimization	- Idle Time - Tractive Force	-	Trigonometric Acceleration	Upstream & Downstream of Traffic Signal	- Pre-timed - Actuated & Coordinated
Mahler & Vahidi (2012)	Predictive Optimal Velocity Planning Algorithm	- Probabilistic SPaT information - Vehicle Status - Queue information	Deterministic Dynamic Programming	- Acceleration & Deceleration Rate - Travel Time	AUTONOMIE (v1210)	-	-	Any Type
Rakha et al. (2012)	-	- Full SPaT information - Vehicle Status - Preceding Vehicle Status - Queue information	Mathematical Optimization	- Fuel Consumption	VT-CPFM-1	- Constant Deceleration - Rakha & Lucic Acceleration	Upstream & Downstream of Traffic Signal	Pre-timed

Table 2.1. (*Continued*)

Author(s)	Dynamic Eco-driving Model	Inputs	Methodology	Optimization Objectives	Fuel Consumption Model	Vehicle Dynamics Models	Analysis Boundary	Traffic Signal Control
Schuricht et al. (2011)	Predictive Driver Assistance	- Full SPaT information - Vehicle Status - Queue information	-	-	Akcelik Statistical Emissions Model	-	-	Pre-timed
Raubitschek et al. (2011)	Predictive Driving Strategy	- Full SPaT information - Vehicle Status	-	-	Dymola	-	Upstream & Downstream of Traffic Signal	Pre-timed
Barth et al. (2011)	Dynamic Eco-Driving	- Full SPaT information - Vehicle Status	Mathematical Optimization	- Idle Time - Tractive Force	CMEM	Trigonometric Acceleration	Upstream & Downstream of Traffic Signal	Pre-timed
Asadi & Vahidi (2011)	PCC	- Full SPaT information - Vehicle Status	Model Predictive Control (MPC)	- Kinetic Energy - Travel Time	Powertrain System Analysis Toolkit (PSAT)	-	-	Pre-timed
Vreeswijk et al. (2010)	-	- Full SPaT information - Vehicle Status	-	- Tractive Force (only during red phase)	EnViVer	-	-	Pre-timed
Saust et al. (2010)	-	- V2I data - V2V data - Queue information	-	-	Empirical Formula (function of work on wheels)	-	-	Pre-timed
Mandava et al. (2009)	Arterial Velocity Planning Algorithm	- Full SPaT information - Vehicle Status	Mathematical Optimization	- Acceleration Rate	CMEM	Constant Acceleration	-	Pre-timed
Li et al. (2009)	ADAS	- Full SPaT information - Travel time to stop line.	-	-	CMEM	-	Upstream & Downstream of Traffic Signal	Pre-timed

2.2 Impact Assessment Framework

The operation and performance of dynamic eco-driving models has been evaluated through:

8. analytical methodologies (Chen et al. 2014; Chen et al. 2015; Hao et al. 2015a; Li et al. 2009; Ma et al. 2017; Rakha et al. 2012),
9. microscopic traffic simulation tools (Asadi & Vahidi 2011; Barth et al. 2011; He et al. 2015; Jiang et al. 2017; Kamalanathsharma et al. 2015; Kamalanathsharma & Rakha 2016; Mandava et al. 2009; Raubitschek et al. 2011; Schuricht et al. 2011; Tielert et al. 2010; Vreeswijk et al. 2010; Xia et al. 2013a; Xia et al. 2013b), and
10. field experiments (controlled and real-traffic) (Almannaa et al. 2017; Hao et al. 2015b; Hao et al. 2018; He et al. 2015; Mahler & Vahidi 2012; Mintsis et al. 2017; Muñoz-Organero & Magaña 2013; Rakha et al. 2016; Raubitschek et al. 2011; Saust et al. 2010; Stahlmann et al. 2017; Weber & Winckler 2013; Xia et al. 2012).

The analysis boundary in most studies encompassed both the road section upstream of the signalized intersection and the downstream one where energy and emission benefits from deceleration strategies are realized. **Table 2.2** depicts the selected evaluation methodology per dynamic eco-driving model and the corresponding energy and traffic impacts. Since energy and vehicle dynamics models markedly affect the fuel efficiency and emissions computations conducted in numerical and simulation studies, we firstly present a relevant discussion regarding their use in impact assessment frameworks of dynamic eco-driving models. Subsequently, a thorough description of each evaluation methodology and an overview of the reported results are provided.

2.2.1 Energy and Traffic Models

Assessing the efficiency of dynamic eco-driving strategies and services has been for long a serious consideration. Several integral parts need to be developed to effectively replicate the behavior of both the service, the user who receives the information from the service, and the system that interacts with the user and the service. To this end, literature has pointed towards two integral modules that are critical to the assessment of dynamic eco-driving services:

- the fuel consumption and emission model, which is not only integrated to the optimization function, but needs to be determined to assess the energy impacts of the service to the system, and
- the vehicle dynamics models, or else the models that should be introduced to accurately replicate the behavior of vehicles under the effect of dynamic eco-driving services.

The latter modules are usually integrated in an impact assessment framework dedicated to enable the estimation of the effects of dynamic eco-driving on traffic and environment. The literature on the fuel consumption and emission models, as well as the vehicle dynamics models are analyzed in the following sections.

2.2.1.1 Fuel Consumption and Emissions Models

The use of fuel consumption and emissions models within the context of dynamic eco-driving is twofold. Fuel consumption or emissions models were explicitly integrated in the optimization function of dynamic eco-driving models (He et al. 2015; Rakha et al. 2012), or they were used after the estimation of the energy-efficient speed profile to quantify energy savings (Barth et al. 2011; Hao et al. 2015a; Li et al. 2009; Mandava et al. 2009; Xia et al. 2013a; Xia et al. 2013b). For those models encompassing a fuel consumption model in their objective function, energy efficiency computations were performed seamlessly and concurrently with the solution of the optimal problem, while for the rest detailed speed trajectories extracted from simulation tools were fed to the fuel consumption and emissions models.

According to dynamic eco-driving literature, black-box fuel consumption models were primarily used to evaluate the energy savings of dynamic eco-driving applications. These are data-driven mathematical models that do not capture physical processes and are divided in three categories according to their inputs: a) engine-based, b) vehicle-based, and c) mode-based. They are considered suitable for evaluating the energy implications of eco-driving applications due to their simplicity and accuracy in real-time estimation of fuel consumption (Zhou et al. 2016). Research findings based on the Comprehensive Modal Emissions Model (CMEM) (vehicle-based black box fuel consumption model) indicated that sharp decelerations to target speed and full throttle accelerations to desired speed (bang-bang control) maximized energy efficiency (Barth et al. 2011; Li et al. 2009; Mandava et al. 2009; Xia et al. 2013a). However, this finding contradicted typical eco-driving behavior and actual measurements. Non-linear power-based or instantaneous speed and acceleration fuel consumption models (vehicle-based black box models) prevented the development of bang-bang control systems and predicted valid and accurate energy and emissions benefits (Chen et al. 2014; Chen et al. 2015; He et al. 2015; Jiang et al. 2017; Rakha et al. 2012; Schuricht et al. 2011). Simplified fuel consumption approaches that utilized the square of-acceleration term were also proven to be highly efficient for accurately solving the fuel minimization problem of CV trajectories in the proximity of signalized intersections (Typaldos et al. 2020b).

2.2.1.2 Vehicle Dynamics Models

Researchers used different vehicle dynamics models to describe the equipped vehicle's transition from current to target speed upstream of the signalized intersection and its return to desired speed on the downstream link. Constant acceleration, linear acceleration, constant-throttle and non-linear acceleration models were adopted. (Mandava et al. 2009) assumed a constant (de)acceleration rate during the aforementioned transition. A study developed trigonometric functions to replicate the increase/decrease of an equipped vehicle speed profile in order to account for ride comfort (Barth et al. 2011). (Chen et al. 2015) considered constant (de)acceleration rates for the transition of the target platoon from the initial (activation zone entry speed) to the target speed and back to the desired speed after crossing the signalized intersection.

However, with respect to acceleration strategies actual vehicle dynamic constraints should be considered in the sense that motor vehicles can accelerate more at lower than at higher speeds. This research direction was followed by (Rakha et al. 2012) who used a constant deceleration model and the Rakha and Lucic acceleration model (Rakha et al. 2004), which is non-linear, for the estimation of fuel-optimal maneuvers. Likewise, (Chen et al. 2014) used a constant deceleration model to estimate the upstream maneuver of the eco-driving vehicle, while a non-uniform acceleration model was used for the downstream maneuver since acceleration decreases with increasing vehicle speed.

Fuel consumption and emissions are significantly impacted from the vehicle dynamics models that are used to describe the vehicle maneuver from current to target speed and subsequently to desired speed downstream of the signalized intersection (Rakha & Ahn 2004). Therefore, it is critical that the vehicle dynamics models that are used for the development and evaluation of dynamic eco-driving models account for actual vehicle capabilities with respect to braking and throttling (Rajamani 2011).

2.2.2 Analytical Methodologies

A summary of the studies that used numerical examples to demonstrate the benefits of dynamic eco-driving near signalized intersections is presented below. A parametric evaluation of an Advanced Driving Alert System (ADAS) developed by (Li et al. 2009) was conducted for different values of green/red ratio, initial conditions (signal timing information, vehicle status and location), activation zone length, and vehicle type, which showed energy and emissions savings on the order of 12 – 14%. (Rakha et al. 2012) focused on the analysis of deceleration strategies, when a CV must reduce speed to arrive at the downstream signalized intersection during the upcoming green window. A sensitivity analysis conducted to test the performance of the model for different initial conditions, vehicle types and signal timing plans indicated savings up to 30% compared to the average fuel consumption.

(Chen et al. 2014) conducted a sensitivity analysis to measure the impacts of their proposed dynamic eco-driving model on emissions and travel time for different values of: a) the distance of the equipped vehicle from the end of the queue when the driver decides to decelerate, b) the time required from the onset of green signal till the last vehicle in the queue begins to accelerate, and c) the weights of the emissions and travel time. The analysis showed that the eco-driving strategy reduces emissions and travel time both for minimization of emissions and minimization of travel time.

A numerical evaluation of the EAD algorithm was conducted for different signal control plans and vehicle approach speeds in (Hao et al. 2015a). Results indicated that fuel and emission savings range between 11% – 30% for low vehicle approach speed (<50 km/h), and 3.3% – 6.2% for vehicle approach speed close to the speed limit (65 km/h). Numerical examples were also used to demonstrate the energy savings generated by a dynamic eco-driving model that estimates fuel-optimal trajectories near signalized intersections taking into consideration queue length information (He et al. 2015).

Furthermore, (Chen et al. 2015) examined the performance of a platoon-based speed control algorithm both for fully obedient platoons and mixed platoons. The parametric analysis results showed that the speed control algorithm produced energy savings compared to conventional driving under any conditions (time to red, time spent by downstream platoon to clear the intersection, driving behavior under eco-driving status). Finally, a numerical study indicated that optimizing vehicle trajectories along a signalized highway section assuming a fully connected and automated road environment can yield fuel savings ranging between 30% – 65% for specific traffic signal cycle lengths, highway section lengths, and saturation flow rates (Ma et al. 2017).

2.2.3 Simulation Studies

Simulation tools, such as microscopic traffic (Casas et al. 2010; Fellendorf & Vortisch 2010; Sykes 2010), or agent-based simulation models (Abar et al. 2017; Kamalanathsharma et al. 2015; Kamalanathsharma & Rakha 2016) have been systematically used for the evaluation of dynamic eco-driving in the vicinity of signalized intersections. The impacts of dynamic eco-driving models as reported by simulative assessment studies are shown in **Table 2.2**.

Tested simulation networks have been either selected to be simplified with hypothetical demand scenarios (Asadi & Vahidi 2011; Barth et al. 2011; He et al. 2015; Jiang et al. 2017; Mandava et al. 2009; Schuricht et al. 2011; Tielert et al. 2010; Xia et al. 2013a; Xia et al. 2013b), or represented actual road networks and were calibrated against field traffic measurements (Kamalanathsharma et al. 2015; Tielert et al. 2010; Vreeswijk et al. 2010). Simulation experiments were run for:

- different network types (urban, suburban, and rural environments) (Asadi & Vahidi 2011; Barth et al. 2011; Kamalanathsharma et al. 2015; Tielert et al. 2010; Vreeswijk et al. 2010),
- network configurations (single lane intersection approach, multi-lane intersection approach, multi-lane arterial corridor) (Asadi & Vahidi 2011; Jiang et al. 2017; Kamalanathsharma et al. 2015; Mandava et al. 2009; Stebbins et al. 2017; Tielert et al. 2010; Xia et al. 2013a; Xia et al. 2013b),
- single vehicle (He et al. 2015) or multi vehicle (Asadi & Vahidi 2011; Tielert et al. 2010; Wang et al. 2019) scenarios
- traffic conditions (under-saturated, saturated, and over-saturated) (Barth et al. 2011; Jiang et al. 2017; Kamalanathsharma et al. 2015; Stebbins et al. 2017; Xia et al. 2013a; Xia et al. 2013b),

- market penetration rates of the dynamic eco-driving technologies (Kamalanathsharma et al. 2015; Xia et al. 2013a; Xia et al. 2013b),
- traffic signal cycle lengths (Barth et al. 2011; Raubitschek et al. 2011; Xia et al. 2013a),
- activation zone lengths (Barth et al. 2011; Mandava et al. 2009; Raubitschek et al. 2011; Tielert et al. 2010; Xia et al. 2013b),
- vehicle status and location information at activation distance (Kamalanathsharma & Rakha 2016; Schuricht et al. 2011), and
- vehicle types (Kamalanathsharma & Rakha 2016; Mandava et al. 2009).

Moreover, different models have been used for assessing the fuel consumption and emissions produced by traffic under the effect of speed advice algorithms in a simulation environment. (Mandava et al. 2009) used the CMEM emissions model (Barth et al. 2000) in a stochastic simulation environment for the quantification of the energy and emissions benefits. (Vreeswijk et al. 2010) applied the statistical emissions model EnViVer (Smit et al. 2007) and (Tielert et al. 2010) the Passenger Car and Heavy Duty Emission Model (PHEM) (Hausberger et al. 2011) in VISSIM simulation environment. (Asadi & Vahidi 2011) used the Powertrain System Analysis Toolkit (PSAT) in SIMULINK for the estimation of the fuel economy of vehicles. (Barth et al. 2011; Xia et al. 2013a) used the microscopic traffic simulation software PARAMICS and CMEM modal emissions model for fuel consumption and emissions quantification. (Raubitschek et al. 2011) integrated the Dymola v5.3 model within MATLAB to estimate fuel consumption, while (Schuricht et al. 2011) conducted experiments using the Intelligent-Driver Model (IDM) to assess the fuel savings potential of a predictive driver assistance system. (Kamalanathsharma & Rakha 2014, Kamalanathsharma et al. 2015) run agent-based simulations in a MATLAB test-bed to test the network-wide impacts of vehicle eco-speed control, and, later, incorporated the Eco-Cooperative Adaptive Cruise Control (ECACC) model into the INTEGRATION microscopic traffic simulation software to conduct network-wide traffic simulation experiments.

Evidence from simulation experiments shows that in single-lane simulation scenarios speed advice benefits levelled off over a market penetration rate of 40 – 50% (Barth et al. 2011; Xia et al. 2013a). On the contrary, in multi-lane scenarios where lane-changing activity of conventional vehicles degrades the performance of the dynamic eco-driving service it was proven that higher market penetration rates (up to 100%) yield higher savings (Xia et al. 2013a). Initial dynamic eco-driving models provided significant benefits only under light or medium demand levels (Barth et al. 2011; Mandava et al. 2009; Xia et al. 2013a). However, when queue discharge information was incorporated in the logic of more advanced dynamic eco-driving models and mobility components were added in their objective functions, energy, emissions and travel time savings were realized under congested traffic conditions as well (Hao et al. 2015a; Jiang et al. 2017; Kamalanathsharma et al. 2015; Kamalanathsharma & Rakha 2016; Xia et al. 2013b).

Furthermore, several simulation studies identified that fuel savings were higher for higher vehicle's approach speed, since the flexibility for changes to a vehicle's trajectory increases at higher speeds (Kamalanathsharma et al. 2015; Kamalanathsharma & Rakha 2014). Findings also demonstrate that higher vehicle offset times reduce fuel savings, since equipped vehicles have to maintain a lower average speed upstream of the traffic lights, and subsequently accelerate to their desired speed from a lower speed on the downstream section (Kamalanathsharma & Rakha 2016, Kamalanathsharma & Rakha 2014; Raubitschek et al. 2011; Schuricht et al. 2011). Moreover, there exists evidence that speed advisory models underperform when the service activation distance is short as there is limited space for equipped vehicles to modify their trajectories accordingly (Kamalanathsharma & Rakha 2016, Kamalanathsharma & Rakha 2014; Xia et al. 2013b).

Overall, energy and emissions savings ranging between 2% – 70% and travel time savings ranging between 2% – 68% were reported in the literature regarding the impacts of dynamic eco-driving on travel efficiency, energy efficiency and the environment (**Table 2.2**). However, it is practically infeasible to directly compare the reported savings from different models because they were developed based on different constraints, assumptions, vehicle and fuel consumption models, as well as initial conditions (vehicle speed, vehicle location, traffic signal plan) (**Table 2.1**).

2.2.4 Human Factors in Simulation Studies

The efficient operation of CVs is profoundly related to the behavioral adaptation of the driver to the information assistance system (Sharma et al. 2018). If drivers fail to comply with the provided advice, behavioral adaptation is not possible and the benefits of the system diminish. Thus, driver's compliance to the system, which depends on personal traits, cognitive and psychomotor functions, situational factors, acceptance and trust, is a very critical factor for realizing benefits from CV applications when the latter are manually driven. However, the influence of driver's compliance on the performance of dynamic eco-driving systems is a topic that has gained limited attention. Moreover, limited focus has been placed on data-driven approaches for simulative assessment of human factors affecting dynamic eco-driving in the vicinity of signalized intersections.

(Xiang et al. 2015) proposed a speed advisory model that could enhance driver's adaptability to dynamic eco-driving advice and provide more fuel savings compared to its naive counterpart (without consideration of driver's behavior). Nonetheless, the latter model accounted for generic driver behavioral traits, its development was not based on field data, and was not evaluated in real world conditions. (Butakov & Ioannou 2016) conducted a driving experiment in downtown Los Angeles encompassing three drivers in order to collect real-world data (speed and acceleration) which were utilized to develop a dynamic eco-driving algorithm for signalized traffic that considered driver's characteristics and preferences (top speed, desired acceleration and deceleration, driver turning maneuvers at intersections). Although their algorithm proved to be computationally efficient, it was explicitly tested in simulation environment (where it demonstrated significant energy savings potential) and the authors did not clarify if it could efficiently adapt in real-time to driver's compliance to speed recommendation. (Tang et al. 2017) introduced a theoretical model formulation for dynamic eco-driving in signalized traffic that took into account driver's response time, acceptance level and execution capabilities. However, model parameters were not calibrated based on real-world data, the model was not assessed in the field, and the authors assumed homogeneous driver characteristics in their microscopic traffic simulation analysis.

A simulation-based impact assessment of driver's compliance to dynamic eco-driving advice at signalized intersections was conducted by (Liao et al. 2018). The latter study assumed fully connected vehicle fleet and precise execution of speed guidance strategies (acceleration, deceleration and constant speed strategies) from compliant driver's side. In reality driver's compliance to speed guidance may vary though depending on driver's skills and surrounding traffic conditions, and might lead to unsuccessful episodes of following dynamic eco-driving advice (e.g. driver partially adapts to speed advice leading to vehicle stop at the end of deceleration strategy). The dimension of driver's adaptability to dynamic eco-driving advice was incorporated into an EAD application that was explicitly developed for actuated signals and CVs (Hao et al. 2018). The EAD application was integrated in a research vehicle and tested under real traffic operations along the El Camino Real corridor in Palo Alto, CA, USA. However, it was neither compared to an EAD version without consideration of driver's adaptability nor to the case of EAD execution from an automated vehicle function.

(Qi et al. 2018) developed an EAD application for drivers of electric vehicles (EVs) that harnessed predictions of human driver errors made by a Markov chain model to estimate fuel efficient driving strategies. The driver error model was built based on real-world driving data collected while testing an EAD application without human error consideration capabilities in a test track. The proposed EAD application showed an average of 12% energy savings compared to its counterpart without driver error consideration, but it was explicitly evaluated via simulation analysis. Finally, a controlled field experiment encompassing one research vehicle and 32 participants was conducted at the Smart Road facility of Virginia's DoT to compare the performance of an advisory (driver controls the vehicle) and an automated (automation function controls the vehicle) dynamic eco-driving system (Almannaa et al. 2019). The automated system showed significant fuel and travel time savings compared to the manual one, but the effects of surrounding traffic in complex traffic situations such as those encountered in public roads were not addressed.

Most simulation studies have assumed that equipped vehicles were highly automated and, thus, could precisely execute the advised fuel-optimal speed profile. However, vehicular fleet is not expected to be fully automated and connected before 2060 even according to optimistic predictions (C-ITS Platform 2017; ERTRAC 2017; Litman 2020; PTOLEMUS 2017). Thus, CV applications will remain advisory to several drivers for a significant time period prior to the realization of a fully connected and automated road transport environment. Within the context of dynamic eco-driving systems this means that it will be in the driver's discretion to comply or not with the proposed speed advice. Consequently, driver's adaptation to speed advice will influence significantly the impacts of the latter services (Tielert et al. 2010). Hence, it is important that the dynamic speed advice is safe and comfortable so that drivers can easily adapt to it.

2.2.5 Field Experiments

The energy and traffic efficiency of existing dynamic eco-driving models was mainly estimated under idealized (not practicable) conditions, and partially proven in real-world traffic (**Table 2.2**). Dynamic eco-driving field experiments (in the proximity of signalized intersections) have been conducted either in test tracks (controlled experiments encompassing isolated signalized intersections) or in real world traffic (signalized arterial corridors and isolated signalized intersections). However, only preliminary results of the latter naturalistic driving studies were reported in the relevant literature.

2.2.5.1 Controlled Experiments

(Raubitschek et al. 2011) conducted field trials to evaluate a predictive driving strategy pertaining to the provision of speed advice upstream of a signalized intersection. These experiments verified their simulation results, which indicated that the predictive driving strategy could reduce the CV's fuel consumption by 10%.

(Weber & Winckler 2013; Xia et al. 2012) deployed a prototypic dynamic eco-driving system that estimated fuel efficient speed advice according to current SPaT information (Barth et al. 2011) and subsequently provided it through a graphical interface to the driver on an isolated test track. The prototypic system was tested on the "Richmond Field Station" test track, where different single-vehicle scenarios were examined under the same conditions in the absence of traffic. The results of the field experiment showed that the prototypic system could reduce stop frequency by 37%, travel time by 1%, and fuel consumption by 14%.

The EAD application for actuated signals was tested at Palmyrita Ave., Riverside CA with the use of a 2008 Nissan Altima research test vehicle (Hao et al. 2015b). The SPaT message was communicated to the test vehicle 300 m upstream of the signalized intersection, which was controlled by a two-phased signal control plan. The EAD test encompassed different traffic conditions on the main street and the cross street. Preliminary results indicated that the EAD application can yield 5% – 10% energy savings for high vehicle approach speeds, and 7% – 26% for low speeds.

A controlled field experiment was set up at the Virginia Smart Road Test facility (Almannaa et al. 2019; Rakha et al. 2016) to evaluate a speed recommendation algorithm. The experiment was conducted with the use of an automated vehicle (2014 Cadillac SRX) equipped with an onboard unit (OBU) for V2I and V2V communication. 32 subjects participated in the study (16 females and 16 males between the ages of 18 – 30) driving the automated vehicle in the vicinity of the equipped signalized intersection existing in the test facility. Driving sessions encompassed different road grades and red offset times. Advice was provided to the subjects through an auditory system in the form of speed recommendation or signal countdown. The experimental findings showed that energy savings on the order of 19% can be realized depending on the road grade, red offset time, and type of advice. Moreover, the system was found capable of yielding travel time savings up to 10%.

2.2.5.2 Real world Experiments

There are few studies that have attempted to evaluate the performance of eco-driving services in real world testbeds. (Saust et al. 2010) tested a cooperative system that estimates energy-efficient (de)acceleration strategies, but also utilizes real time V2I and V2V data to supplement traffic data from conventional sensors to optimize the signalization of adaptive traffic control systems along the ring road of Braunschweig, Germany, which is a two-lane arterial road. Fuel consumption estimation results based on an empirical formula, indicated that the optimized strategy could reduce the needed work and the corresponding fuel consumption by 35%.

A preliminary version of a dynamic eco-driving system that embedded probabilistic signal timing information in the optimization framework was programmed into an iPhone 3GS and implemented in downtown Greenville, South Carolina (Mahler & Vahidi 2012). Clock synchronization challenges were the largest obstacle to be overcome during field experiments. The experiments showed that drivers were able to avoid idling at traffic lights during light traffic conditions and low pedestrian volumes.

(Weber & Winckler 2013; Hao et al. 2015a) implemented their prototypic dynamic eco-driving system for actuated and coordinated traffic signals in real-life traffic conditions on the "El Camino Real" test site in Palo Alto, CA, USA. A comprehensive evaluation of the field experiment conducted along the El Camino Real corridor with the dynamic eco-driving technology was presented by (Hao et al. 2018). Findings showed that the energy savings were not found to be statistically significant for the entire trips' duration, opposite to emissions savings. Interestingly, interference from preceding vehicles was found to deteriorate the performance of the system (Hao et al. 2018).

An eco-driving assistant that estimates energy-efficient deceleration (voice) advice was deployed and validated in actual traffic conditions (Muñoz-Organero & Magaña 2013). The eco-driving assistant was installed in five different market available vehicle models, which were driven by nine different drivers for 180 test drives in urban traffic conditions. Field trials showed that the system can achieve a maximum of 4.9% fuel consumption reduction by minimizing fast deceleration patterns in case a vehicle stop cannot be avoided at the traffic lights.

(He et al. 2015) used an approximation model to predict the speed trajectory of a vehicle travelling along a signalized arterial (Trunk Highway 55) in the city of Minneapolis, Minnesota, given that spatial and temporal constraints due to queues and estimated trajectories of following vehicles were readily available through the SMART-Signal system installed on the aforementioned arterial. Results showed that fuel consumption for the predicted trajectory was 29% lower in the expense of 9% longer travel time compared to the actual trajectory without advice.

Recently, the functional operation of a GLOSA system was evaluated based on a field operation test (FOT) that was conducted under naturalistic driving conditions at the DRIVE C2X test site in Gothenburg, Sweden (Stahlmann et al. 2017). The real-world tests were implemented in the vicinity of three fully equipped traffic lights using ten retrofitted prototype vehicles. The analysis of the recorded data from the field experiments indicated that information distance and communication coverage are two aspects of dynamic eco-driving systems that significantly influence their energy and emission saving potential. The authors also noted that existing simulations studies did not thoroughly address the influence of communication latency on dynamic eco-driving benefits.

(Mintsis et al. 2017) evaluated the operation and performance of a cooperative speed advice service that was tested along an urban arterial corridor in the city of Thessaloniki, Greece. The field test encompassed 12 equipped signalized intersections and 200 taxis equipped with OBUs. A model-based approach was used to quantify CO_2 emissions of the equipped vehicles based on real-world vehicle trajectories. A rigorous statistical analysis of the field data showed that CVs compliant to speed advice emitted 9% lesser CO_2 emissions compared to the non-compliant ones. Furthermore, driver's compliance to speed advice was found to be strongly related to the type of message transmitted ("accelerate", "decelerate", or "maintain speed"), the remaining time of the signal status, and finally the dynamic eco-driving service zone distance.

Table 2.2. Evaluation methodologies of existing dynamic eco-driving models and corresponding impacts

Author(s)	Speed Advisory Model Name	Evaluation Methodology	Test Network Configuration	Vehicle Type	Energy Savings	Emissions Savings	Travel Time Savings	Real-time Ready
Ma et al. (2021)	Eco-CACC	Simulation (MATLAB/Simulink & SUMO)	Multiple Signalized Intersections, Columbus, Ohio, USA	5 electric passenger cars	8%	-	-	-
Yang et al. (2021)	Cooperative Driving Framework	Simulation (PTV VISSIM)	Plymouth Rd, Ann Arbor, Michigan, USA	Passenger Cars	7.4%	-	33%	✓
Han et al. (2020)	PTO-GFC	Numerical Analysis	Hypothetical Single Lane Intersection Approach	Multiple CAVs	48%	-	40%	-
Yao & Li (2020)*	Decentralized Model for CAV Trajectory Optimization	Numerical Analysis	Hypothetical Isolated Signalized Intersection	Passenger Cars	-	-	-	-
Wang et al. (2019)	CED	Simulation (PTV VISSIM)	University Avenue, Riverside, California, USA	Passenger Cars	7.1%	59% (CO) 57% (HC) 55% (NO_x)	-	-
Wang et al. (2018)**	Cluster-Wise Cooperative EAD	Numerical Simulation (MATLAB/Simulink)	Hypothetical 2-lane Intersection Approach	16 Passenger Cars	11%	16% (CO) 9.76% (HC) 2% (NO_x)	-	-

*A composite index encompassing travel time, fuel consumption and inverse time-to-collision is used to demonstrate the performance of the model.

**Energy and emissions savings are provided with reference to an Ego-EAD application.

Table 2.2. (*Continued*)

Author(s)	Speed Advisory Model Name	Evaluation Methodology	Test Network Configuration	Vehicle Type	Energy Savings	Emissions Savings	Travel Time Savings	Real-time Ready
Hao et al. (2018)	EAD	Field Experiment (Real-world traffic)	"El Camino Real" test site	Single-vehicle (2.5L 4-cylinder)	2% (all trips)	7% (CO) 18% (HC) 13% (NO_x)	-	-
Jiang et al. (2017)	Dynamic Eco-driving under Partially Connected and Automated Vehicles Environment	Simulation (Excel VBA, MATLAB, VISSIM)	Hypothetical Intersection	-	2.02%	1.97%	10.80%	✓
Stahlmann et al. (2017)	GLOSA	Field Experiment (Real-world traffic)	DRIVE C2X test site (Gothenburg, Sweden)	10 retrofitted prototype vehicles	-	-	-	✓
Almannaa et al. (2019)	Speed Recommendation Algorithm	Field Experiment	Virginia Smart Road Test facility	2014 Cadillac SRX	19%	-	10%	✓
Mintsis et al. (2017)	Dynamic Eco-Driving	Field Experiment (Real-world traffic)	Signalized arterial corridor (Thessaloniki, Greece)	200 taxis	-	9% (compliant vs noncompliant)	-	✓

Table 2.2. (*Continued*)

Author(s)	Speed Advisory Model Name	Evaluation Methodology	Test Network Configuration	Vehicle Type	Energy Savings	Emissions Savings	Travel Time Savings	Real-time Ready
Kamalanathsharma & Rakha (2016)	ECACC	MATLAB	-	30 top sold vehicles in the US	-	-	-	✓
Wang et al. (2016)	Speed Guidance Model	Simulation (EstiNet)	3.7km urban arterial road in Beijing	-	-	2.13%	8.15%	-
Hao et al. (2015a)	EAD	Numerical Evaluation	Hypothetical Intersection	-	3%-12%	5%-20% (CO) 3%-14% (HC) 6%-21% (NO_x)	-	✓
Hao et al. (2015b)	EAD	Controlled Experiment	Palmyrita Ave, Riverside CA	2008 Nissan Altima	5%-27%	-	-	✓
Chen et al. (2015)	Platoon-Based Dynamic Eco-driving	Simulation (INTEGRATION)	Cross Intersection (Blacksburg, Virginia)	-	13%	13% (CO, HC, CO_2, and NO_x)	38%	
Xiang et al. (2015)	CAEHV-C	Simulation	-	-	-	-	-	-
He et al. (2015)	-	MATLAB (GPOPS)	-	-	29%	-	-9%	✓

Table 2.2. (*Continued*)

Author(s)	Speed Advisory Model Name	Evaluation Methodology	Test Network Configuration	Vehicle Type	Energy Savings	Emissions Savings	Travel Time Savings	Real-time Ready
Muñoz-Organero & Magaña (2014)	Eco-driving Assistant	Field Experiment (Real-world traffic)	Urban Network	5 different vehicles (series-production)	4.9%	-	-	✓
Chen et al. (2014)	-	MATLAB (Sensitivity Analysis)	-	-	-	50% (NO_x)	14%	-
Xia et al. (2013b)	Dynamic Eco-Driving for Connected Vehicles	Simulation (PARAMICS)	Hypothetical Intersection	Single and Multi-Vehicle	31%	-	-	✓
Xia et al. (2013a)	Dynamic Eco-Driving	Simulation (PARAMICS)	11-signalized Arterial Corridor	Single and Multi-Vehicle	12.5%	13% (CO_2)	0.7%	✓
Weber & Wrinclker (2013)	Dynamic Eco-Driving	Field Experiment	"Richmond Field Station" test track "El Camino Real" test site	BMW Mid-sized Sedan	14%	-	-	✓
Mahler & Vahidi (2012)	Predictive Optimal Velocity Planning Algorithm	MATLAB	-	-	-	-	-	✓
		Field Experiment	(Greenville, South Carolina)	-	-	-	-	
Rakha et al. (2012)	-	MATLAB	-	-	30%	-	-	-
Schuricht et al. (2011)	Predictive Driver Assistance	Simulation (IDM)	-	-	8.7%	-	-	-

Table 2.2. (*Continued*)

Author(s)	Speed Advisory Model Name	Evaluation Methodology	Test Network Configuration	Vehicle Type	Energy Savings	Emissions Savings	Travel Time Savings	Real-time Ready
Raubitschek et al. (2011)	Predictive Driving Strategy	MATLAB Field Experiment	- BMW Test Track (Aschheim, Munich)	-	10%	-	-	✓
Barth et al. (2011)	Dynamic Eco-Driving	Simulation (PARAMICS)	Hypothetical 10-signalized Arterial	Mid-sized Sedan	12%	12% (CO_2)	2%	✓
Asadi & Vahidi (2011)	PCC	SIMULINK (MATLAB)	Urban road Suburban road	-	47%	56% (CO_2)	-	-
Tielert et al. (2010)	Speed Adaptation Model	Simulation (VISSIM)	Single-lane road segment Karlsruhe's inner city	EURO4 Otto and Diesel engines	22% 8%	80% (CO); 35% (NOx); 18% (PM) -	-	-
Vreeswijk et al. (2010)	-	Simulation (VISSIM)	Four-leg Intersection (Rotterdam)	-	-	5% (CO_2 & NO_x)	-	✓
Saust et al. (2010)	-	Field Experiment	Ring road of Braunschweig (two-lane arterial road)	-	35%	-	-	✓
Mandava et al. (2009)	Arterial Velocity Planning Algorithm	Stochastic Simulation	Hypothetical 10-signalized Arterial	LDV24 LDV17	12%-14%	12%-14% (CO_2)	-	-
Li et al. (2009)	ADAS	Parametric Analysis Simulation	-	-	14% 8%	-	-	-

2.3 Limitations and the Way Forward

The analysis of the literature indicated that the level of sophistication of dynamic eco-driving models is gradually advancing. However, there are certain shortcomings that need to be systematically addressed in future studies. Conceptually, most approaches are entirely driven from energy and traffic efficiency leaving aside safety considerations. Evidently, the road safety component can be integrated as a complementary indicator to the structure of the optimization function of dynamic eco-driving models.

Furthermore, this dissertation identified that human factors are partially and abstractly addressed in current forms of dynamic eco-driving simulation studies. Integrating predictive models that can account for the compliance of the users to speed advice systems or other behavioral characteristics in relation to the interaction of users with dynamic eco-driving services will result in a much more realistic representation of how these services may affect the system. To this end, models should be more data driven, rather than solely theory based, and leverage empirical observations encompassing different driver types, vehicle types and traffic conditions so that accurate predictions regarding the performance of dynamic eco-driving applications can be made. Hence, implementation should be linked to controlled field experiments and naturalistic driving studies, which demand significant funding and technological readiness.

This links to another limitation related to impact assessment frameworks. The performance of dynamic eco-driving models has been primarily tested with the use of analytical methodologies and simulation tools. Only few field experiments were conducted on controlled test tracks or actual signalized road networks. In terms of impact assessment results, it is, thus, evident that there is limited information of what the impact of such technologies will be in real traffic (i.e. when implemented massively to large-scale networks). Existing studies indicate that actual energy and emissions savings from dynamic eco-driving are more conservative compared to simulation findings. Moreover, communication aspects are expected to significantly influence the respective environmental benefits. Therefore, introducing further testbeds and standardized procedures to: a) benchmark the efficiency and effectiveness of dynamic eco-driving models, and b) determine the signalized intersection approaches where road, traffic and communication factors favor the implementation of dynamic eco-driving, will enable the proper development of such systems.

In relation to the modeling, this dissertation reveals that some of the most critical desired characteristics of an advanced and robust dynamic eco-driving model are:

- the dynamic eco-driving model control logic should consider both full and partial SPaT information, vehicle status and location information, queue discharge information, car-following behavior, and generic V2V real-time information (status of the leading vehicle),
- the optimal controller of the speed advice model should consider mobility (travel time), energy efficiency (fuel consumption) and safety (surrogate safety measures) indicators for the estimation of the fuel-optimal speed trajectory,
- the solution method for the corresponding formulated optimization problem should be computationally efficient enough to render the speed advisory system functional in real-time deployments,
- non-linear power based, or speed-acceleration based microscopic fuel consumption and emissions models should be incorporated in the objective function of the optimal controller,
- linear deceleration and non-linear acceleration models (vehicle dynamics models) should be selected for the computation of the entire (upstream and downstream) eco-driving maneuver,
- gear shifting modeling should be encompassed to capture the effects of gear choice on dynamic eco-driving,
- the speed advice model should be rendered functional with any type of signal control strategy (pre-timed, actuated, actuated and coordinated, adaptive),
- the speed advice model should consider SPaT information from multiple downstream signalized intersections for the estimation of the energy and traffic optimal trajectory.

Smoothing traffic via vehicles' trajectory planning and coordination is a robust, yet, complex traffic management and control problem that is receiving increasing attention due to the introduction of CAVs. Most dynamic eco-driving systems smooth traffic by estimating individual fuel-optimal speed advice based on the SPaT and MAP (topology) message in the vicinity of signalized intersections. Latest studies proposed mathematical formulations that allow for the provision of multiple different speed advice during the course of an energy and traffic optimized trajectory (Stebbins et al. 2017). Moreover, they developed methodologies that estimate near real-time safe, energy and traffic efficient trajectories for platoons of vehicles by solving the lead-vehicle problem assuming that the leading vehicle is a CAV (Ma et al. 2017; Stebbins et al. 2017; Zhou et al. 2017).

However, existing studies have not addressed in a rigorous mathematical way the implications of lateral vehicular interactions on trajectory planning along multi-lane road segments near signalized intersections. Dynamic eco-driving has been mainly studied as a centralized traffic control scheme based mainly on V2I communication for the estimation of the energy and traffic efficient trajectories. Development of cooperative maneuvering within mixed traffic streams through the introduction and standardization of the relevant communication message sets (Cooperative Awareness Message, Collective Perception Message, Maneuver Coordination Message etc.) provides the opportunity for converting the aforementioned traffic management and control scheme into a hybrid one (encompassing both V2I and V2V communications). Moreover, future studies should also account for the heterogeneous characteristics of the vehicular fleet and the heterogeneous vehicle destinations. Finally, it would be very interesting to further investigate the coordination of dynamic eco-driving with adaptive traffic signals, since up to date research has shown very promising results.

3 Methodological Approach

The state-of-the-art review (cf. Section 2) indicated that limited focus was previously placed on the comfort and safety of dynamic eco-driving technologies (Mintsis et al. 2020). Early evidence from field testing of an eco-cruise control system in the vicinity of traffic signalized intersections showed that manual speed adaptation based on countdown advice proved less comfortable, but equally safe and desirable compared to automated eco-cooperative adaptive cruise control (Rakha et al. 2016). Thus, there is significant potential for enhancing dynamic eco-driving performance via the introduction of novel features that improve comfort, user acceptance and safety.

Undoubtedly, drivers/passengers would be more willing to adopt dynamic eco-driving if it ensured comfortable, safe and intuitive speed advice. According to the profile of existing deceleration strategies, a CV initially decelerates and subsequently cruises at a steady-state speed towards a signalized intersection until the signal status changes to green, when vehicle accelerates back to its desired speed beyond the signalized intersection. This implies that existing dynamic eco-driving services instruct CVs to cruise at significant steady speed while the vehicle approaches the signalized intersection and the signal status remains red. In this case, many drivers/passengers would feel uncomfortable driving/riding a vehicle that cruises in close vicinity to a signalized intersection while the traffic light status is still red. That would be especially true in the early stages of CV market introduction when mixed traffic conditions are expected to prevail on the streets and drivers/passengers will be less familiar with CV technology.

This work proposes and evaluates enhancements on an existing dynamic eco-driving model (velocity planning algorithm) that encompass the following novel features:

- provision of non-crawling speed advice, and
- vehicle acceleration commencement prior to CV arrival at signalized intersection at the end of deceleration strategies

Additionally, findings from the state-of-the-art review (cf. Section 2) showed that no previous study utilized real world data from a large scale dynamic eco-driving field experiment conducted in public urban roads to model driver's adaptation to fuel efficient speed advice. This dissertation addresses the latter research gap by exploiting empirical evidence from a multi-vehicle multi-driver dynamic eco-driving experiment conducted along an urban arterial corridor to develop a decision tree model (DT) that emulates driver's adaptation to dynamic eco-driving advice in the proximity of signalized intersections. Moreover, the DT is integrated in the control logic of an existing dynamic eco-driving model. Finally, an extensive and thorough microscopic traffic simulation analysis that encompasses an actual urban arterial corridor that was calibrated against real traffic conditions is conducted to compare the performance of:

- the enhanced velocity planning algorithm against the original velocity planning algorithm
- advisory dynamic eco-driving against automated dynamic eco-driving

Figure 3.1 depicts the mathematical models used for the analysis of the behavior and the impacts of the different dynamic eco-driving systems considered in the context of this dissertation.

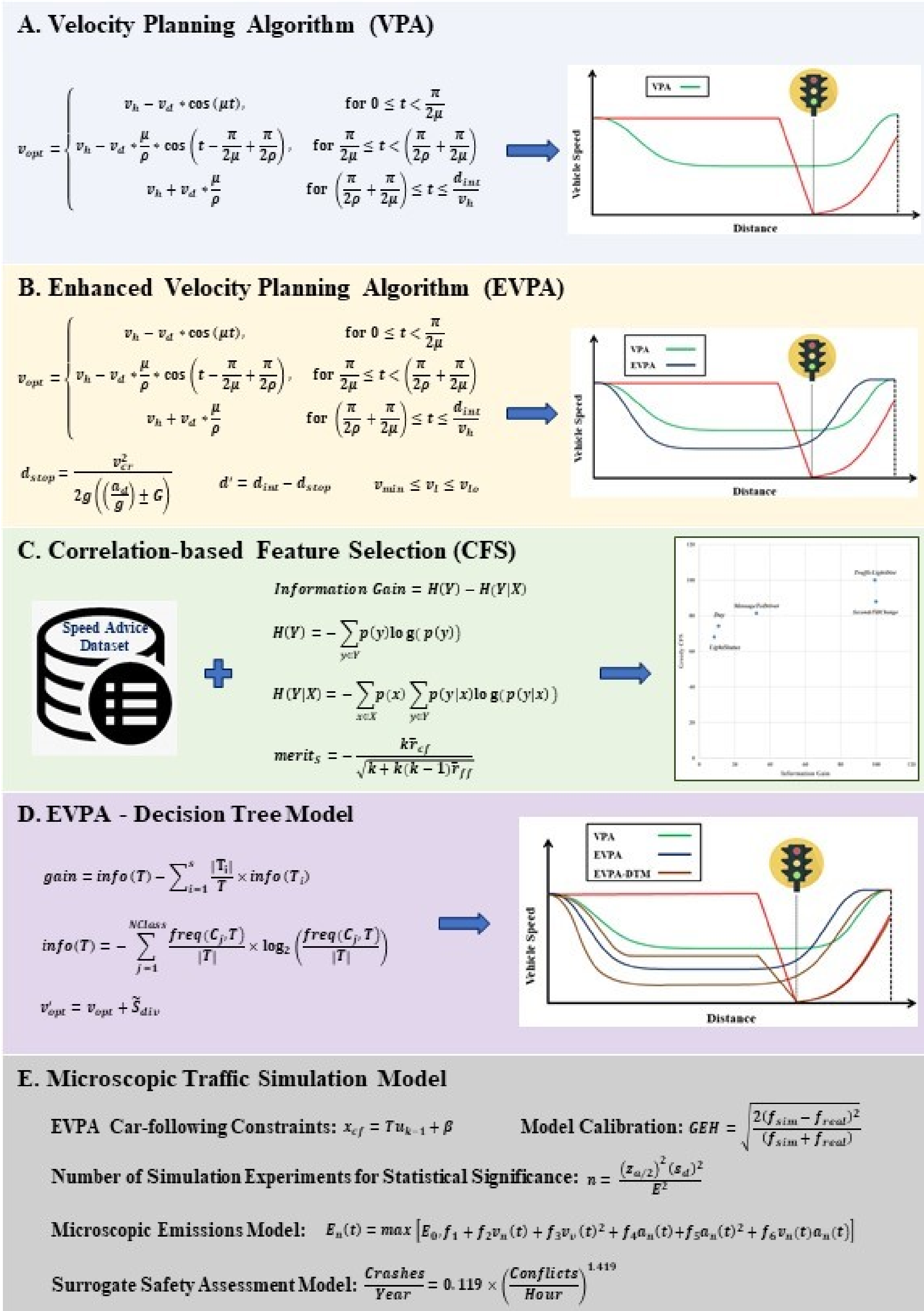


Figure 3.1. Mathematical models used for analyzing the behavior and impacts of different dynamic eco-driving systems

3.1 Enhanced Speed Advice

Enhanced dynamic eco-driving accounts for intuitive speed advice that drivers/passengers can easily and conveniently adapt to, and encompasses comfortable accelerations/decelerations, acceptable cruising speeds, as well as guidance that facilitates safe interactions with surrounding road users and elements (e.g. traffic lights). As mentioned above, existing literature has overlooked specific aspects of speed advice pertaining to comfort and safety which this dissertation aims to address. To this end, we present in the following sections the velocity planning algorithm (VPA) previously developed by (Xia et al. 2013a) and an Enhanced VPA (EVPA) version proposed by this dissertation that promotes speed advice comfort and safety without adversely impacting energy and traffic efficiency (Mintsis et al. 2021).

3.1.1 Velocity Planning Algorithm (VPA)

(Xia et al. 2013a) introduced VPA considering that energy savings can be realized when drivers exhibit the following behavior:

- maintain a steady-state speed near the speed limit,
- keep a safe headway distance from the leading vehicle, and
- avoid idling, or idle the least possible time at the traffic light if this is unavoidable.

Thus, an optimization problem was formulated that minimized a vehicle's tractive force and idling time while accounting for ride comfort and the local speed limit (v_{lim}). To avoid stopping at a traffic light, a vehicle should arrive at the signalized intersection during a green signal status. Based on the current signal status, a green arrival interval can be estimated as:

$$t_{arrival} = \begin{cases} [0, t_r\} \text{ or } [t_g, t_{r1}), & \text{if signal status=green} \\ [t_g, t_r), & \text{if signal status=red} \end{cases} \tag{1}$$

where t_r is the time to the upcoming red phase, t_g represents the time to the next green phase, and t_{r1} is the time to the second red phase. Thus, if the signal is green, a vehicle can either cruise at current speed or accelerate to a target speed to pass through the intersection during the first green window or decelerate and cross the intersection during the second green window. If the signal is red (yellow time is considered to be red time), the vehicle can cruise at current speed or decelerate to a target speed to cross the intersection during the upcoming green window.

The possible values of $t_{arrival}$ can range between $[t_l, t_h]$, where t_l and t_h are low and high values according to Equation 1. Given the range $[t_l, t_h]$ and the vehicle's distance to intersection d_{int}, the possible target velocities $v_{arrival}$ can be expressed as the range $[v_l, v_h]$, where v_l is the maximum between zero and $v_{lo}(v_{lo} = d_{int}/t_h)$ and v_h is the minimum between v_{lim} and $v_{ho}(v_{ho} = d_{int}/t_l)$. Evidently, d_{int} and signal timing information are key parameters for the estimation of energy optimal speed trajectories.

When $v_{arrival}$ is estimated, the provision of speed advice to CV is determined according to its current speed v_c. If v_c lies within $[v_l, v_h]$, then the vehicle can pass the intersection cruising at current speed. Alternatively, it can accelerate or decelerate with respect to v_h, which (Xia et al. 2013a) have selected as the target velocity to achieve travel time savings apart from environmental benefits. The energy-efficient speed profiles are estimated according to the following functions:

$$v_{opt} = \begin{cases} v_h - v_d * \cos(\mu t), & \text{for } 0 \leq t < \dfrac{\pi}{2\mu} \\ \\ v_h - v_d * \dfrac{\mu}{\rho} * \cos\left(t - \dfrac{\pi}{2\mu} + \dfrac{\pi}{2\rho}\right), & \text{for } \dfrac{\pi}{2\mu} \leq t < \left(\dfrac{\pi}{2\rho} + \dfrac{\pi}{2\mu}\right) \\ \\ v_h + v_d * \dfrac{\mu}{\rho} & \text{for } \left(\dfrac{\pi}{2\rho} + \dfrac{\pi}{2\mu}\right) \leq t \leq \dfrac{d_{int}}{v_h} \end{cases} \tag{2}$$

where v_d is equal to $v_h - v_c$. Positive v_d values generate acceleration profiles, and negative values generate deceleration profiles. The only unknown parameters in Equation 2 are μ and ρ, which determine the acceleration/deceleration rate. The higher the value of μ, the higher the acceleration/deceleration rate. The values of μ and ρ can be computed by solving the following three constraints:

$$
\begin{cases}
\int_0^{\frac{\pi}{2\mu}} (v_h - v_d * \cos(\mu t))dt + \int_{\frac{\pi}{2\mu}}^{\frac{\pi}{2\rho}+\frac{\pi}{2\mu}} \left(v_h - v_d * \frac{\mu}{\rho} * \cos\rho\left(t - \frac{\pi}{2\rho} + \frac{\pi}{2\mu}\right)\right) dt \\
+ \left(v_h + v_d * \frac{\mu}{\rho}\right) * \left(\frac{d_{int}}{v_h} - \frac{\pi}{2\rho} - \frac{\pi}{2\mu}\right) = d_{int} \\
jerk_{max} = |v_d * \mu * \rho| \leq 10 \; and \; a_{max} \leq 2.5 \, m/s^2 \\
\mu = \max\{\mu\}
\end{cases}
\quad (3)
$$

The first constraint in Equation 3 is the distance constraint, which ensures vehicle's arrival at the downstream signalized intersection in the shortest time. The second constraint pertains to ride comfort. The third was set based on the finding of (Xia et al. 2013a), which suggests that minimization of fuel consumption and emissions occurs for the largest possible μ value (i.e. a vehicle accelerates sharply instead of smoothly to v_h). Moreover, it has to be noted that VPA can be explicitly implemented at signalized intersections with fixed signal control plans, and it does not consider queue dynamics at signalized intersections. A more detailed description of VPA can be found in (Xia et al. 2013a).

3.1.2 Enhanced Velocity Planning Algorithm (EVPA)

This dissertation introduced enhancements to the control logic of the VPA accounting for actual behavioral traits of drivers. The EVPA increases the comfort and safety of the provided speed advice to facilitate acceptance of dynamic eco-driving service from the driver's/passenger's side.

The control logic of the reference model implies that the minimum speed advice is an explicit function of the vehicle's traveling state (approach speed and distance to the signalized intersection) and the signal timing information of the signalized intersection. Thus, v_l could acquire rather low values (e.g. 10 km/h), which implies that a vehicle might be advised to cruise towards a signalized intersection at a crawling speed. However, it is legitimate to assume that drivers would refrain from driving below a minimum speed threshold (anxiety reasons), irrespective of the provided speed advice. Thus, the authors propose that $v_{arrival}$ is not only bounded on the upper limit by the speed limit, but also on the lower limit by a minimum acceptable speed value ($v_{\min}$). Therefore, v_l would become the maximum between $v_{\min}$ and $v_{lo}(v_{lo} = d_{int}/t_h)$. It is expected that this enhancement will increase the indirect benefits of dynamic eco-driving, since legacy vehicles

(LVs) will overtake CVs less frequently, thus inducing less turbulence to traffic. Additionally, previous research has shown that cruising at low speeds at the end of deceleration strategies might incur higher energy consumption, even compared to a standstill strategy (Raubitschek et al. 2011).

The second enhancement also pertains to deceleration strategies. According to the control logic of existing dynamic eco-driving models, a CV's arrival at traffic lights after the implementation of a deceleration strategy is concurrent with the onset of the green phase. However, many drivers/passengers would feel uncomfortable riding a vehicle that cruises at high steady speed in close vicinity to a signalized intersection while the signal status is still red. Therefore, this dissertation suggests that the lowest cruising speed v_{cr} of the initially estimated deceleration profile is used for the computation of the CV's practical stopping distance, assuming it had complied with the initial deceleration strategy. In this case, the vehicle's practical stopping distance d_{stop} is given by Equation 4:

$$d_{stop} = \frac{v_{cr}^2}{2g\left(\left(\frac{a_d}{g}\right) \pm G\right)} \tag{4}$$

where a_d is the deceleration rate, g is the gravitational constant, and G is the roadway grade. Equation 4 provides an estimate of typical braking distances and is more simplistic and usable than the theoretical stopping distance one. Given the assumption that CVs fully stop and road grades are small, mass factor accounting for moments of inertia during braking (which is considered for the estimation of theoretical stopping distance) can be ignored due to its small effects (Mannering et al. 2007). Moreover, we assume that friction is always guaranteed in our simulation experiments and anomalous situations such as sudden and strong braking do not occur.

Subsequently, the practical stopping distance is subtracted from d_{int}, and the result $\left(d' = d_{int} - d_{stop}\right)$ is returned to the algorithm for the estimation of an enhanced deceleration profile. According to this updated deceleration profile, the CV decelerates to a lower cruising speed v'_{cr} compared to the initial one, but the onset of the green phase occurs prior to the CV's arrival to the signalized intersection. Moreover, sufficient time and space remain available for the CV to stop in case of red light running from the opposite direction. Since the practical stopping distance is a function of the vehicle's cruising speed, the EVPA is expected to perform efficiently within a wide range of cruising speeds. The enhanced dynamic eco-driving service is expected to be perceived as more intuitive, convenient and safer by drivers, who would thus increase their confidence regarding the system's operation and efficiency.

3.2 Modelling Driver's Compliance to Speed Advice

Each driver has a unique way of navigating through traffic, which is affected by various elements. In the traditional vehicle-road landscape, these may include socio-economic and physiological factors as well as personality traits, skills, and desires (Hellinga and Mandelzys 2011; Mantouka et al. 2019; Sharma et al. 2018; Tselentis et al. 2019; Vlachogiannis et al. 2020). In a CV environment, one should add the perception of drivers on the reliability of the advice system and the quality of information.

To address the stochasticity induced by human factors in modelling driver compliance to speed advice, we first determine the factors affecting driver's compliance to energy-efficient speed advice and then develop a DT model to emulate the decision-making process of driver adaptation to the latter advice.

3.2.1 Factors Affecting Driver's Compliance to Speed Advice

To evaluate the factors that may affect the driver's compliance to speed advice, a mixture of feature selection strategies is implemented based on the Information Gain criterion and the Correlation-based Feature Selection (CFS) algorithm. The scope is to reveal which of the observed features – from a given feature vector – provide redundant information given an output variable. The joint consideration of two different criteria for revealing the factors that may affect the compliance to speed advice aims to enhance the consistency of the results.

Information Gain is a symmetrical metric of strength between a feature X and a target variable Y. It is based on the entropy, which is considered as a measure of system's unpredictability. Information Gain quantifies the gain of about Y after observing X according to Equation 5:

$$Information\ Gain = H(Y) - H(Y|X) \tag{5}$$

where $H(Y)$ and $H(Y|X)$ are the entropies of X and Y after observing respectively, given by Equations 6 – 7:

$$H(Y) = -\sum_{y \in Y} p(y) \log (p(y)) \tag{6}$$

$$H(Y|X) = -\sum_{x \in X} p(x) \sum_{y \in Y} p(y|x) \log (p(y|x)) \tag{7}$$

where $p(y)$ is the marginal probability of Y and $p(y|x)$ the conditional probability of Y given X.

The CFS algorithm produces a ranking of features' subsets from the original feature vector according to a correlation based heuristic evaluation function (Hall 1999). The merit of a subset S is given by Equation 8:

$$merit_S = -\frac{k\bar{r}_{cf}}{\sqrt{k + k(k-1)\bar{r}_{ff}}} \tag{8}$$

where k are the features in the subset, $\bar{r}_{cf}$ is the mean feature-class correlation, and $\bar{r}_{ff}$ is the average feature-feature inter-correlation. The concept is to detect subsets of features that are highly correlated to a class, yet uncorrelated with each other. In this specific implementation, a greedy hill climbing search algorithm is implemented to search the feature space from the optimum subset.

3.2.2 Decision Tree Model of Driver's Compliance to Speed Advice

This dissertation considered a greedy top-down DT whose training evolves in two stages: growing and pruning (Quinlan 1987). For the growing stage, the algorithm considers the partition of the training set using the outcome of a discrete function of the input attributes in each iteration based on a divide-and-conquer strategy. The selection of the most appropriate function is made according to splitting measures. After the selection of an appropriate split, each node further subdivides the training set into smaller subsets, until no split gains sufficient splitting measure or a stopping criterion is satisfied.

The splitting criterion is based on the information gain of an attribute a, which relates to entropy (Ruggieri 2002) and is calculated based on Equation 9:

$$gain = info(T) - \sum_{i=1}^{s} \frac{|\mathrm{T_i}|}{T} \times info(T_i) \tag{9}$$

where attribute a is discrete and $T_1, \dots, T_s$ are the subsets of T and $info(T)$ is the entropy function given by Equation 10:

$$info(T) = -\sum_{j=1}^{NClass} \frac{freq(C_j, T)}{|T|} \times \log_2\left(\frac{freq(C_j, T)}{|T|}\right) \tag{10}$$

The growing phase continues until a stopping criterion is triggered (i.e. maximum tree depth has been reached).

During the pruning stage, a reduced error-pruning algorithm is implemented. The algorithm starts by considering the entire tree that resulted from the growing stage, and for each internal node it compares the classification error produced on the pruning set where the subtree T_t is kept, with the classification error made when t is turned into a leaf and was associated with the best class. This branch pruning operation is repeated on the simplified tree until further pruning increases the misclassification rate.

The output of the DT is defined as the possible divergence range between the realized speed and the advised speed. The average speed divergence $\widetilde{S_{div}}$ is selected stochastically from a possible range of values as dictated by the DT presented in Section 5.2. During the simulation timeline, an acceleration/deceleration profile is estimated per CV that enters a dynamic eco-driving service zone upstream of a signalized intersection. The speed profile is transformed uniformly by adding the average speed divergence to the initial speed vector produced by EVPA. The transformed speed profiles v'_{opt} are estimated according to the Equation 11:

$$v'_{opt} = v_{opt} + \tilde{S}_{div} \tag{11}$$

3.3 Microscopic Traffic Simulation Framework

A microscopic traffic simulation tool (Aimsun, version 8.1.2) was used to conduct the simulation analysis. A dedicated Aimsun API was built to replicate vehicle behavior during the operation of the latter dynamic eco-driving systems (cf. Section 3.3.1). VPA and EVPA dictated behavior of vehicles that automatically executed speed advice (automated case), while EVPA-DT reflected vehicle behavior when drivers manually adapted to provided speed advice (advisory case). The architecture of the proposed microscopic traffic simulation framework is depicted in **Figure 3.2**.

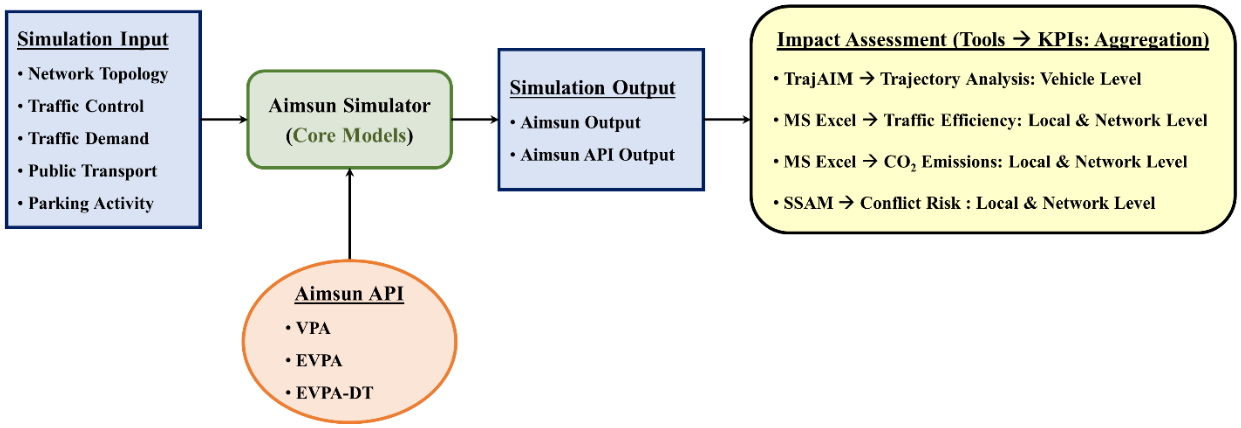


Figure 3.2. Simulation framework for evaluating advisory and automated dynamic eco-driving

3.3.1 (E)VPA(-DT) – Application Programming Interface (API)

VPA, EVPA, and EVPA-DT were simulated in Aimsun with the use of an API that was directly interfaced with the core Aimsun models. The API estimates a single energy optimal driving strategy for every CV that enters the dynamic eco-driving service activation zone. Then, the CV becomes "tracked" in the simulation and strictly follows (VPA and EVPA cases) or adapts to (EVPA-DT case) the provided speed advice (every simulation time step) until it crosses the signalized intersection. However, a CV can discard speed advice if it enters car-following state. An empirical formula was used to assess the car-following state of CVs during the simulation (Pipes 1953). The maximum car-following distance is given by Equation 12:

$$x_{cf} = Tu_{k-1} + \beta \tag{12}$$

where T is a time constant, u_{k-1} is the speed of the following vehicle, and β is the average distance between two vehicles in standstill. If a CV's distance to the leader becomes shorter than x_{cf}, then it becomes "untracked" in the simulation and its motion is subsequently dictated by the Aimsun driver models. In this case, an updated speed advice is not provided to the CV even though it is still driving within the activation zone. The behavior of CV beyond the activation zone is determined by Aimsun driver models that are parametrized to reflect manual driving conditions.

The length of the activation zone is set equal to the total length of the corresponding signalized intersection approach (IA: road section between two consecutive intersections). During the simulation of VPA, the estimated speed advice can range between 10 – 50 km/h. On the other hand, while EVPA or EVPA-DT are simulated the estimated speed advice can range between the minimum cruising speed after deceleration (20 km/h) and the speed limit (50 km/h). **Table 3.1** provides an elaborate list of the parameter values that affect the operation of the examined dynamic eco-driving models (VPA, EVPA, and EVPA-DT) in the simulation experiments.

Table 3.1. Parameter values of dynamic eco-driving models used in the simulation experiments

Variables	**Description**	**Value(s)**
v_{lim}	Speed limit (km/h)	50
μ	Acceleration rate parameter (m/s^2)	0.15
v_{min}	Minimum cruising speed after deceleration (km/h)	20
g	Gravitational constant (m/s^2)	9.807
a_d	Normal deceleration rate (m/s^2)	4.00
G	Road grade $(\%)$	0
T	Time constant (sec)	1.02
β	Average headway distance in standstill $(meters)$	3.5

The graphical user interface (GUI) of the Aimsun API enables the configuration of dynamic eco-driving deployment per examined IA in the simulator. Configuration entails definition of dynamic eco-driving service activation zone, selection of dynamic eco-driving algorithm (VPA, EVPA or EVPA-DT), relevant algorithmic parameters, vehicle types receiving speed advice, and number of simulation replications that dynamic eco-driving will be executed. An elaborate description of the developed Aimsun API capabilities and features is provided in Appendix A.

3.3.2 Microscopic Emission Model

To estimate CO_2 emissions within the simulation loop (second-by-second estimation, 1 Hz.), the Panis microscopic emission model calibrated with real world emission data is used (Panis et al. 2006). As this model combines multiple non-linear regression models to estimate emission functions per vehicle type and pollutant (with instantaneous speed and acceleration as explanatory variables) it was considered relevant for the evaluation of the environmental impacts of dynamic eco-driving. The generic form of the model's equations is provided subsequently:

$$E_n(t) = max\begin{bmatrix} E_0, f_1 + f_2 v_n(t) + f_3 v_v(t)^2 + f_4 a_n(t) \\ +f_5 a_n(t)^2 + f_6 v_n(t) a_n(t) \end{bmatrix} \tag{13}$$

where $v_n(t)$ and $a_n(t)$ are the instantaneous speed and acceleration of vehicle n at time t, E_o is the lower limit of emissions specified for each vehicle and pollutant type, and f_1 to f_6 are emissions constants specific for each vehicle and pollutant type determined via regression analysis.

The fleet composition with respect to engine type for Greece was obtained from (ACEA 2017). To this end, in our simulation experiments taxis, heavy duty vehicles (HDV), and buses run on diesel engines. Passenger cars are divided into the following shares according to their fuel type: 92% petrol, 5% diesel, and 2% LPG. The emission constants used for the estimation of CO_2 emissions per combination of vehicle and engine type are presented in **Table 3.2**.

Table 3.2. CO_2 emission constants per combination of vehicle and engine type

Vehicle Type	**Engine Type**	E_0	f_1	f_2	f_3	f_4	f_5	f_6
Car	Petrol	0	0.553	0.161	-0.003	0.266	0.511	0.183
Car	Diesel	0	0.324	0.086	0.005	-0.059	0.448	0.23
Car	LPG	0	0.6	0.219	-0.008	0.357	0.514	0.17
Taxi	Diesel	0	0.324	0.086	0.005	-0.059	0.448	0.23
HDV	Diesel	0	1.52	1.88	-0.07	4.71	5.88	2.09
Bus	Diesel	0	0.904	1.13	-0.043	2.81	3.45	1.22

3.4 Surrogate Safety Assessment Model (SSAM)

SSAM is a software utility that was developed to facilitate safety assessment of new traffic facility designs. It is methodologically founded on the notion of conflict, which resembles observable situations in which two or more road users approach each other in time and space to such an extent that there is risk of collision if their movements remain unchanged. SSAM validation efforts have proven that there is strong positive correlation between SSAM conflict data and real-world crash data (Gettman et al. 2008), which is expressed by Equation 14 and justifies that those conflicts comprise credible proxies for traffic safety evaluation.

$$\frac{Crashes}{Year} = 0.119 \times \left(\frac{Conflicts}{Hour}\right)^{1.419} \tag{14}$$

SSAM can utilize vehicle trajectory output generated from several microscopic simulation tools (i.e. Paramics, VISSIM, TEXAS, and AIMSUN) in a predefined and standardized format, to algorithmically identify different conflict types according to the conflict angle (i.e. crossing, lane change, and rear-end) and estimate indicators (surrogate safety measures) that dictate propensity and severity of conflicts (Gettman & Head 2003).

Time-to-Collision (TTC) is a benchmark surrogate safety measure for the identification of conflict propensity that indicates the expected time for two vehicles to collide if they remain at their present speed and on the same path, and is given by Equation 15:

$$TTC_{i.t} = \begin{cases} \dfrac{\left(X_{i-1,t} - X_{i,t}\right) - L_{i-1,t}}{V_{i,t} - V_{i-1,t}} & for\ vehicles\ travelling\ in\ same\ direction \\ \dfrac{D_{i,t}}{V_{i,t}} & for\ vehicles\ travelling\ in\ different\ direction \end{cases} \tag{15}$$

where $X_{i-1,t}$ and $X_{i,t}$ stand for the positions of the preceding and following vehicle, $L_{i-1,t}$ denotes the length of the preceding vehicle, $V_{i,t}$ and $V_{i-1,t}$ represent the velocities of the following and preceding vehicle, and $D_{i,t}$ is the distance between the projected collision point and vehicle i.

Conflict severity can be examined with the use of the DeltaS surrogate safety measure, which indicates the maximum relative speed of two conflicting vehicles throughout the duration of a conflict event and is mathematically defined by Equation 16:

$$DeltaS = \left\| V_{i-1,t} - V_{i,t} \right\| \tag{16}$$

Road safety impact assessment of CV technologies has been conducted via real world experiments (Maile & Degrossi 2009) and with the use of microscopic traffic simulation tools (Morsink et al. 2008) that utilize surrogate measures of safety to indicate conflict risk for both uninterrupted and interrupted traffic flow (Archer 2005; Dalla Chiara et al. 2009; Dalla Chiara et al. 2014; Gettman

& Pu 2006; Kim & Sul 2009). Specifically, SSAM has been previously used to evaluate the safety performance of EAD applications (Li et al. 2018), lower-level automation functions in a connected and automated road environment (Rahman et al. 2019), and generic CAV behavior at different intersection types (Virdi et al. 2019). In the context of this dissertation, SSAM is used to compare safety implications of advisory (EVPA-DT) and automated dynamic eco-driving systems (EVPA).

3.5 Experimental Setup

3.5.1 Simulation Testbed

A detailed microscopic simulation model of an urban arterial corridor in the city of Thessaloniki, Greece, was developed with the use of the microscopic traffic simulation tool Aimsun. Its total length is 15 km (road grade is nearly zero across the full length of the corridor) and it encompasses 26 signalized intersections (17 equipped with road-side units) which are controlled by pre-timed signal control plans. VPA, EVPA and EVPA-DT were deployed on 23 signalized intersection approaches (IA) (highlighted in yellow) of the examined simulation network (**Figure 3.3**). Side-street parking and seven public transport lines (along with their corresponding time plans) that traverse the central business district (CBD) of Thessaloniki were simulated as well.

Figure 3.3. Dynamic eco-driving test site in Thessaloniki, Greece (real world and simulation)

A thorough macroscopic calibration process was conducted to ensure the ability of the microscopic traffic simulation model to replicate actual traffic operations (without dynamic eco-driving service) on the examined road network. Calibration parameters of Aimsun driver models (car-following, lane-changing, and gap-acceptance models) were adjusted for the reconciliation of field and simulated traffic counts. Field traffic data were obtained from several traffic detectors that monitor traffic conditions in the CBD of Thessaloniki. The latter data contain traffic volumes, average time mean speed, and travel time information for selected network routes.

Field and simulated traffic counts were used for the conduct of the appropriate statistical test (GEH) to verify the validity of the simulation model (Chu et al. 2003). The GEH statistic is given by Equation 17:

$$GEH = \sqrt{\frac{2(f_{sim} - f_{real})^2}{(f_{sim} + f_{real})}} \tag{17}$$

where f_{sim} is the simulated flow, and f_{real} is the observed flow. The estimated GEH values for volume and speed counts were lower than 5 for more than 85% of the selected detector stations (**Table 3.3** and **Table 3.4**). Moreover, GEH index was also lower than 5 when comparing average travel time between field and simulation along the examined urban arterial corridor. Thus, the calibration procedure demonstrated that the simulation model can credibly replicate traffic operations pertaining to manual driving on the test network.

Table 3.3. GEH values obtained from field and simulation traffic flow counts

Detector No.	Field Flow (veh)	Simulated Flow (veh)	GEH Statistic
1	1628	1556	1.80
2	3218	3053	2.94
3	2875	2678	3.74
4	2571	2461	2.20
5	2293	2104	4.04
6	2398	2126	5.73
7	2324	2095	4.87
8	2219	2075	3.12
9	2488	2252	4.85
10	2546	2292	5.17
11	2575	2317	5.22
12	2093	2088	0.10
13	584	583	0.05
14	365	377	0.63
15	132	118	1.24
16	143	148	0.37
17	425	430	0.26
18	511	534	1.01
19	530	569	1.68
20	711	721	0.36
21	848	883	1.18

Table 3.4. GEH values obtained from field and simulation time mean speed counts

Detector No.	Field Speed (km/h)	Simulated Speed (km/h)	GEH Statistic
1	45.23	41.33	0.59
2	30.13	31.81	0.30
3	29.56	35.49	1.04
4	32.12	37.71	0.95
5	33.25	37.41	0.70
6	29.23	33.40	0.74
7	26.50	30.41	0.73
8	25.36	27.69	0.45
9	27.98	33.77	1.04
10	44.76	38.94	0.90
11	43.65	51.63	1.16
12	44.74	46.57	0.27
13	35.36	47.42	1.88
14	34.69	53.49	2.83
15	31.63	32.16	0.09
16	32.47	28.73	0.68
17	34.71	40.99	1.02
18	40.62	49.60	1.34
19	45.69	52.56	0.98
20	52.36	41.32	1.61
21	47.26	54.28	0.98

However, we also deem that our simulation model remains valid for different market penetration rates of dynamic eco-driving technology, since we assumed that CVs are manually driven beyond the service activation zone and existing literature (Alam & McNabola 2014; Guanetti et al. 2018; Huang et al. 2018; Mintsis et al. 2020; Taiebat et al. 2018; Vahidi & Sciarretta 2018; Wadud et al. 2016) addressing the impacts of dynamic eco-driving on traffic operations does not indicate changes to route choice due to speed advice provision in the proximity of signalized intersections.

3.5.2 Simulation Scenarios – VPA vs EVPA

The performance of the VPA and the EVPA were assessed for different traffic demand levels and different penetration rates of the dynamic eco-driving technology (**Table 3.5**). In total, 48 scenarios were simulated (38 with service on and 10 with service off). The calibration scenario corresponds to D100 traffic demand level (initial demand input to the microscopic simulation model). The effect of the penetration rate of the CV technology was tested both for uncongested (D50) and congested (D100) traffic conditions. On the other hand, the performance of CV technology for a wide spectrum of traffic conditions (uncongested – near congested – congested/D10 – D100) was evaluated for three different penetration rates (low – moderate – high/P15 – P50 – P100). Speed advice was explicitly provided to passenger cars and taxis among the simulated vehicle types (passenger cars, taxis, trucks, and buses), since the VPA model was explicitly developed for light-duty vehicles.

Table 3.5. Simulated demand levels and penetration rates for comparison of VPA vs EVPA performance

Demand Level (D%)	Penetration Rate (P%)							
	P0	P5	$P10$	$P15$	$P25$	$P50$	$P75$	$P100$
D10	✓	×	×	✓	×	✓	×	✓
D20	✓	×	×	✓	×	✓	×	✓
D30	✓	×	×	✓	×	✓	×	✓
D40	✓	×	×	✓	×	✓	×	✓
D50	✓	✓	✓	✓	✓	✓	✓	✓
D60	✓	×	×	✓	×	✓	×	✓
D70	✓	×	×	✓	×	✓	×	✓
D80	✓	×	×	✓	×	✓	×	✓
D90	✓	×	×	✓	×	✓	×	✓
D100	✓	✓	✓	✓	✓	✓	✓	✓

Aimsun is a stochastic microscopic traffic simulation tool. Thus, multiple runs of each simulated scenario were executed so that the obtained simulation outputs can be statistically significant. Initially, five runs of the calibration scenario were executed (each corresponding to a different random seed) and statistics of the average network speed were collected. The required number of runs is determined based on the standard deviation of speed for a specific significance level and the tolerable error (Ott & Longnecker 2004). The significance level was selected to be 95% and the tolerable error equal to 0.5 km/h. Since the standard deviation of the average network speed of the initial sample was estimated as 0.398 km/h, the required number of runs was determined to be 10 according to Equation 18:

$$n = \frac{\left(z_{a/2}\right)^2 (s_d)^2}{E^2} \tag{18}$$

where n is the number of required runs, $z_{a/2}$ is the critical value of the normal distribution at the significance level $(1 - a)$, and E is the allowable error.

3.5.3 Simulation Scenarios – EVPA vs EVPA-DT

Impact assessment of advisory (EVPA) and automated (EVPA-DT) dynamic eco-driving was conducted for 8 different penetration rates of LVs, CVs and CAVs in the fleet mix. LVs were assumed manually driven and non-equipped with dynamic eco-driving technology, CVs could receive energy-efficient speed advice but drivers of the corresponding vehicles should manually adapt to it (EVPA-DT), while CAVs were assumed equipped with automation functions that could execute the provided speed advice in an accurate and timely manner (EVPA). A complete list of simulated scenarios per penetration rate of each vehicle type is depicted in **Table 3.6**. A single demand level corresponding to moderate traffic conditions was considered, since previous research indicated that EVPA does not operate efficiently during congestion (Mintsis et al. 2021). The latter demand level represents 50% of total trips simulated in the calibrated demand scenario. Additionally, simulation experiments explicitly encompassed passenger cars in this case. Finally, each simulation scenario was executed 10 times (cf. Section 3.5.2), so that statistical significance of simulation analysis was guaranteed.

Table 3.6. Simulated penetration rates of advisory and automated dynamic eco-driving services

Scenario No.	Vehicle Type Penetration Rate (%)		
	LV	**CV**	**CAV**
1	100	-	-
2	75	25	-
3	50	25	25
4	25	50	25
5	-	50	50
6	-	25	75
7	-	100	-
8	-	-	100

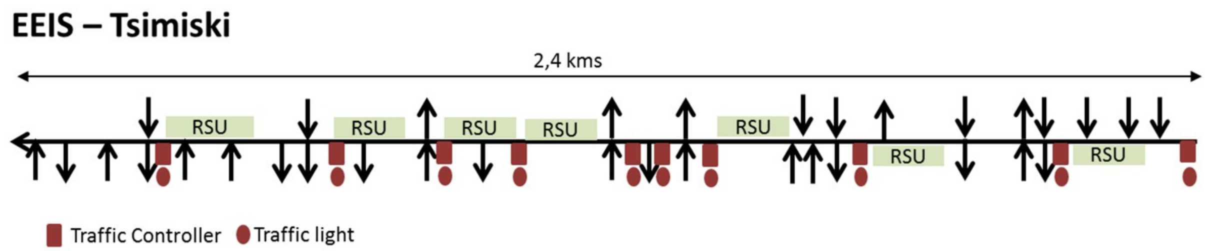
4 Data Collection from Real-world GLOSA Applications

4.1 Energy Efficient Intersection (EEI)

The Energy Efficient Intersection (EEI) is a GLOSA service that aims to reduce vehicular energy consumption and emissions in the vicinity of signalized intersections. The operation of the EEI service relies on I2V communication and specifically the exchange of the SPaT message between the infrastructure and the CV. Upon reception of the SPAT message the CV's OBU can estimate an energy efficient driving strategy which is presented to the driver via a Human-Machine Interface (HMI) in the form of speed advice and countdown information (increased anticipation of the upcoming traffic light status). A pilot operation of the EEI service was conducted along an urban arterial corridor (Tsimiski St.) in the city of Thessaloniki, Greece in the context of the Compass4D project (Mitsakis et al. 2014).

Tsimiski St. is one of the main urban arterial corridors of Thessaloniki's CBD which serves approximately 50.000 vehicles per weekday (60% of which are through-traffic). It is equipped with modern traffic monitoring and adaptive signal control devices, which are connected to the Traffic Management Centre (TMC) of the city. Tsimiski St. is congested during morning and afternoon peak hours, since the CBD of the city attracts multiple business, leisure and housing activities. Traffic lights along Tsimiski St. operate under fully adaptive mode (OMNIA system) and are managed by the Region of Central Macedonia. Information regarding the status of signal phase and timing is thus known and can be transmitted to CVs via 7 road-side units (RSUs) installed along the arterial. **Figure 4.1** depicts the location of the RSUs along Tsimiski St. (panel a), the location of traffic light controllers, as well as the side-streets intersecting the urban arterial corridor (panel b).

(a)



(b)

Figure 4.1. (a) RSU placement along Tsimiski St., (b) location of traffic light controllers and side-streets intersecting Tsimiski St.

4.1.1 System Architecture

4.1.1.1 Functional Overview

This section provides an abstract description of the EEI system which is platform and technology independent. It encompasses the main interactions among the functional elements of the EEI system which is comprised of several subsystems (vehicles, road-side infrastructure, TMC, other back-office installations) that cooperate to achieve some common goal or support a common policy. The latter collaboration entails different roles and actions per EEI system component. **Figure 4.2** shows a generic functional architecture of the EEI system, which is comprehensively presented in (Alcaraz et al. 2015).

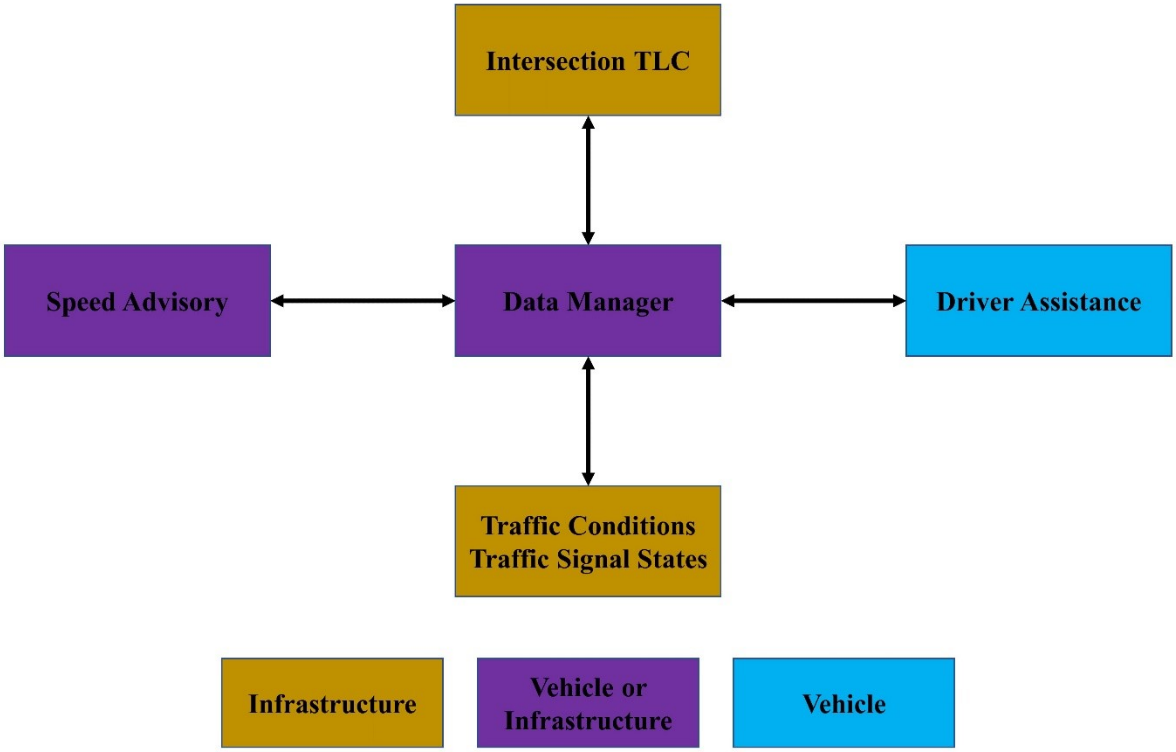


Figure 4.2. Functional architecture of the EEI system

A description of each functional component and its role in the context of the EEI system is provided below:

- **Intersection TLC:** It is comprised of the switching unit for the signal head states, the unit for processing detector data, the proxy gateway for the RSU and the communication unit to connect with the TMC.
- **Data Manager:** It enables the interfacing of the different functional components by providing access to static and dynamic data.
- **Traffic Conditions and Traffic Signal States:** This component enables the processing of traffic signal (SpaT information) and detector data (flow and speed counts).
- **Speed Advisory:** Computes energy optimal driving strategies for single vehicles and intersection approaches based on the SPaT message. It is installed on the vehicle side.
- **Driver Assistance:** It is the vehicle sub-system that interacts with the driver by presenting information from infrastructure and/or vehicle applications via HMI.

Moreover, the interactions among the functional components encompass the following flow of information and processes. The “Speed Advisory” component periodically reads from the “Data Manager” signal group states including residual times (SPaT information) and – if available – local traffic states via detector data. On the basis of the signal state information and prevailing traffic conditions “Speed Advisory” calculates energy optimal driving strategies (speed profiles) per intersection approach and signal group. The latter speed profiles are written into “Data Manager”, which periodically dispatches them to the “Driver Assistance”. The driver eventually receives speed advice via the “Driver Assistance” sub-system. An elaborate depiction of the information flow between the different functional components is shown in **Figure 4.3**.

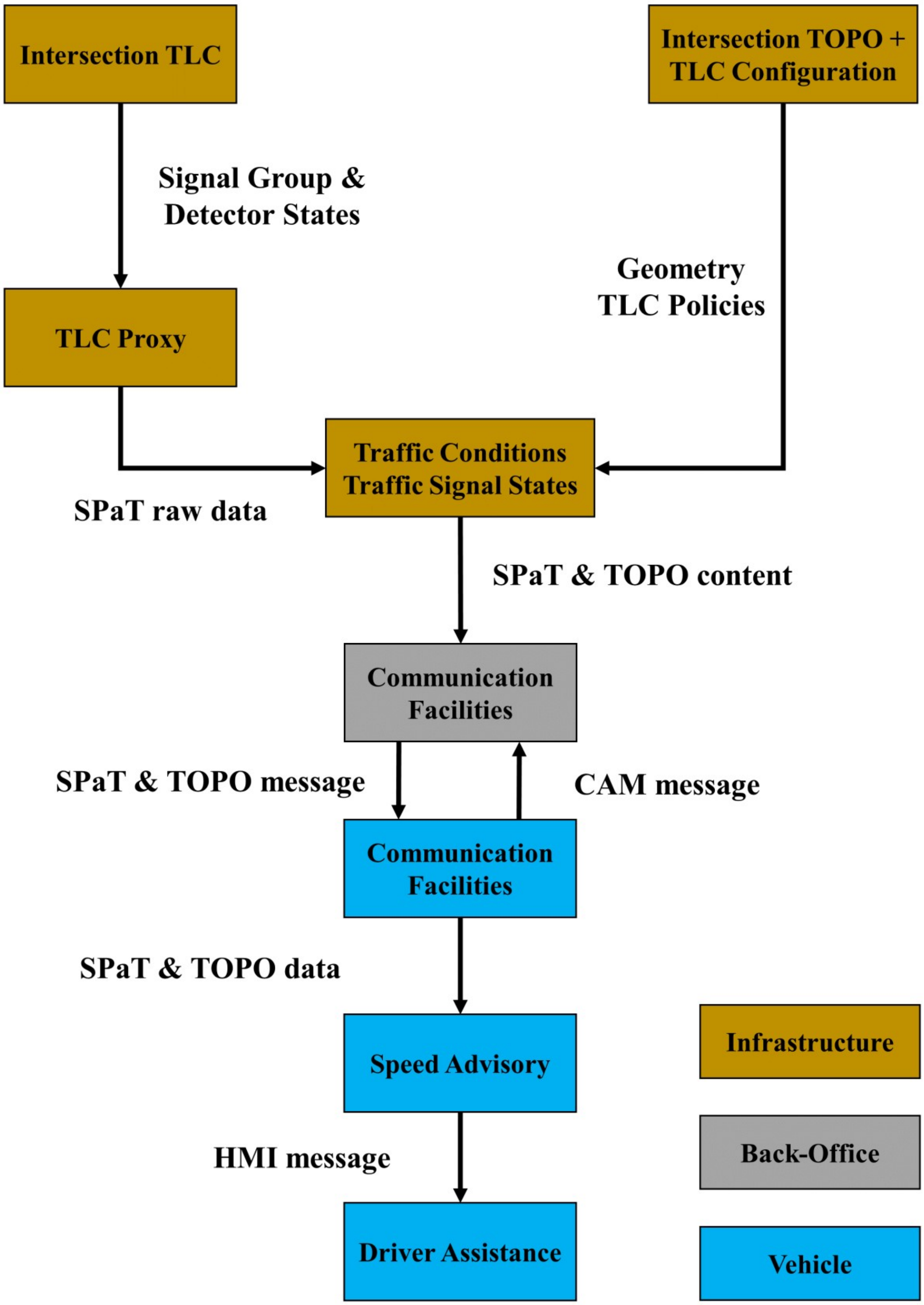


Figure 4.3. Information flow between functional components of the EEI system

4.1.1.2 Physical Architecture

The actual EEI system deployed along Tsimiski St. is comprised of the OBUs installed on the CVs, equipment installed on the road-side traffic controllers, software installed on the existing TMC of Thessaloniki, and the Pilot Operation Management System (POMS).

The existing TMC is equipped with hardware and network infrastructure (server room) that enables the hosting of the new applications (back-office software) required for the operation of the EEI system (**Figure 4.4**). The new applications are responsible for the generation of the C-ITS messages that make possible the communication between the CVs and infrastructure and their installation has been done remotely by the software suppliers. Via their installation the existing OMNIA & MISTIC software configurations of the existing TMC have been upgraded (Traffic Signal Predictor, Cooperative Back-end) in order to support C-ITS services such as EEI.

Figure 4.4. TMC at the city of Thessaloniki, Greece

The OMNIA platform installed on Tsimiski St. provides a common interface for all the traffic related systems in the city center of Thessaloniki. The system includes 12 traffic controllers, 8 surveillance cameras, 5 AUTOSCOPE cameras, 11 radars and 5 Variable Message Signs (VMS). It supports real-time monitoring of prevailing traffic conditions (MISTIC conducts validation, normalization and synchronization of the collected traffic data) and traffic signal plan selection.

Android tablets were selected as OBUs for installation on the CVs side (**Figure 4.5**). The devices were installed on the side of the dashboard and were used for both estimating and showing speed advice messages to taxi drivers. The EEI application developed in the context of the Compass4D project could be downloaded from the Google Play App Store and installed on the tablets. It was operating on the top of the taxi dispatching application.

Figure 4.5. OBU (Android Tablet) equipped with 3G/LTE capabilities

POMS was developed by CERTH/HIT and is hosted at its the mobility laboratory (**Figure 4.6**). It is comprised of hardware (2 large monitors) and software responsible for storing, processing and visualizing data collected during the pilot operation of the EEI system (**Figure 4.7**). It is equipped with the following features:

- A direct connection to the TMC used to obtain traffic related information.
- Connection to OBUs that upload data collected via the existing GPRS (3G/4G) connection of the taxi fleet company to POMS. This allows POMS to monitor the performance of the EEI services in real time.
- Information collected from the TMC and the OBUs is automatically processed and stored at a central database in a common format.

- Monitoring and visualization capabilities for inspecting the system operation and generating periodic reports that summarize its performance.

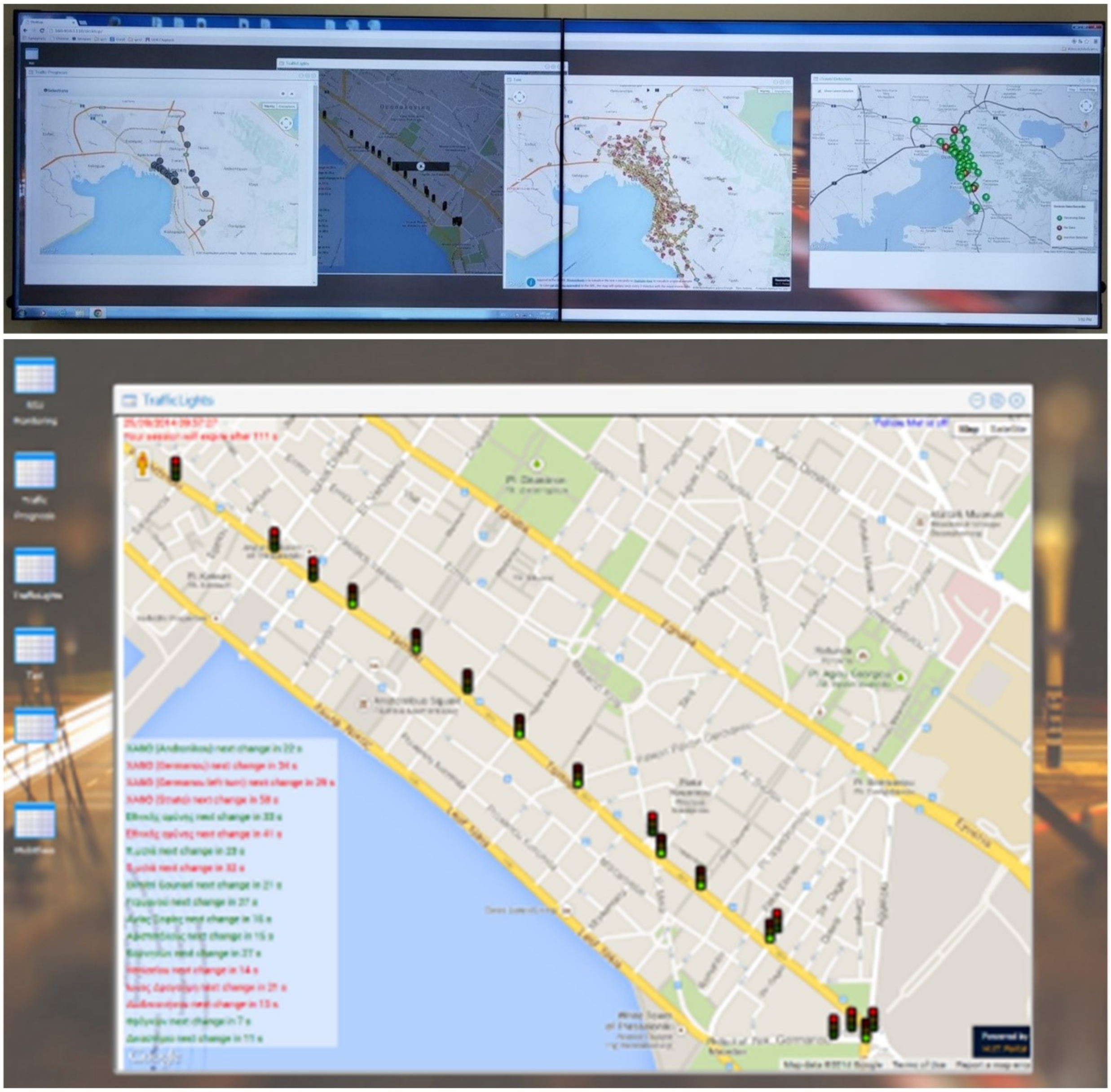


Figure 4.6. POMS infrastructure (hardware and software)

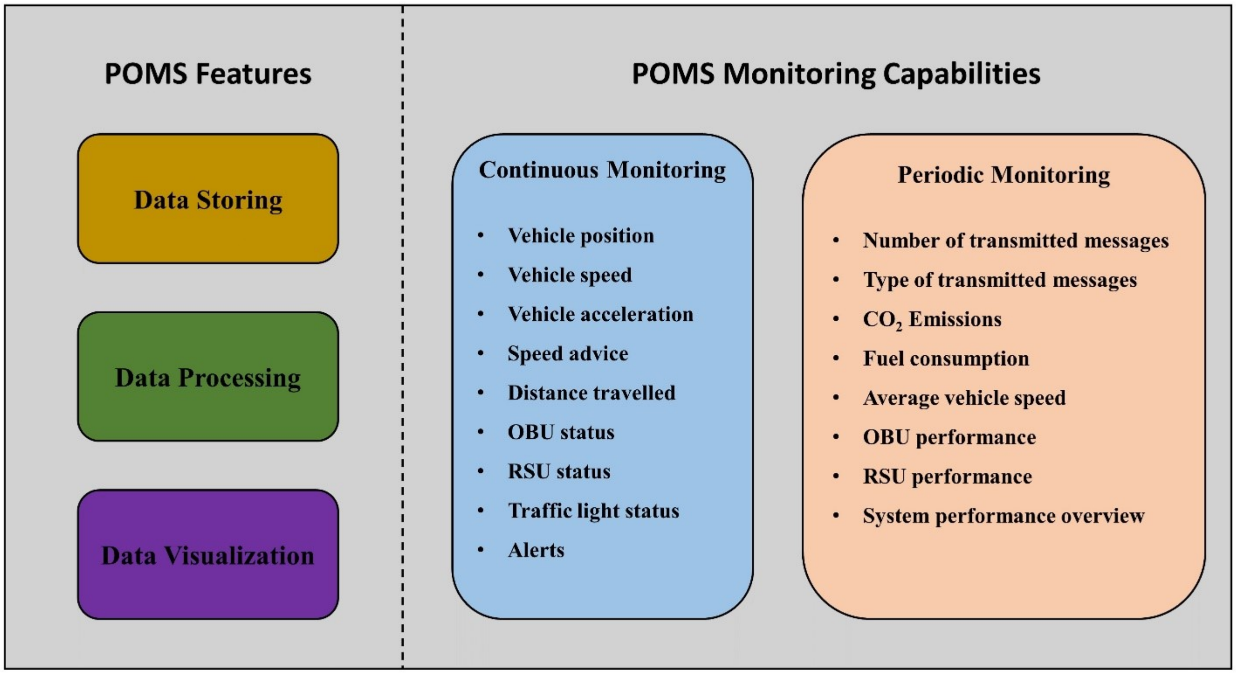


Figure 4.7. POMS features and monitoring capabilities

The physical architecture of the EEI system in the context of the pilot site of Thessaloniki is depicted in **Figure 4.8**. According the to the latter architecture, the Intersection TLCs initially send SPaT information to the TMC, which subsequently provides SPaT and TOPO information to a web service via OMNIA. OBUs connect to the web service via 3G/LTE in order to retrieve it and estimate an energy efficient driving strategy based on the current CV position and speed (GPS), the distance to the traffic light (TOPO), and the time to green/red (SPAT). The energy efficient speed advice is shown to the taxi driver via the OBU/HMI while the CV is approaching the traffic light. Finally, OMNIA collects Cooperative Awareness Messages (CAM) from CVs including information about their state (speed, acceleration, position and heading) and then transmits the relevant information to POMS.

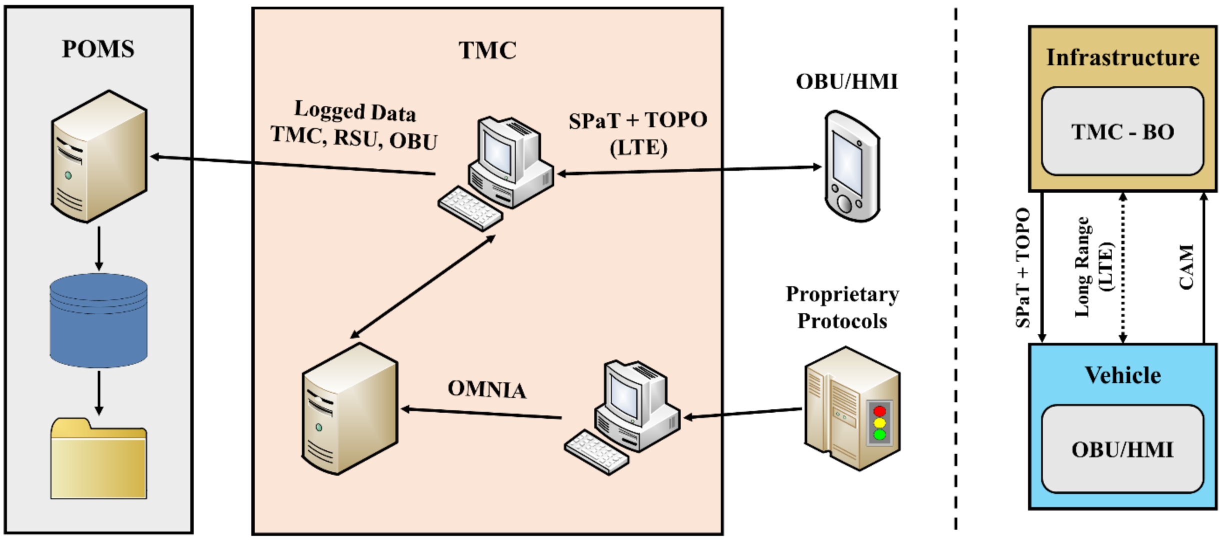


Figure 4.8. Physical architecture of the EEI system in the city of Thessaloniki

4.1.2 Pilot Operation and Management

The pilot operation of the EEI service encompassed 200 taxis equipped with OBUs that executed speed advice estimated based on the EVPA algorithm along 12 signalized intersection approaches. When CVs entered the EEI service activation zone (road sections between two consecutive traffic lights) the EEI application installed on the OBU would pop-up a dedicated screen showing information on remaining time to the next signal state and suggested speed advice so that CVs could cross the signalized intersection without stopping (**Figure 4.9**). Speed advice and signal status countdown information were provided every 3 seconds to taxi drivers who could manually adapt to it. Data from RSUs and OBUs were logged into a central database (maintained in POMS) in a time resolution similar to the speed advice update intervals (3 sec) throughout the whole pilot operation period.

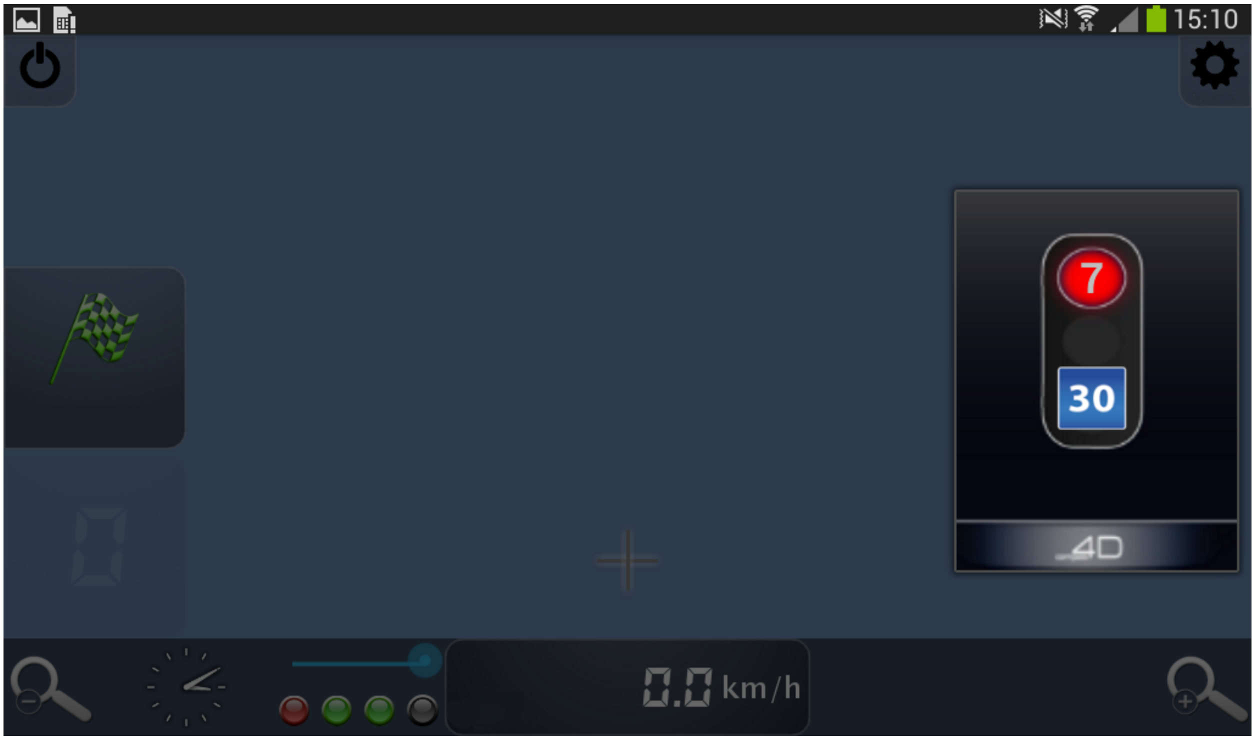


Figure 4.9. EEI application showing countdown information and speed advice

The pilot operation of the EEI service on Tsimiski St. spanned between November 2014 and August 2015. The baseline phase (EEI system deactivated) commenced on the 1st of November with a set of four drivers. The service was activated on the 15th of November for a set of 15 drivers in order to obtain preliminary feedback, while on the 15th of December the service became available for all 606 taxi drivers that were involved in this FOT. The timeline of the main phases of the pilot operation of the EEI service in Thessaloniki is depicted in **Table 4.1**.

Table 4.1. Main phases of the pilot operation of the EEI service in Thessaloniki

Dates	Operations
Oct – Nov 2014	Installation of EEI system equipment
Nov – Dec 2014	Baseline pilot operation (EEI system deactivated)
Jan – Aug 2015	Pilot operation of the EEI system
Apr – May 2015	Updates to system configuration and operation

A few representative figures summarizing EEI system performance throughout the pilot operation period are summarized below:

- 23,965,358 GPS locations were collected within the EEI service activation zone (179,506 per day). The average number of GPS locations per driver and per day was 872. Moreover, the number of collected GPS locations showed a linear increase during the pilot operation following the corresponding increase in the number of drivers participating in the FOT.
- The distribution of collected GPS location during the day coincides with demand for taxi trips. **Figure 4.10** indicates that peaks are observed at 13:00 pm and 18:00 pm.

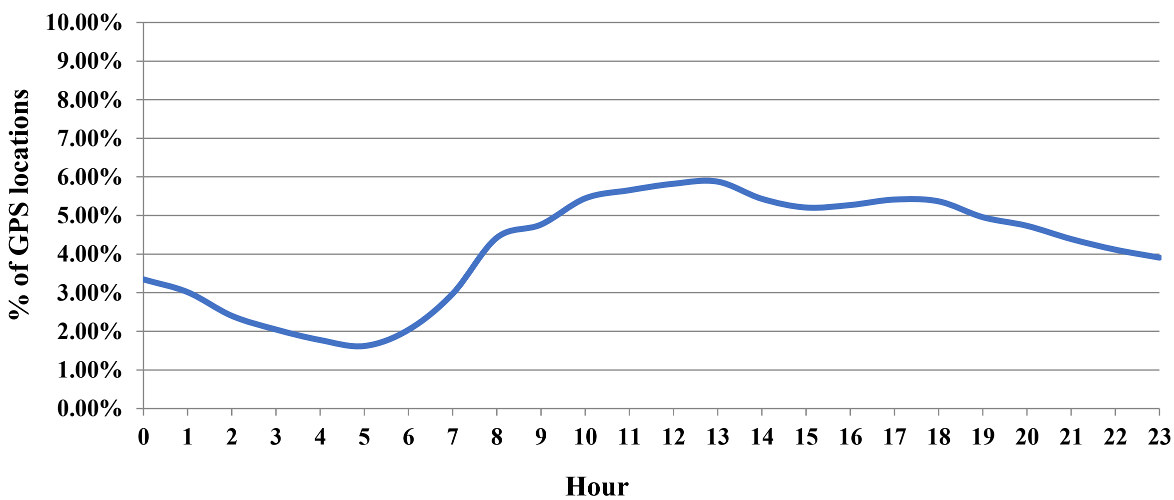


Figure 4.10. Distribution of collected GPS locations per hour of day

- 606 drivers participated in the pilot site activities covering a total of 95,566 km during 7,428 driving hours along Tsimiski St. The daily average number of drivers travelling within the EEI service activation zone was 178, while the average number of days that each driver tested the system was 76.
- Transmission of SPaT information from the RSUs side was primarily consistent between Apr – Jun 2015 (**Figure 4.11**), while the majority of RSUs transmitted SPaT messages for approximately 40% of the pilot operation timeline (**Figure 4.12**).

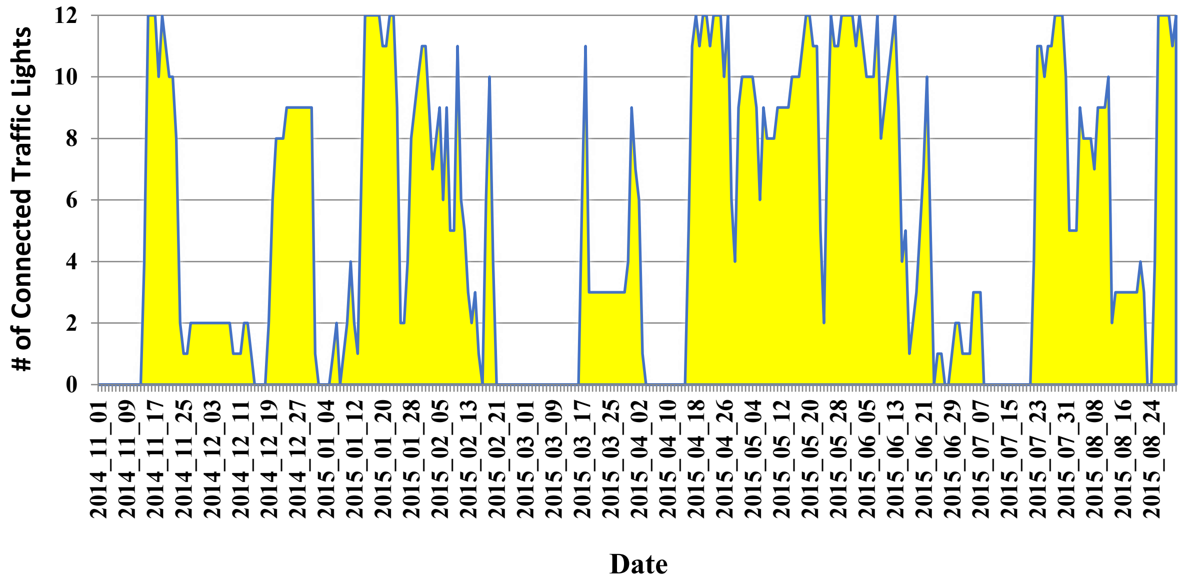


Figure 4.11. Number of connected TLCs providing SPaT information per day

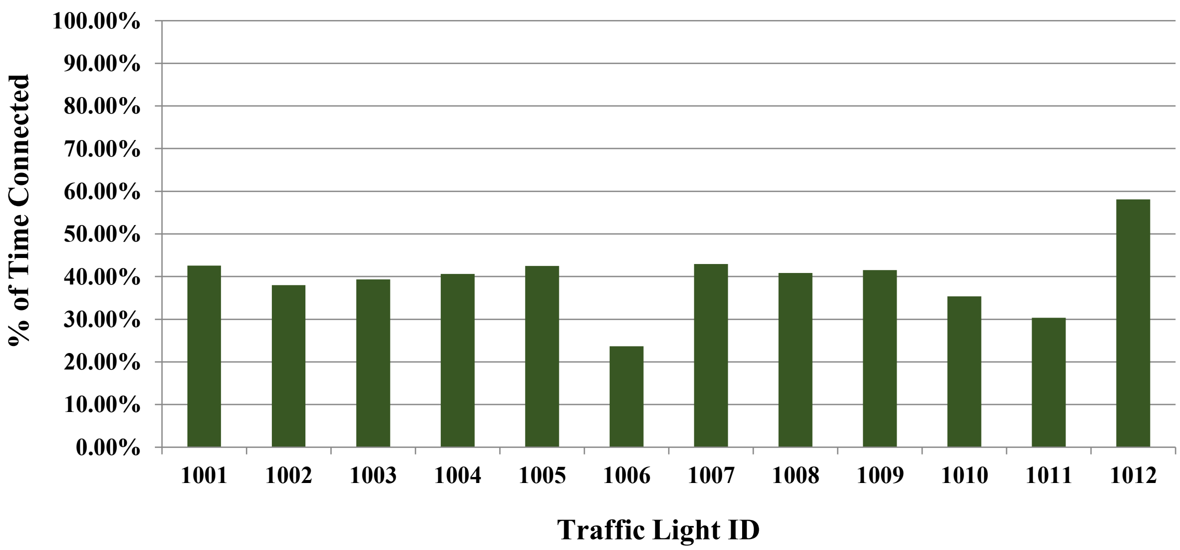


Figure 4.12. Percent of time that equipped TLCs were providing SPaT information throughout the pilot operation period

- A total of 8.086 speed advice messages were provided to taxi drivers. Acceleration advices were mainly given during green signal phase (**Table 4.2**), while deceleration and maintain speed advices were given during red signal phase as expected based on the EVPA control logic (**Table 4.3**). The most common situation was to advice drivers to attain 30 km/h driving speed, which was the minimum allowable speed that could be provided via the EEI service.

Table 4.2. Advised driving strategies during green phase

Speed Advise (km/h)	Driving Strategy		
	"Acceleration"	*"Deceleration"*	*"Maintain Speed"*
30	2156	716	688
40	1054	197	219
50	453	-	-

Table 4.3. Advised driving strategies during red phase

Speed Advise (km/h)	Driving Strategy		
	"Acceleration"	*"Deceleration"*	*"Maintain Speed"*
30	-	938	676
40	-	407	377
50	-	-	205

More elaborate information with respect to the pilot operation of the EEI service in Thessaloniki, Greece can be found in (Vernet et al. 2016).

4.1.3 Speed Advice Dataset

As aforementioned, real-time data pertaining to the pilot operation of the EEI service were recorded and stored in POMS. At the end of the pilot, the dataset in POMS contained 8090 distinct speed advice records, along with information pertaining to type of transmitted speed advice messages, suggested energy-optimal driving speeds, IDs of EEI service activation zones, timestamps of CVs upon entry in the latter zones, instantaneous position and speed of CVs, distance of CVs from the signalized intersection and remaining time of the current traffic signal status on message reception. An analysis of the latter dataset which was used for the development of the EVPA-DT can be found in (Mintsis et al. 2017). A description of the exact variables used for the development of the EVPA-DT is given in **Table 4.4**, while an excerpt of the actual dataset is provided in **Table 4.5**.

Table 4.4. Dataset variables used for the development of EVPA-DT

Variable Name	Variable Description
Vehicle ID	Unique ID assigned to individual CVs
Message Timestamp	Unique timestamp assigned to transmitted speed advice message
Zone ID	Unique ID assigned to each EEI service activation zone
Message Type	Type of transmitted messsage (“Accelerate”, “Decelerate”, and “Maintain”)
Speed Advice	Energy-optimal driving speed (km/h)
Vehicle Speed	Instantaneous speed of CV (km/h)
Distance to Traffic Light	Distance between CV and equipped signalized intersection (m)
Signal Group	Signal group for which energy-optimal speed advice is estimated
Remaining Phase Duration	Remaining time of running signal phase (sec)
Traffic Light Status	Status of traffic light (“Green”, or “Red”)

Table 4.5. Excerpt from the speed advice dataset maintained in POMS

Vehicle ID	Message Timestamp	Zone ID	Message Type	Speed Advice (km/h)	Vehicle Speed (km/h)	Distance to Traffic Light (m)	Signal Group	Remaining Phase Duration (sec)	Traffic Light Status
50065	2014-11-22 08:32:20.000	500651416645088	decelerate	30	47.856	291.43	100201	18	G
50065	2014-11-22 08:32:23.000	500651416645088	decelerate	30	53.195	288.83	100201	15	G
50123	2014-11-26 16:30:35.000	501231417019389	accelerate	30	36.136	372.36	101101	13	G
50123	2014-11-26 16:30:38.000	501231417019389	accelerate	30	37.944	347.82	101101	7	G
50123	2014-11-26 16:30:41.000	501231417019389	maintain	30	40.945	313.57	101101	4	G
50123	2014-11-26 16:30:47.000	501231417019389	maintain	30	40.446	215.38	101101	24	R
50123	2014-11-26 16:30:50.000	501231417019389	maintain	30	40.346	185.82	101101	21	R
50123	2014-11-26 16:31:05.000	501231417019389	decelerate	30	17.615	116.45	101201	12	R
50123	2014-11-26 16:31:08.000	501231417019389	decelerate	30	15.784	79.35	101201	9	R
50123	2014-11-26 16:31:08.000	501231417019389	decelerate	30	15.784	79.35	101201	6	R
50123	2014-11-26 16:31:11.000	501231417019389	maintain	30	11.775	50.89	101201	3	R
50123	2014-11-26 17:28:34.000	501231417022909	accelerate	40	33.007	462.24	101101	40	G
…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…
50123	2014-11-27 14:35:42.000	501231417098934	accelerate	30	19.489	317.11	101101	64	G
50123	2014-11-27 14:35:45.000	501231417098934	accelerate	40	19.549	294.11	101101	64	G
50123	2014-11-27 14:35:48.000	501231417098934	accelerate	40	20.983	268.71	101101	40	G
50123	2014-11-27 14:35:51.000	501231417098934	accelerate	40	18.791	241.1	101101	40	G
50123	2014-11-27 14:36:00.000	501231417098934	decelerate	40	12.709	140.61	101101	34	G
50123	2014-11-27 14:36:03.000	501231417098934	accelerate	50	10.562	97.24	101101	28	G

5 Implementation and Results

Simulation results have been comprehensively analyzed for two sets of simulation scenarios presented in the methodological section (cf. Section 3.5). Initially, the performance of VPA and EVPA systems has been compared according to environmental benefits and traffic impacts. Subsequently, the structure of the DT is presented and its results are interpreted to explain driver adaptation to dynamic eco-driving advice. Finally, the performance of advisory (EVPA-DT) and automated (EVPA) dynamic eco-driving systems has been assessed with the use of mobility, safety and environmental performance measurements.

5.1 Impact Assessment – VPA vs EVPA Performance

Simulative assessment of scenarios depicted in **Table 3.5** considered environmental and traffic efficiency KPIs, and was conducted for the following levels of analysis:

- Individual vehicle performance under manual, VPA and EVPA driving
- Dynamic eco-driving service zone (local impacts at IA level)
- Network scale (encompassing road sections beyond dynamic eco-driving service zones)

Individual vehicle behavior was examined on the basis of vehicle trajectory output provided by Aimsun. To this end, a custom web-based application named TrajAIM (Trajectory Analysis for Microsimulation) that enables the generation of multiple plots from vehicle trajectory data (e.g. distance vs time, speed vs distance, acceleration vs speed etc.) and the comparison of vehicle trajectories from different simulation experiments was developed. Elaborate information with respect to TrajAIM capabilities and features can be found in Appendix B. Local and corridor-wide impacts of dynamic eco-driving were evaluated with the use of sub-path (spatially coinciding with dynamic eco-driving service zones) and system (entire network) simulation output.

A specific notation scheme was adopted to simplify description of simulation results. Capital letters were assumed for different traffic lights of the simulated network appearing in **Figure 3.3** and were used to denote IAs of particular interest to this analysis. For example, {N→M} denotes the IA between traffic lights N and M. Moreover, the arrow symbol dictates the direction of traffic along the IA. For scenarios encompassing dynamic eco-driving, it is also implied that VPA and EVPA are deployed along the corresponding IA.

5.1.1 Individual Vehicle Performance

The analysis of individual vehicle performance encompasses four different types of plots:

- speed vs distance
- speed vs time
- cumulative CO_2 emissions vs distance, and
- acceleration vs speed.

These plots reveal the influence of dynamic eco-driving on CV behavior and the corresponding CV performance in terms of CO_2 emissions. The CV performance displayed in **Figure 5.1** and **Figure 5.2** pertains to traffic demand level D50, penetration rate P100 and two different routes of the test site.

Figure 5.1 shows information about a single CV performance along IA:{R→Q} (one-way multi-lane road segment). While the CV has to stop at the traffic light in the "do-nothing" scenario, it can adopt a deceleration strategy in the VPA and EVPA scenarios to avoid a standstill and generate lesser CO_2 emissions. However, it can be seen (in the focus area of the right top plot) that the EVPA algorithm allows the CV to cruise at a marginally lower speed compared to the VPA one, and consequently begin acceleration approximately 10 m upstream of the traffic light (when the signal status changes to green).

As explained in Section 3.1.2 of this dissertation, the latter behavior can promote comfort, safety and user acceptance of the system since the CV will not reach the traffic light (in red status) at cruising speed (enhanced speed advice), and increase intersection safety since there will be further available time for intersection clearance or CV tactical maneuvering in case of red light running from vehicles driving along other directions (possible scenario in mixed traffic conditions). Interestingly, the EVPA deceleration strategy does not adversely impact CO_2 emissions savings. This is also justified by the same acceleration/deceleration patterns between VPA and EVPA depicted in **Figure 5.1** (bottom right plot).

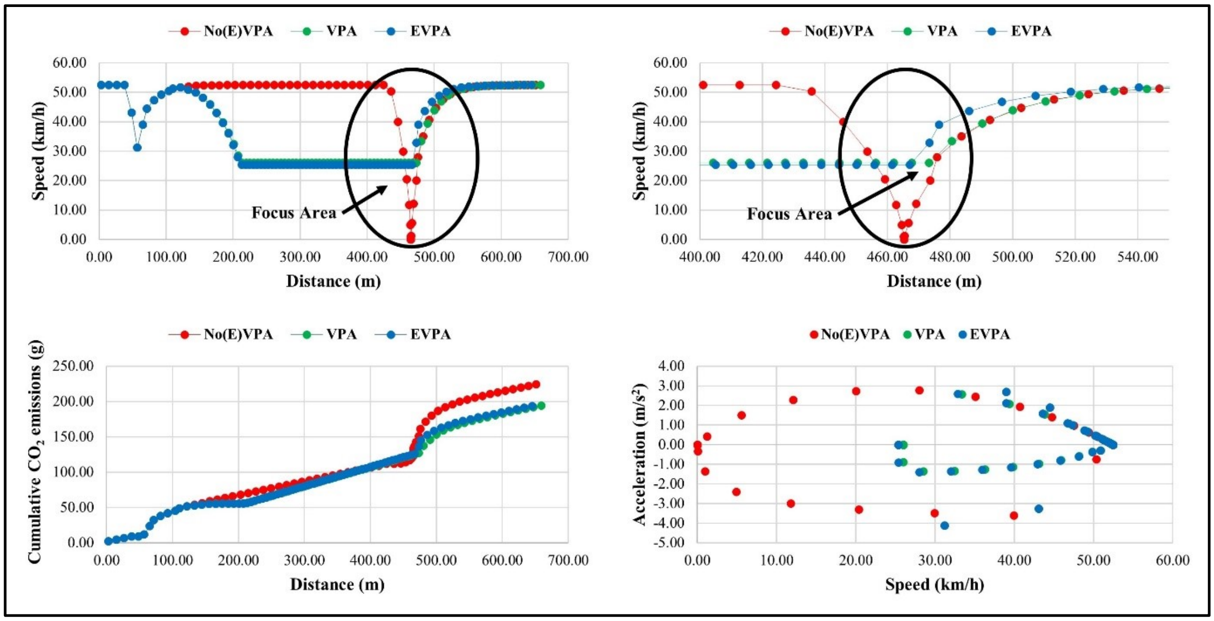


Figure 5.1. VPA vs EVPA: Individual vehicle performance on IA:{R→Q}

The behavior of an individual CV with (VPA and EVPA) and without ("do-nothing") dynamic eco-driving technology is examined along the urban arterial corridor {O→A}. Every signalized intersection is equipped with an RSU along the corridor (one-way four-lane urban arterial corridor with reserved bus lane on the right-most lane and side-street parking on the left-most lane), thus enabling CVs to implement separate acceleration/deceleration strategies per IA.

Figure 5.2 (top plots) indicates that VPA allows the CV to successfully execute a deceleration strategy thrice, while EVPA only once given road characteristics, prevailing traffic conditions, and deployed traffic signal plan. However, the first two deceleration strategies suggested by VPA lead to rather low cruising speeds (< 20 km/h) that can be non-acceptable by drivers or passengers in the case of fully automated vehicles. Moreover, they yield CO_2 emissions savings that are not significant compared to the "do-nothing" and EVPA scenarios when the same CV has to fully stop at the traffic light and accelerate back to desired speed from standstill.

Nonetheless, a noteworthy observation is that dynamic eco-driving alters the traffic patterns of CVs even in space and time intervals that energy optimal driving strategies are not applied or possible. This phenomenon can generate unfavorable conditions for the CV due to surrounding traffic (queued vehicles disrupting the adoption of speed advice) or mistimed entrance at an intersection approach. Hence, the cumulative CO_2 emissions of the CV (EVPA case) eventually surpass those of the unequipped equivalent (left bottom plot) along the examined path. Finally, results demonstrate that the VPA produces milder acceleration/deceleration rates for the examined CV (right bottom plot), and thus lesser cumulative CO_2 emissions along its travelled path {O→A}.

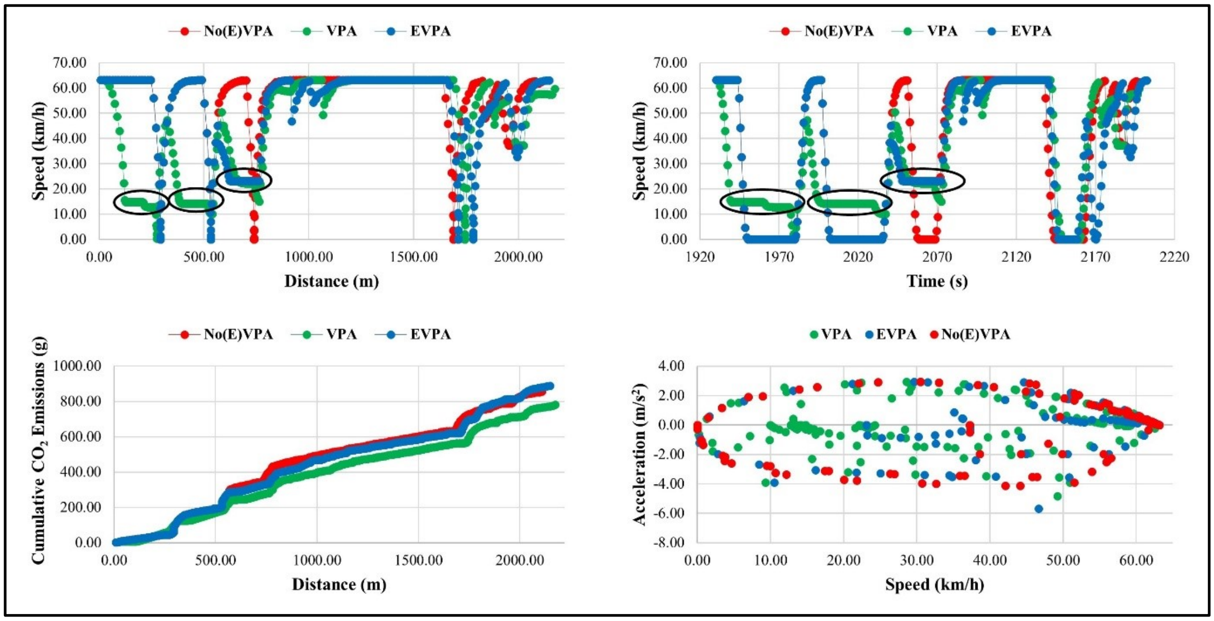


Figure 5.2. VPA vs EVPA: Individual vehicle performance on urban arterial corridor {O→A}

5.1.2 Dynamic Eco-driving Service Zone

A plethora of information is provided to scrutinize the performance of dynamic eco-driving on two benchmark IAs of the test site and compare the behavior of VPA and EVPA methods. The evaluation of the different algorithms is conducted in terms of:

- CO_2 emissions (gr/km)
- number of stops per vehicle, and
- mean travel time (seconds).

The reported travel time and CO_2 emissions results also consider the road sections downstream of the examined IAs where benefits from energy efficient deceleration strategies can be realized. Results are analyzed for traffic demand levels D50 (uncongested conditions) and D100 (congested conditions), and penetration rates ranging between P5 – P100.

IA:{R→Q} was selected as benchmark in the context of this dissertation since it is isolated and vehicle arrival patterns are not influenced by implementation of dynamic eco-driving along upstream IAs (**Figure 5.3**). Moreover, it is a one-way four-lane road section spanning up to 360 m where there is available space for CVs to adopt dynamic eco-driving maneuvers. SPaT messages are received up to 360 m upstream of signalized intersection Q by CVs, and 65.00 s of the signal cycle (72.22% of the cycle duration) are allocated to the through movement (speed advice is estimated specifically for this movement). The minimum cruising speed is 20 km/h in the case of EPVA, and 10 km/h in the case of VPA. An influence zone calibration parameter of 0.01 indicates that CVs will reach the traffic signal on red light status while driving at cruising speed at the end of a deceleration strategy (VPA scenario). On the other hand, a 0.5 parameter value (EVPA scenario) ensures that CVs' acceleration will commence prior to arrival on red signal status to the intersection stop line.

Intersection Approach Name	M. Alexandrou Ave. – {R → Q}	
Communication Zone	SPaT received 360 m upstream of Traffic Light Q	
	Algorithmic Parameters	
Algorithm Name	**EVPA**	**VPA**
Acceleration Rate Parameter (m/s^2)	0.15	0.15
Influence Zone Calibration Parameter	0.50	0.01
Minimum Cruising Speed after Deceleration (km/h)	20.00	10.00
Car-following Rule	Enabled	Enabled
Enforce Minimum Allowable Speed Rule	Yes	Yes
	Traffic Signal Plan (Traffic Light: Q)	
Control Type	Pre-timed	
Cycle Duration (sec)	90.00	
Green Time allocated for Through Movement (sec)	65.00	
Green Time/Cycle Duration (%)	72.22	

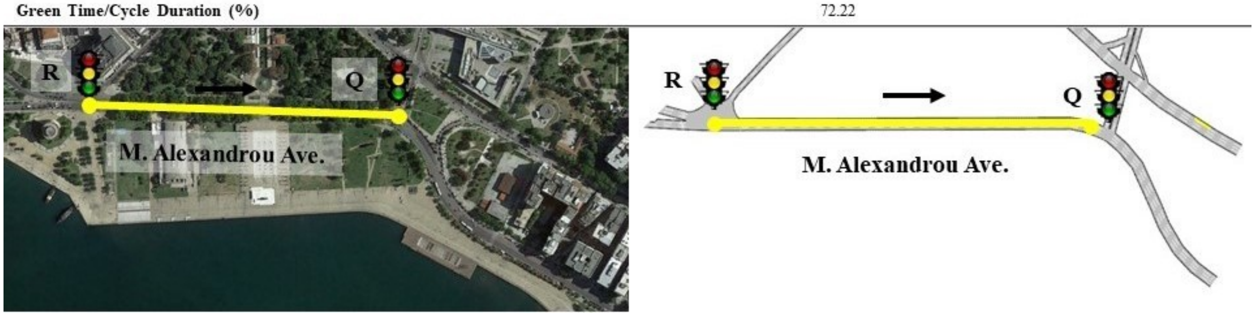


Figure 5.3. Dynamic eco-driving deployment information on IA:{R→Q}

Despite increased demand in D100, traffic conditions remain uncongested along IA:{R→Q} (**Figure 5.4**). Mean travel time (min/km) is slightly affected by dynamic eco-driving (bottom plots) and mostly for higher penetration rates (> 75%). Both VPA and EVPA manage to significantly reduce idling (number of stops/veh) in mixed traffic, while stop events almost vanish in the case of fully equipped fleet (middle plots). However, it can be noticed that for low to intermediate penetration rates (P15 – P50) and highest demand level (D100) EVPA outperforms VPA in terms of preventing CV stops at traffic light Q. VPA advices lower cruising speeds in the context of deceleration strategies, and thus non-equipped vehicles (which represent the highest share in the fleet mix for low penetration rates of dynamic eco-driving technology) tend to overpass CVs causing more stops at traffic lights compared to the EVPA scenario. Both algorithms generate CO_2 emissions savings beyond medium penetration rate (P50) that are maximized for fully equipped fleet (P100). Maximum CO_2 emissions savings rise approximately to 7.0% (top plots) and do not occur in the expense of significant travel time costs (bottom plots). Moreover, VPA and EVPA exhibit similar CO_2 emissions savings potential in the case of IA:{R→Q}.

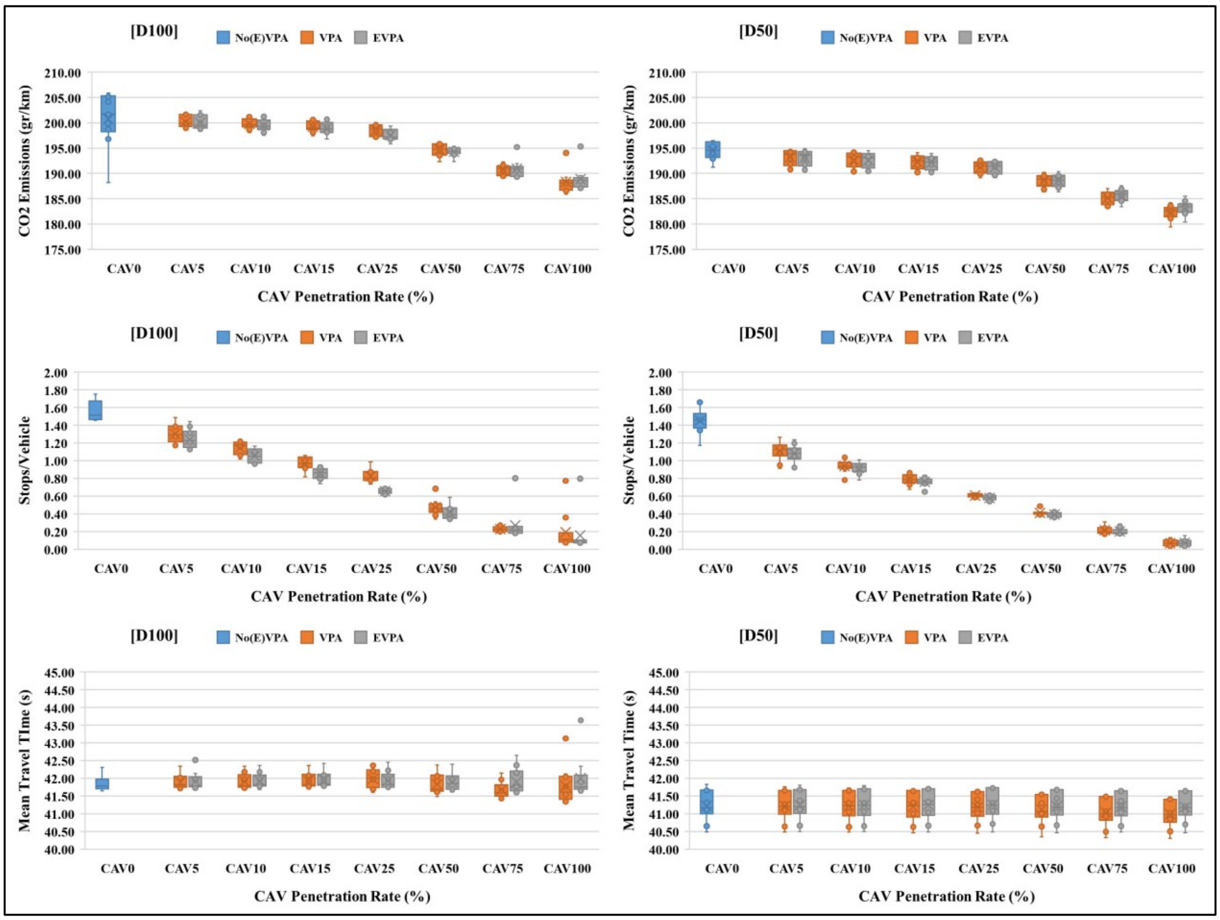


Figure 5.4. VPA vs EVPA: KPIs of dynamic eco-driving deployment on IA:{R→Q}

The reason IA:{N→M} is selected as benchmark and studied explicitly is multifold (**Figure 5.5**). IA:{N→M} is part of urban arterial corridor {O→A} where dynamic eco-driving is deployed on all signalized IAs (**Figure 3.3**). It is one of the few IAs on urban arterial corridor {O→A} that spans 240 m long, thus providing enough space for CVs to execute dynamic eco-driving maneuvers. Additionally, it is fed with traffic by three different IAs (i.e. {O→N}, {P→N}, and {R→N}) where dynamic eco-driving is also applied. Hence, vehicle arrival patterns vary significantly on IA:{N→M} giving the opportunity to test dynamic eco-driving for different CV approach speeds (also influenced upstream by dynamic eco-driving). Furthermore, 62.00 s of the signal cycle (68.89 % of the cycle duration) are allocated to the through movement (speed advice is estimated specifically for this movement). Consequently, there is adequate red duration to induce energy efficient deceleration strategies. Algorithmic settings (VPA and EVPA) for IA:{N→M} are similar to that of {R→Q}.

Intersection Approach Name	Tsimiski St. – {N → M}	
Communication Zone	SPaT received 240 m upstream of Traffic Light M	
	Algorithmic Parameters	
Algorithm Name	**EVPA**	**VPA**
Acceleration Rate Parameter (m/s^2)	0.15	0.15
Influence Zone Calibration Parameter	0.50	0.01
Minimum Cruising Speed after Deceleration (km/h)	20.00	10.00
Car-following Rule	Enabled	Enabled
Enforce Minimum Allowable Speed Rule	Yes	Yes
	Traffic Signal Plan (Traffic Light: M)	
Control Type	Pre-timed	
Cycle Duration (sec)	90.00	
Green Time allocated for Through Movement (sec)	62.00	
Green Time/Cycle Duration (%)	68.89	

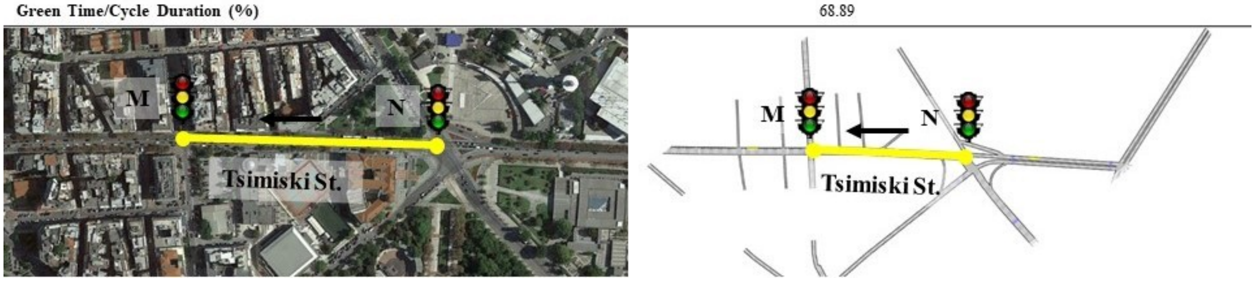


Figure 5.5. Dynamic eco-driving deployment information on intersection approach {N→M}

Congested conditions prevail along IA:{N→M} for the highest demand level (D100). Mean travel time increases four times compared to uncongested conditions (D50) for the "do-nothing" scenario (**Figure 5.6**). The deployment of dynamic eco-driving further disrupts traffic flow on IA:{N→M} for higher penetration rates. As explained in Section 3 of this dissertation, both VPA and EVPA do not account for traffic light queues when estimating acceleration/deceleration strategies. Therefore, CVs can receive speed advice upon entrance to the intersection approach but eventually will need to abort it (due to reaching tail of queue), thus escalating travel time and CO_2 emissions. Noticeably, EVPA outperforms VPA on the basis of the examined KPIs (left plots – D100) for the majority of the tested penetration rates (most significant difference for higher penetration rates). Due to the higher minimum speed advice threshold in the case of EVPA (i.e. 20 km/h), lesser speed advices are provided to equipped vehicles, hence reducing the intensity of disruption to the traffic flow and CO_2 emissions performance incurred by dynamic eco-driving.

On the other hand, traffic conditions are uncongested along IA:{N→M} for the intermediate demand scenario (D50). Queued traffic almost diminishes at traffic light M (**Figure 5.6** – middle right plot) for higher penetration rates (> 75%). EVPA generates CO_2 emissions savings along IA:{N→M}, which approximately rise to 13.0% and 8.5% reduction compared to the “do-nothing” and VPA scenarios respectively (**Figure 5.6** – top right plot). Notably, EVPA exhibits significantly improved performance compared to VPA with respect to emissions reduction, although it adapts speed advice to improve comfort and safety. Finally, it can be observed that for low to intermediate penetration rates vehicle stops increase with deployment of VPA. This phenomenon occurs due to the behavior of non-equipped vehicles as it was explained in the aforementioned analysis of simulation results for IA:{R→Q} as well.

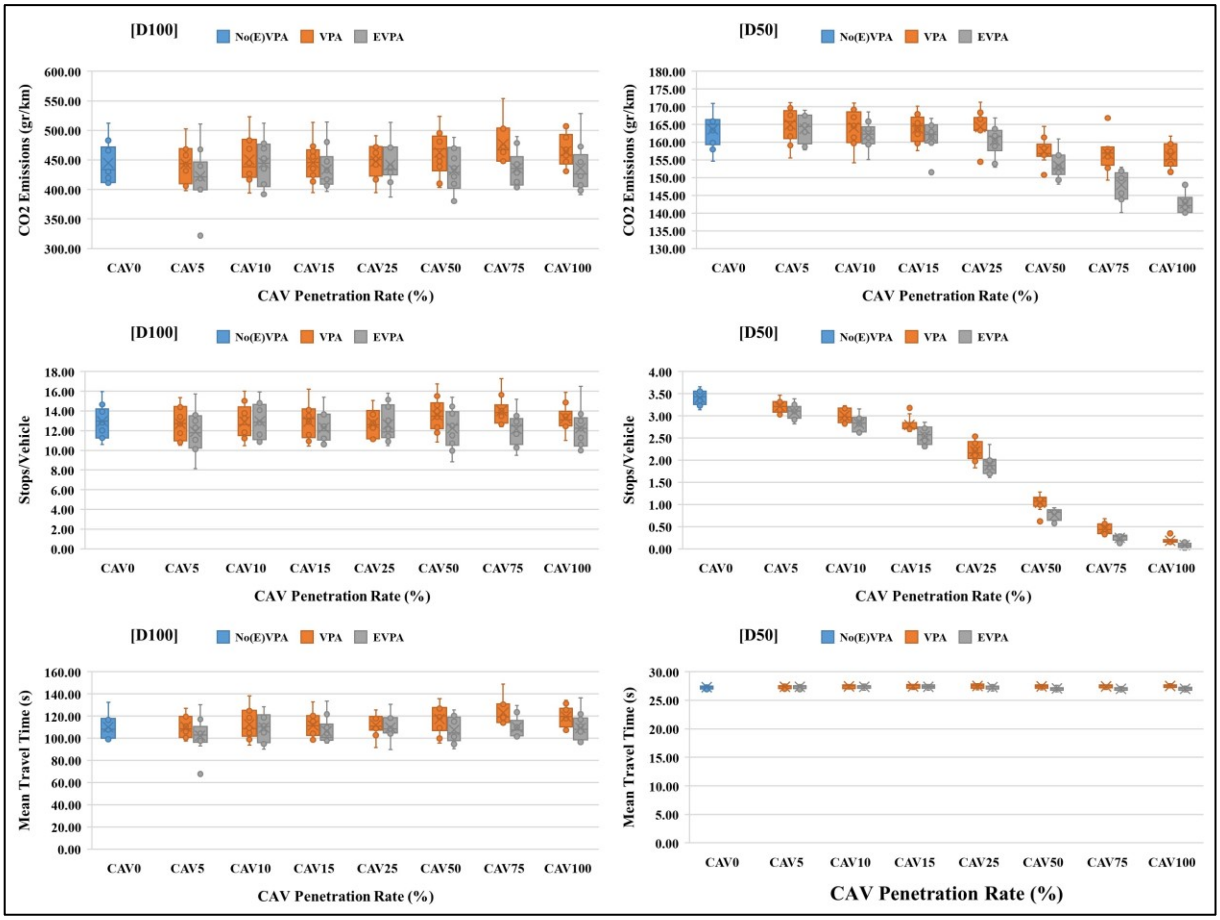


Figure 5.6. VPA vs EVPA: KPIs of dynamic eco-driving deployment on IA:{N→M}

5.1.3 Corridor-wide Impacts

The impacts of dynamic eco-driving (VPA and EVPA) on network performance are assessed in terms of:

- average network speed
- CO_2 emissions per kilometer driven (gr/km), and
- average stop time per kilometer driven (s/km).

Corridor-wide statistics are reported for the full spectrum of examined demand levels (D10 – D100) and two penetration rates (P50 and P100) to identify triggering points for VPA and EVPA activation according to the prevailing traffic conditions on the examined test site.

Figure 5.7 indicates that both VPA and EVPA can yield CO_2 emissions savings when average network speed is over 25 km/h (D10 – D80), but the latter savings are insignificant though.

Moreover, corridor-wide savings diminish as traffic demand shifts from light to moderate (D10→D80). On the other hand, the tested algorithms exhibit similar performance to the do-nothing" case for heavy traffic conditions (congestion) when average stop time increases significantly both for 50% and 100% penetration rates. As aforementioned, this is reasonable considering that both algorithms are not designed to account for traffic light queues when estimating energy efficient speed advice. Moreover, it can be seen that lower share of CVs in the fleet mix (P50) results in slightly lesser impacts of dynamic eco-driving on the network scale compared to the case of fully equipped fleet (P100).

VPA generates marginally higher CO_2 emissions savings compared to EVPA in uncongested conditions when the whole test site is considered. However, these savings are realized in the expense of marginally increased travel times. Longer travel times are expected in the VPA scenarios due to the minimum speed advice threshold (i.e. 10 km/h). Lower CO_2 emissions on the network level can be attributed to more energy efficient patterns generated by VPA at areas of the network where speed advice is not implemented successfully or at all as previously highlighted and explained in the analysis of single vehicle performance. Finally, the lower stop times observed for VPA can be also ascribed to crawling speeds that can be advised by the latter algorithm.

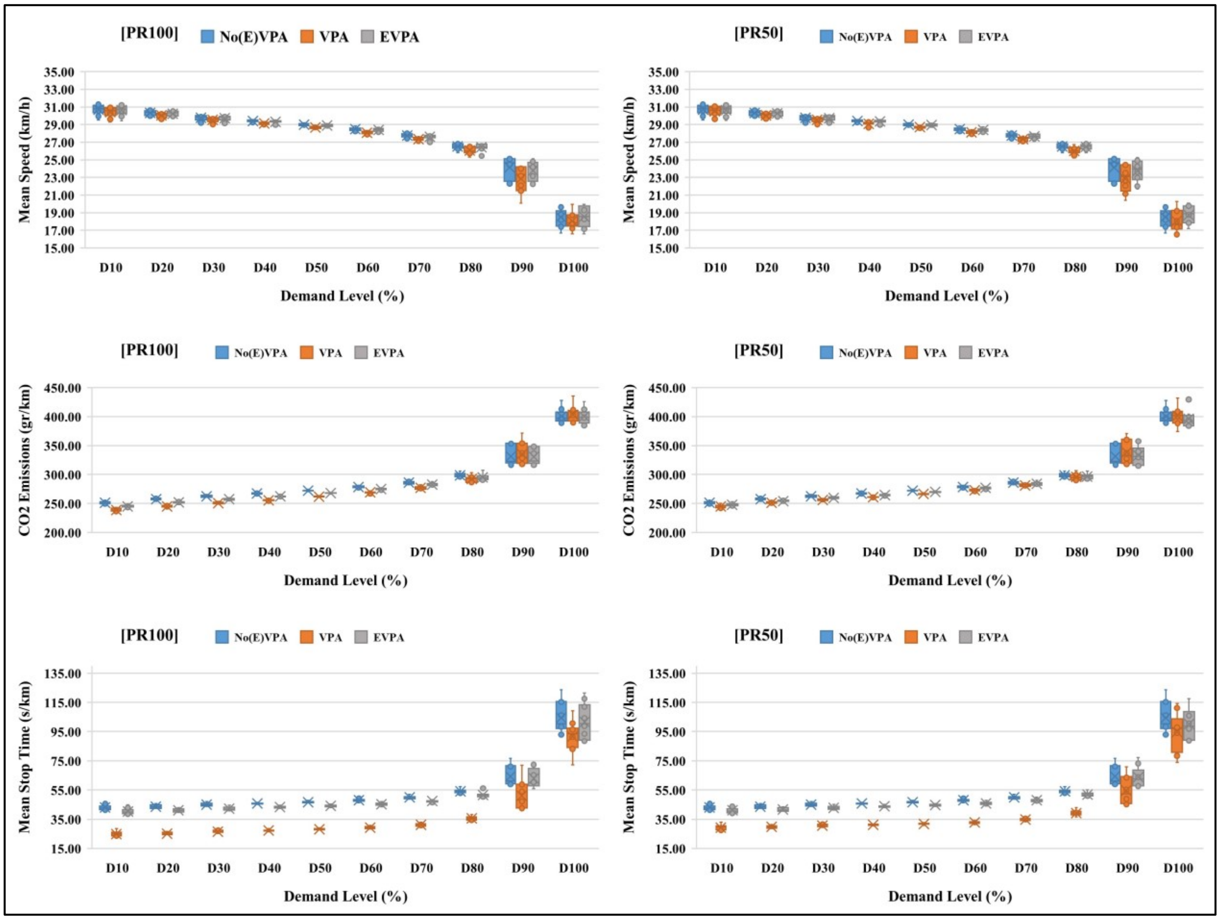


Figure 5.7. VPA vs EVPA: Average network KPIs of dynamic eco-driving deployment on the examined urban arterial corridor

5.1.4 Discussion

Simulation results indicate that EVPA can exhibit similar or even better performance compared to VPA for specific road characteristics, activation distances of dynamic eco-driving service, traffic conditions and traffic signal plans, despite adapting speed advice to improve user acceptance and intersection safety. It is also noteworthy, that improved EVPA performance occurs when VPA advices deceleration strategies that encompass cruising speeds that undercut the minimum cruising speed after deceleration ($v_{\min}$). For this reason EVPA and VPA performance is similar along IA:{R→Q}, while EVPA significantly outperforms VPA in the case of IA:{N→M}. Moreover, the fact that EVPA suggests vehicle acceleration prior to CV arrival at the signalized intersection at the end of deceleration strategies does not weaken its ability to yield CO_2 emissions savings.

On the other hand, the analysis of individual vehicle performance and corridor-wide statistics revealed that VPA slightly outperforms EVPA in terms of environmental benefits on the network level. Nonetheless, this occurs at the cost of marginally higher travel times. Both VPA and EVPA generate different traffic patterns on the examined test site even in areas where speed advice is not feasible due to surrounding traffic or mistimed arrival at intersection approach.

Moreover, both algorithms do not produce significant corridor-wide emissions savings compared to the "do-nothing" scenario even for low to moderate traffic demand. As it can be seen in **Figure 3.3**, traffic lights are closely spaced beyond traffic light M along the urban arterial corridor {O→A}, where the speed limit is 50 km/h along {O→A}. Thus, dynamic eco-driving benefits diminish due to low approach speeds, confined speed range and space for adapting to speed advice, and VPA/EVPA algorithmic logic that considers single signalized intersections for estimating energy efficient driving strategies instead of multi-intersection corridors controlled by traffic lights. Previous research has also indicated that inappropriate deployment of dynamic eco-driving could even generate environmental disbenefits due to unfavorable factors (Rakha et al. 2012; Rakha et al. 2016; Tielert et al. 2010; Xia et al. 2013a). Hence, the deployment scheme of dynamic eco-driving that encompasses road design characteristics, activation distance of the service, traffic signal plans and traffic conditions significantly affect its energy efficiency and emissions savings potential. According to the latter information, it is important to identify the deployment scheme that enables EVPA to perform efficiently (in terms of CO_2 emissions reduction) on the network scale. Thus, travel time, user acceptance and safety benefits also provided by EVPA can be realized.

Additionally, we show that VPA and EVPA deteriorate traffic conditions during congestion since they do not consider traffic light queues for speed advice estimation. The corresponding simulation results pose irregular patterns with respect to speed advice efficiency and CO_2 emissions. Notably, interactions between CVs and LVs become more complex especially in the case of VPA when crawling speeds can be advised to CVs. Finally, it is of note that we assumed full diver compliance to speed advice in the context of these simulation scenarios. However, human factors can exert significant impacts on traffic flow performance (Ni et al. 2017) and intersection safety (Hurwitz 2009; Johansson & Rumar 1971).

5.2 Speed Advice Adaptation modelling based on Real World Data

Information Gain and greedy CFS algorithm were used to extract the relative significance of each feature included in **Table 4.5** to speed advice compliance (cf. Section 3.2.1). Results of the aforementioned analysis are summarized in **Figure 5.8**. The three most critical variables are the distance from the traffic lights when speed advice is received by the vehicle (*TrafficLightDist*), the time remaining until the change of the traffic light status (*SecondsTillChange*), and the type of message (i.e. maintain speed, accelerate, decelerate) the driver receives from the dynamic eco-driving system (*MessageToDriver*). These results are significant for the development of predictive algorithms that may explain the compliance of the users to speed advice and enhance their effectiveness in real-world applications.

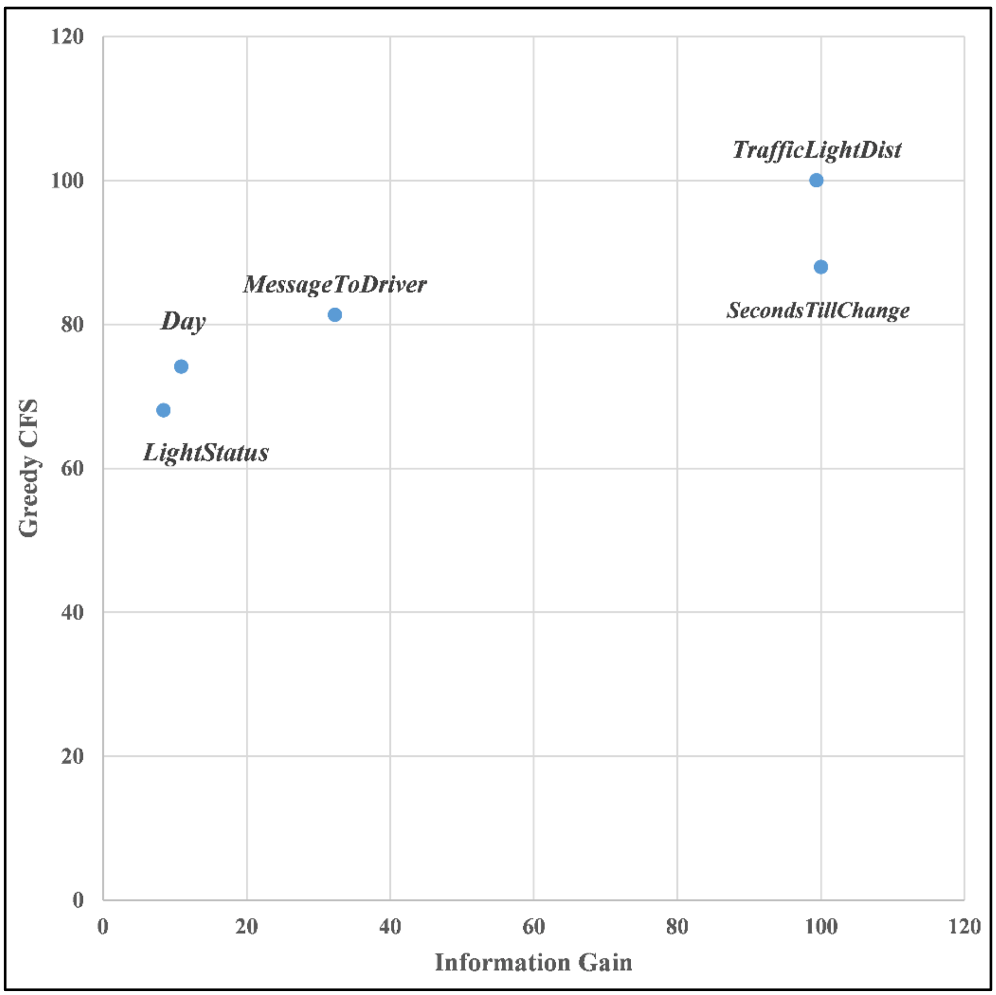


Figure 5.8. Graphical representation of the influential features based on Information Gain and greedy Correlation-based Feature Selection (CFS) algorithm

A DT modelling driver's adaptation to speed advice was developed based on the finding of the latter analysis, the methodology presented in Section 3.2.2, and the dataset obtained from the pilot operation of EVPA in the city of Thessaloniki (cf. Section 4.1.3). For the scope of this analysis, a new variable was created and defined as the instantaneous speed divergence S'_{div} between the vehicle's average speed during a short time interval after the reception of the speed advice message and the speed advice (actual speed divergence at the time of first speed advice message reception was excluded to prevent bias in the estimation of the DT). Instantaneous speed divergence values were used for the estimation of the average speed divergence $\widetilde{S_{div}}$ per dynamic eco-driving maneuver. The output of the DT (average speed divergence) is related to the distance to the downstream signalized intersection, the time remaining until the signal's status change, and the type of message transmitted. All variables considered in the analysis were discretized to achieve improved performance in the DT training process. The classification accuracy equals 81%. The resulting tree is depicted in **Figure 5.9**.

The most critical feature for driver speed adaptation is the type of message. If the message is "Accelerate", drivers most likely will adapt speed, so that the speed divergence between travel speed and the speed advice ranges between [-11.92, 19.91]. If driver receives either a "Decelerate" or "Maintain Speed" message, then speed adaptation is influenced by the distance from the downstream signalized intersection. Specifically, if the distance is longer than 350.64 m, the speed divergence will range between [-11.92, 19.91]. If distance is shorter than 350.64 m and the time to signal status change is lower than 47.5 sec, the speed divergence will be between [-11.92, 19.91] in the "Maintain Speed" case. Otherwise, when the time to signal status change is greater than 47.5 sec, the speed divergence will be between [-15.33, 11.92] in the "Maintain Speed" case. In case of "Decelerate" advice, speed divergence will range between [-15.33, 11.92] and [-11.92, 19.91] for distances to traffic lights shorter than 178.31 m and longer than 350.64 m respectively. On the other hand, if distance to traffic lights rangers between [178.31, 350.6] m and the time to signal status change is lower than 47.5sec, then speed divergence will range between [-11.92, 19.91]. If time to signal status change is greater than 47.5 sec, then speed divergence will be negative and ranging between [-15.33, 11.92].

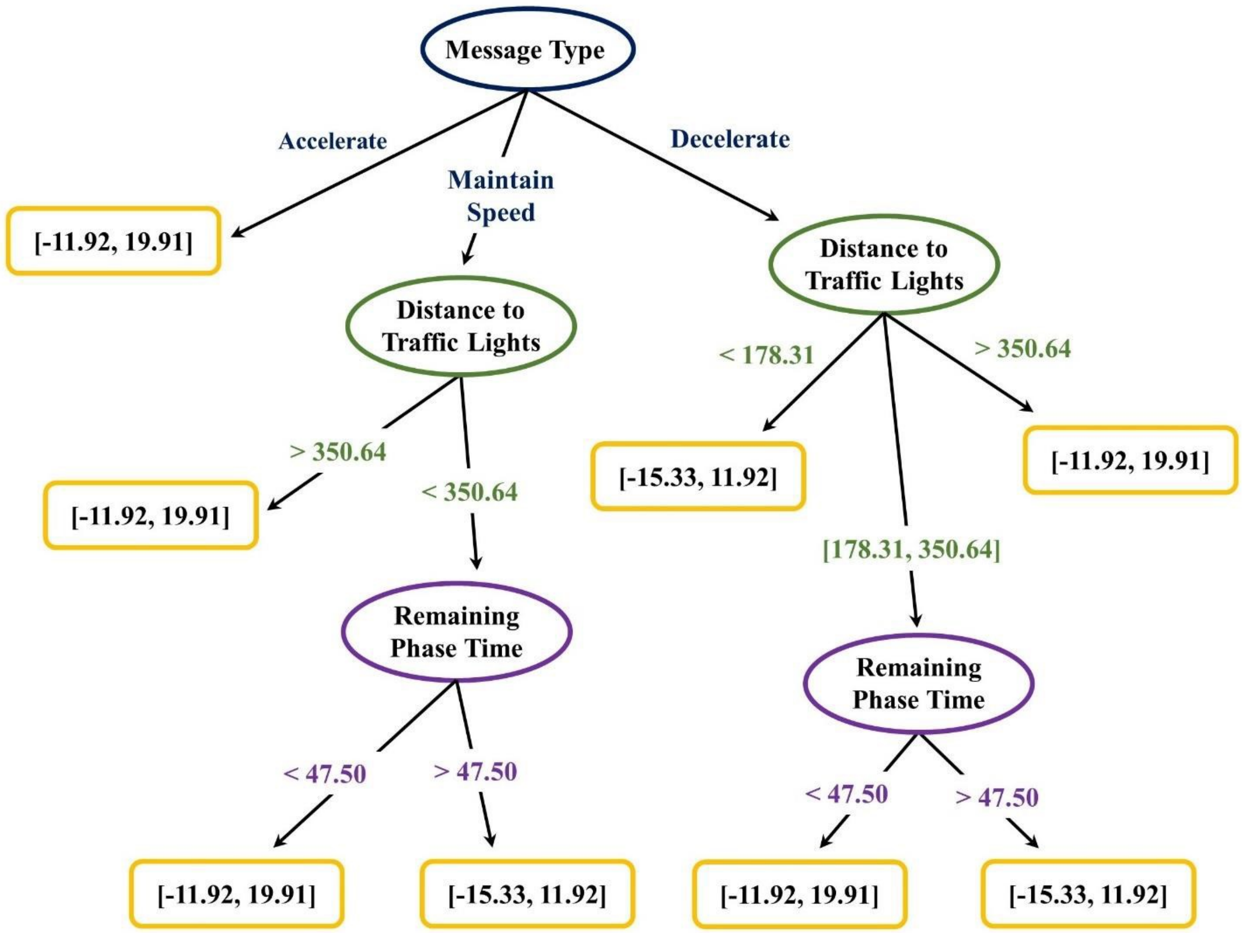


Figure 5.9. DT for modelling driver compliance to speed advice

Exemplary transformations of deceleration profiles according to EVPA-DT are depicted in **Figure 5.10**. For instance, a CV might drive faster than the proposed energy-efficient deceleration strategy (positive speed divergence case), thus arriving at the stop line prior to the onset of green signal status. Thus, the CV will accelerate to desired speed from full stop along the downstream road section and most probably yield emissions equivalent to those of an unequipped manually driven vehicle. On the other hand, a CV might drive slower than the proposed energy-efficient deceleration strategy (negative speed divergence case), and avoid a full stop at the signalized intersection. However, in an urban setting that speed advice cannot range significantly due to speed limit constraints its energy efficiency will be lower compared to that of a CAV which can accurately execute the energy optimal driving strategy. Finally, a CV might successfully adapt to speed advice and execute a maneuver similar to the EVPA estimated one (neutral speed divergence) which yields the highest emissions savings.

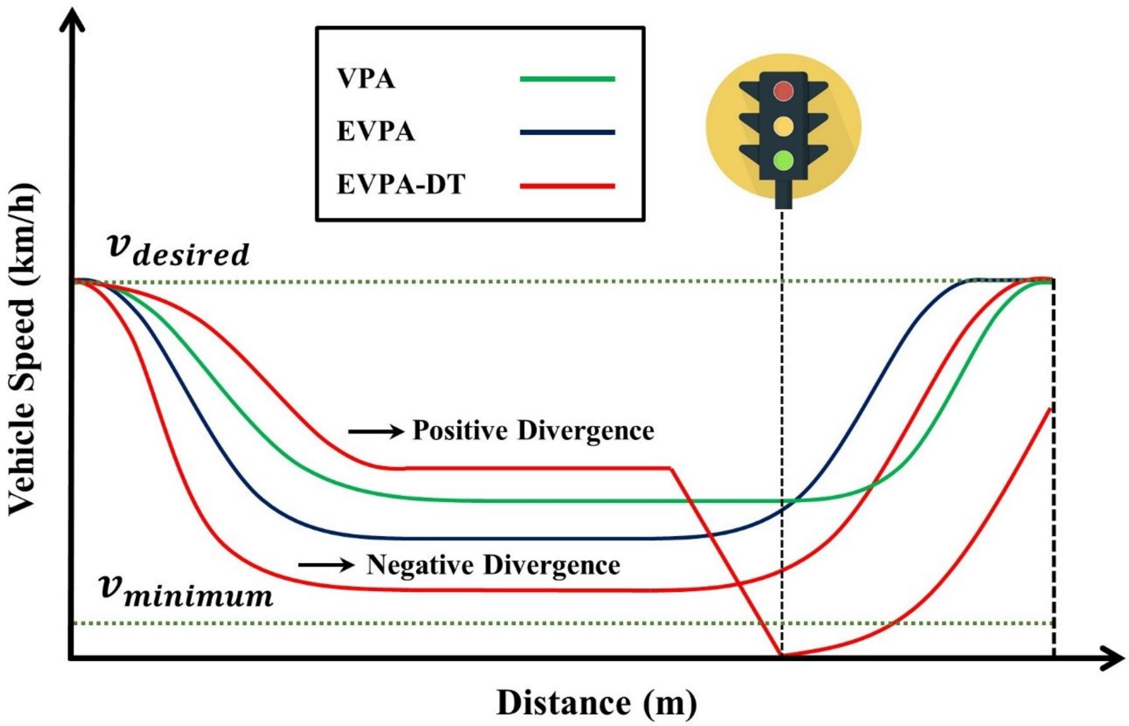


Figure 5.10. Exemplary energy-efficient deceleration strategies per dynamic eco-driving model

5.3 Impact Assessment – EVPA vs EVPA-DT Performance

Simulative assessment of scenarios depicted in **Table 3.6** considered surrogate safety measures apart from environmental and traffic efficiency KPIs. Safety assessment was conducted based on conflict risk measures and relevant statistics derived directly via SSAM. The following aspects of the simulation analysis implemented for the comparison of VPA vs EVPA performance were also adopted for the comparison of EVPA vs EVPA-DT performance:

- considered levels of analysis
- tools used for the estimation of environmental and traffic efficiency KPIs, and
- notation scheme for the description of simulation results.

5.3.1 Individual Vehicle Performance

The analysis of individual vehicle performance enables the examination of advisory dynamic eco-driving (EVPA-DT) emissions savings potential in contrast to automated dynamic eco-driving

(EVPA), and manual driving ("do-nothing" scenario). To this end, the following two types of plots have been generated based on vehicle trajectory information:

- speed vs distance, and
- cumulative CO_2 emissions vs distance.

The latter plots have been created for three specific vehicles which exhibit different behavior in terms of adapting to dynamic eco-driving advice (deceleration strategies) along IA:{R→Q} (**Figure 5.11**). LV trajectories have been extracted from "Scenario 1" and pertain to manual driving, CV trajectories have been extracted form "Scenario 7" and pertain to EVPA-DT driving, and CAV trajectories have been extracted from "Scenario 8" and pertain to EVPA driving.

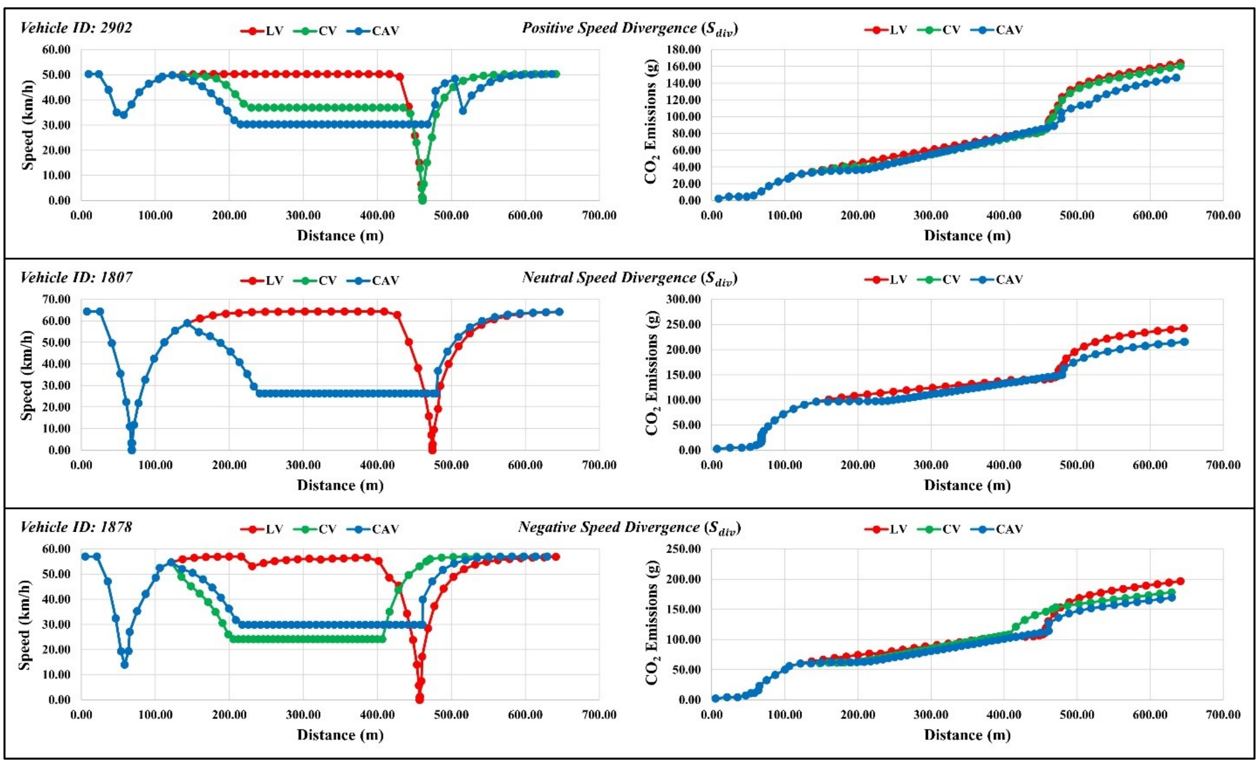


Figure 5.11. EVPA vs EVPA-DT: Individual vehicle behavior along IA: {R→Q}

Vehicle "2902" adopts higher speed (green line) compared to the advised one (blue line also reflecting automated dynamic eco-driving) when equipped with advisory dynamic-eco driving technology (positive speed divergence case). Thus, it arrives to the stop line prior to the onset of green traffic light status and has to stop (as in the case of manual driving). Consequently, it has to accelerate to desired speed from full stop and its cumulative CO_2 emissions are almost similar to the case of manual driving. On the other hand, Vehicle "1807" succeeds in precisely following the advised speed when equipped with advisory dynamic-eco driving system (CV line superimposed by CAV line in the middle plots). Hence, its CO_2 emissions savings coincide with the case when Vehicle "1807" was equipped with automated dynamic eco-driving. Finally, Vehicle "1878" adopts lower speed (negative speed divergence) compared to the advised one when equipped with advisory dynamic-eco driving system, but still manages to cross the signalized intersection without stopping. Therefore, it achieves CO_2 emissions savings compared to the "do-nothing" case, but they are lower than the automated dynamic eco-driving case. The analysis of individual vehicle behavior indicated that performance of advisory dynamic eco-driving ranges between that of manual driving (without speed advice provision) and automated dynamic eco-driving depending on the driver's adaptation to the advised driving strategy.

5.3.2 Dynamic Eco-driving Service Zone

Local impacts of advisory and automated dynamic eco-driving have been evaluated along the IAs (i.e. {N→M} and {R→Q}) that were also used for the analysis presented in Section 5.1.2. The rationale for the selection of the latter two IAs is based on favorable conditions with respect to available space and time for the execution of dynamic eco-driving advice, and variability in terms of vehicle arrival patterns, geometrical and operational characteristics.

Reported environmental and traffic efficiency KPIs encompass number of stops per vehicle, CO_2 emissions (gr/km), and mean travel time (seconds) per IA. Estimation of CO_2 emissions and travel time results also considered vehicle behavior on the road sections downstream of the examined IAs, where benefits from energy-efficient driving strategies can be realized. Environmental and traffic efficiency KPIs along IAs {N→M} and {R→Q} are shown in **Figure 5.12**.

Simulation results indicate that variability in adoption of dynamic eco-driving advice between different IAs is possible when the dynamic eco-driving system is advisory. For example, advisory and automated dynamic eco-driving perform equally well along IA:{N→M}, while automated dynamic eco-driving yields more substantial reductions in stop events and CO_2 emissions along IA:{R→Q}. Superiority of automated dynamic eco-driving performance along IA:{R→Q} is caused due to insufficient adoption rates during advisory system operation, which can be ascribed to driver behavior issues and/or surrounding road environment characteristics and conditions. Although advisory dynamic eco-driving cannot outperform the automated variant of the system, its performance is superior or at least equal to the case of fully unequipped fleet as also highlighted in the analysis of individual vehicle behavior. Moreover, it can be observed that presence of LVs in the fleet mix induces higher variability in simulation results and lower emissions reduction due to more complex vehicle interactions which stem from increased heterogeneity in vehicle behavior. Finally, both advisory and automated dynamic eco-driving have marginal impacts on experienced travel time along the examined IAs.

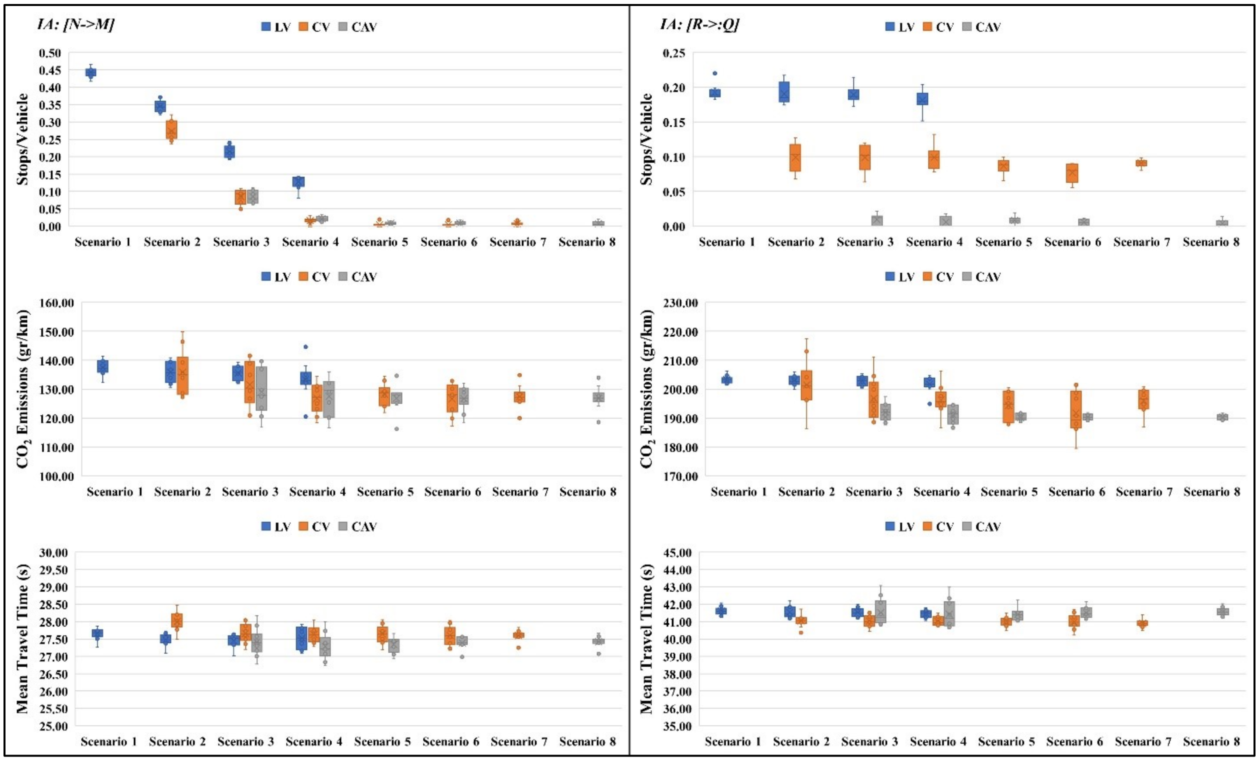


Figure 5.12. EVPA vs EVPA-DT: Environmental and traffic efficiency KPIs along IAs {R→Q} and {N→M}

Safety assessment of advisory and automated dynamic eco-driving on the local level has been conducted via the estimation of number of conflicts (crossing, rear-end, and lane change), propensity of conflicts, and severity of conflicts. TTC is used as a surrogate safety measure for the quantification of conflict propensity, while DeltaS is used as a surrogate safety measure for the quantification of conflict severity. In the context of this analysis, conflicts with TTC values smaller than 1.5 s are explicitly considered as safety critical. Safety KPIs along IAs {N→M} and {R→Q} are depicted in **Figure 5.13**.

The introduction of dynamic eco-driving technology (both advisory and automated) has profound homogenizing effects on traffic flow and diminishes rear-end conflicts as its penetration increases in the fleet mix. Higher frequency of conflict events is explicitly observed for scenarios encompassing non-equipped manually driven vehicles (LVs) which yield more complex vehicle interactions (e.g. LV conducting lane change or overtaking maneuver in response to CV/CAV adherence to deceleration advice). However, conflicts are minimized along IA:{R→Q} only in the case of increased CAV percentage, due to lower adoption rates of dynamic eco-driving advice from CVs (equipped with advisory systems) as previously inferred from traffic efficiency results (stops/vehicle). Finally, marginal differences among the examined scenarios with respect to conflict propensity (mean TTC) and severity (DeltaS) are not statistically significant.

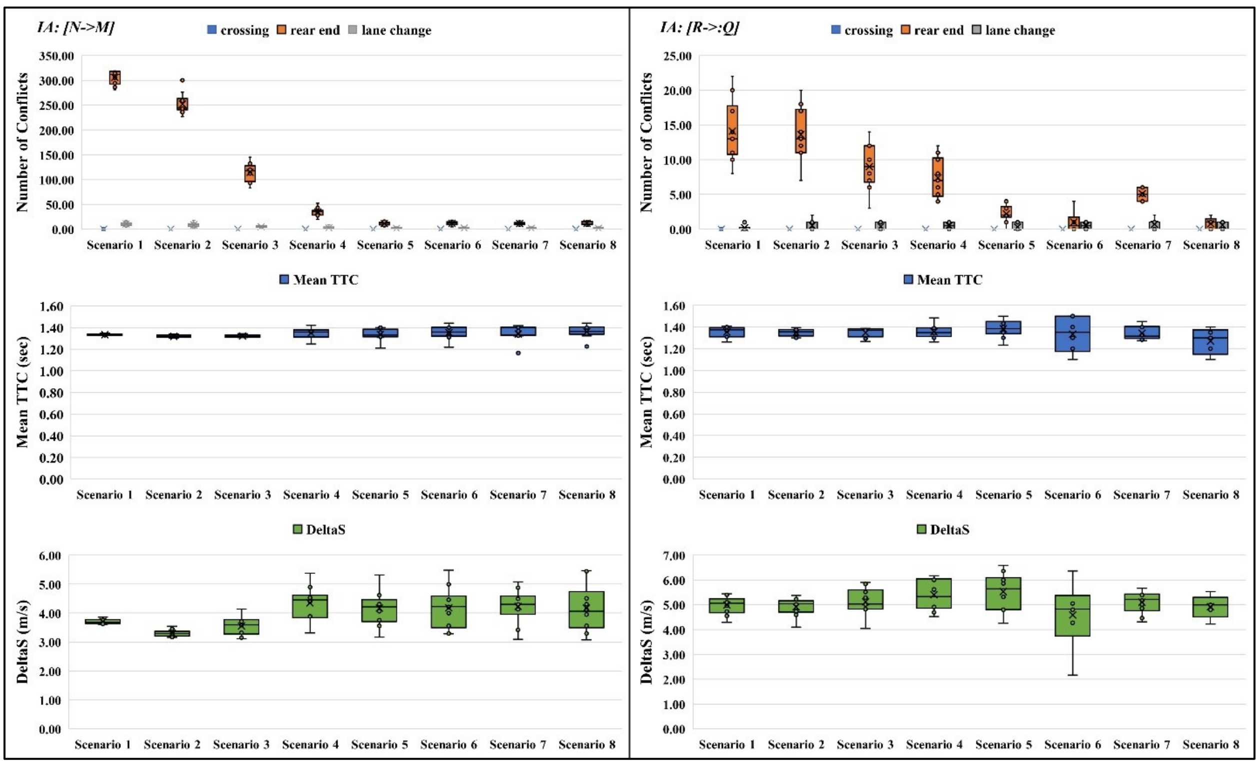


Figure 5.13. EVPA vs EVPA-DT: Safety KPIs along IAs {R→Q} and {N→M}

5.3.3 Corridor-wide Impacts

The corridor-wide impacts of dynamic eco-driving (advisory and automated) on CO_2 emissions and traffic efficiency are shown in **Figure 5.14** and have been evaluated based on average stop time per kilometer driven (s/km), CO_2 emissions per kilometer driven (gr/km), and average network speed (km/h). Dynamic eco-driving (advisory and automated) reduces average stop time by approximately 4% – 6%, while higher variability in average stop time is observed when traffic heterogeneity is increased (Scenarios 3 & 4). Maximum CO_2 emissions savings (2.5 %) compared to manual driving are realized for a fleet fully equipped with automated dynamic eco-driving technology, while the latter savings reduce to 1.6 % when the fleet is fully equipped with advisory dynamic eco-driving. Simulation findings at network scale also confirm that advisory dynamic eco-driving performance with respect to environmental KPIs resides between that of manual driving and automated dynamic eco-driving. Finally, the introduction of dynamic eco-driving does not affect average network speed during uncongested traffic operations.

Statistical testing has been conducted via SSAM to compare corridor-wide surrogate safety measures (TTC and DeltaS) among simulated scenarios in a pair-wise fashion. **Table 5.1** depicts the number of conflict events that were used to estimate mean and variance of TTC and DeltaS per scenario, as well as the values of the latter measures. The results of "t" statistical tests that compared differences of mean TTC and DeltaS values for each pair of simulated scenarios are also shown in **Table 5.1** together with respective percental differences.

SSAM results indicate that differences are statistically significant for both propensity (TTC) and severity (DeltaS) of conflicts only between "Scenario 1" (non-equipped fleet) and "Scenarios 2 & 8" that encompass vehicles equipped with dynamic eco-driving (advisory or automated). However, the differences in terms of conflict propensity which favor the case on non-equipped fleet are very small (0.8 %), while the ones relating to conflict severity which favor fleets with shares of equipped vehicles are higher (~ 3% – 5 %). As far as comparison of pairs of scenarios which encompass CVs and/or CAVs are concerned, it can be observed that TTC differences are insignificant, while DeltaS differences are significant but not profound. Moreover, the latter DeltaS differences show that conflict severity is reduced as the share of automated dynamic eco-driving increases in the fleet mix.

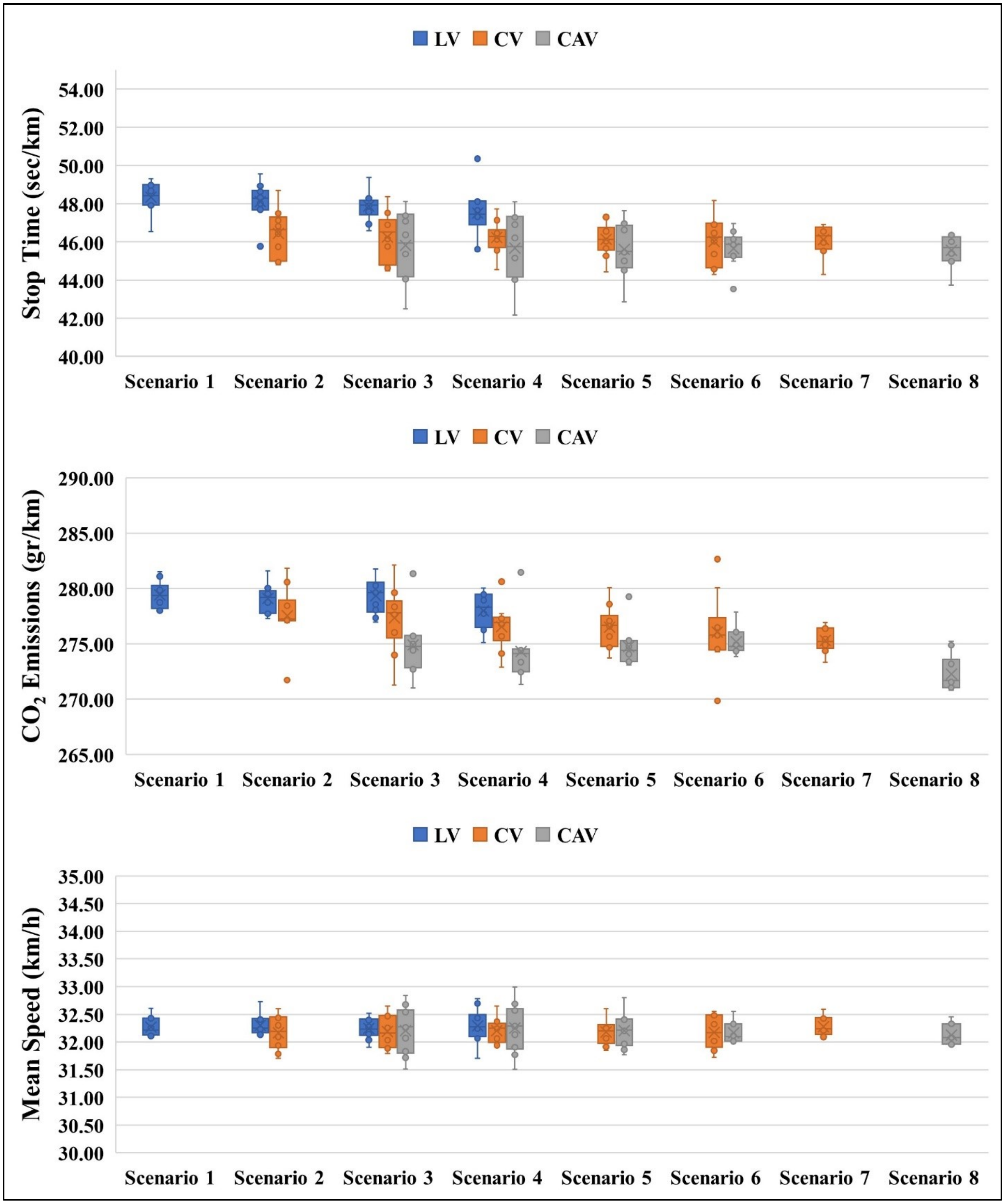


Figure 5.14. EVPA vs EVPA-DT: Environmental and traffic efficiency impacts of dynamic eco-driving at corridor scale

Table 5.1. EVPA vs EVPA-DT: Statistical comparison of surrogate safety measures at network scale

A vs B	Measure	Mean A	Variance A	Records A	Mean B	Variance B	Records B	t value	Diff (%)
1 vs 2	TTC	1.30	0.05	26425	1.29	0.06	26288	2.20*	**0.8**
	DeltaS	3.85	3.62	26425	3.78	3.87	26288	4.25*	**1.8**
1 vs 3	TTC	1.30	0.05	26425	1.29	0.06	25582	2.00*	**0.8**
	DeltaS	3.85	3.62	26425	3.76	3.98	25582	5.32*	**2.3**
1 vs 4	TTC	1.30	0.05	26425	1.29	0.06	25285	3.59*	**0.8**
	DeltaS	3.85	3.62	26425	3.72	3.94	25285	7.37*	**3.4**
1 vs 5	TTC	1.30	0.05	26425	1.29	0.06	25782	3.08*	**0.8**
	DeltaS	3.85	3.62	26425	3.66	3.99	25782	11.1*	**4.9**
1 vs 6	TTC	1.30	0.05	26425	1.29	0.06	25885	2.36*	**0.8**
	DeltaS	3.85	3.62	26425	3.66	3.94	25885	11.13*	**4.9**
1 vs 7	TTC	1.30	0.05	26425	1.29	0.06	25218	2.74*	**0.8**
	DeltaS	3.85	3.62	26425	3.70	3.99	25218	8.86*	**3.9**
1 vs 8	TTC	1.30	0.05	26425	1.29	0.06	26068	2.94*	**0.8**
	DeltaS	3.85	3.62	26425	3.67	3.93	26068	10.88*	**4.7**
2 vs 3	TTC	1.29	0.06	26288	1.29	0.06	25582	-0.19	0.0
	DeltaS	3.78	3.87	26288	3.76	3.98	25582	1.11	0.5
2 vs 4	TTC	1.29	0.06	26288	1.29	0.06	25285	1.43	0.0
	DeltaS	3.78	3.87	26288	3.72	3.94	25285	3.13*	**1.6**
2 vs 5	TTC	1.29	0.06	26288	1.29	0.06	25782	0.89	0.0
	DeltaS	3.78	3.87	26288	3.66	3.99	25782	6.80*	**3.2**
2 vs 6	TTC	1.29	0.06	26288	1.29	0.06	25885	0.18	0.0
	DeltaS	3.78	3.87	26288	3.66	3.94	25885	6.80*	**3.2**
2 vs 7	TTC	1.29	0.06	26288	1.29	0.06	25218	0.56	0.0
	DeltaS	3.78	3.87	26288	3.70	3.99	25218	4.62*	**2.1**
2 vs 8	TTC	1.29	0.06	26288	1.29	0.06	26068	0.75	0.0
	DeltaS	3.78	3.87	26288	3.67	3.93	26068	6.55*	**2.9**
3 vs 4	TTC	1.29	0.06	25582	1.29	0.06	25285	1.61	0.0
	DeltaS	3.76	3.98	25582	3.72	3.94	25285	1.99*	**1.1**
3 vs 5	TTC	1.29	0.06	25582	1.29	0.06	25782	1.09	0.0
	DeltaS	3.76	3.98	25582	3.66	3.99	25782	5.60*	**2.7**
3 vs 6	TTC	1.29	0.06	25582	1.29	0.06	25885	0.37	0.0
	DeltaS	3.76	3.98	25582	3.66	3.94	25885	5.60*	**2.7**
3 vs 7	TTC	1.29	0.06	25582	1.29	0.06	25218	0.76	0.0
	DeltaS	3.76	3.98	25582	3.70	3.99	25218	3.46*	**1.6**
3 vs 8	TTC	1.29	0.06	25582	1.29	0.06	26068	0.94	0.0
	DeltaS	3.76	3.98	25582	3.67	3.93	26068	5.35*	**2.4**
4 vs 5	TTC	1.29	0.06	25285	1.29	0.06	25782	-0.54	0.0
	DeltaS	3.72	3.94	25285	3.66	3.99	25782	3.61*	**1.6**
4 vs 6	TTC	1.29	0.06	25285	1.29	0.06	25885	-1.24	0.0
	DeltaS	3.72	3.94	25285	3.66	3.94	25885	3.60*	**1.6**
4 vs 7	TTC	1.29	0.06	25285	1.29	0.06	25218	-0.86	0.0
	DeltaS	3.72	3.94	25285	3.70	3.99	25218	1.48	0.5
4 vs 8	TTC	1.29	0.06	25285	1.29	0.06	26068	-0.68	0.0
	DeltaS	3.72	3.94	25285	3.67	3.93	26068	3.34*	**1.3**
5 vs 6	TTC	1.29	0.06	25782	1.29	0.06	25885	-0.71	0.0
	DeltaS	3.66	3.99	25782	3.66	3.94	25885	-0.02	0.0
5 vs 7	TTC	1.29	0.06	25782	1.29	0.06	25218	-0.32	0.0
	DeltaS	3.66	3.99	25782	3.70	3.99	25218	-2.11*	**-1.1**
5 vs 8	TTC	1.29	0.06	25782	1.29	0.06	26068	-0.15	0.0
	DeltaS	3.66	3.99	25782	3.67	3.93	26068	-0.29	-0.3
6 vs 7	TTC	1.29	0.06	25885	1.29	0.06	25218	0.39	0.0
	DeltaS	3.66	3.94	25885	3.70	3.99	25218	-2.09*	**-1.1**
6 vs 8	TTC	1.29	0.06	25885	1.29	0.06	26068	0.57	0.0
	DeltaS	3.66	3.94	25885	3.67	3.93	26068	-0.27	-0.3
7 vs 8	TTC	1.29	0.06	25218	1.29	0.06	26068	0.18	0.0
	DeltaS	3.70	3.99	25218	3.67	3.93	26068	1.83*	**0.8**

5.3.4 Discussion

Simulation findings across all levels of analysis indicate that performance of advisory dynamic eco-driving can be inferior or equal to that of automated dynamic eco-driving, but superior or equal to that of non-equipped manually driven vehicles. Performance of advisory dynamic eco-driving is highly related to adoption rate of energy optimal driving strategies which may spatially vary and is significantly affected by driver characteristics and several elements of surrounding road environment (e.g. behavior of other road users, traffic signal operation etc.). The latter findings coincide with similar results from a controlled field experiment of advisory and automated dynamic eco-driving systems (Almannaa et al. 2019).

It is noteworthy that in our work speed divergence is uniformly added to the values of the speed profile initially estimated by EVPA. Thus, oscillatory driver adaptation to speed advice which might induce episodes of dynamic eco-driving which are less environmentally friendly compared to manual driving (without speed advice support) are not reflected in our simulation experiments. However, considering that emissions benefits mainly occur due to prevention of stop events at the signalized intersection (vehicles avoid acceleration to desired speed from full stop) we deem that our modelling approach credibly captures the average effects of advisory dynamic eco-driving on environmental and traffic KPIs.

DT model development was based on the full real-world dataset, which was not partitioned in groups representing different traffic conditions (uncongested, near-congested, congested) due to the absence of traffic count data pertaining to the pilot testing period and the fact that taxis are legally allowed to use the bus lane on the examined urban arterial corridor (neither was vehicle position provided on a per lane basis in the original dataset, nor could it be inferred). Thus, it is legitimate to assume that efficiency of advisory dynamic eco-driving could be expected higher than in our simulation analysis during uncongested traffic conditions, while the reverse trend could be expected during congested traffic conditions.

Additionally, pilot operation of advisory dynamic eco-driving on the public road test site explicitly encompassed taxi drivers. To the author's best knowledge, the potential differences between professional and non-professional drivers in terms of following dynamic eco-driving advice have not been assessed by previous research. Instead, focus has been placed on the identification of the most efficient means (audio, visual, haptic etc.) for conveying dynamic eco-driving advice to nonprofessionals drivers (Tang et. al. 2016). However, taxi drivers are more experienced and familiar with traffic operations on the examined test site than regular passenger car drivers, and it is legitimate to assume that their efficiency in adapting to speed advice is increased due to the better driving skills they possess. Thus, overall short-term benefits of advisory dynamic eco-driving across the whole vehicle fleet can possibly be lower than predicted in this dissertation. However, accumulating familiarity of regular drivers with advisory dynamic eco-driving systems on the long run can yield higher benefits in terms of CO_2 emissions, traffic efficiency and safety. Moreover, dynamic eco-driving training programs have the potential to significantly improve the effectiveness of both professional and non-professional drivers in terms of energy efficient driving in the vicinity of signalized intersections.

Safety assessment of dynamic eco-driving indicated that conflict risk and severity are substantially reduced when the automated variant of the system is deployed. This is a reasonable outcome considering the homogenizing effect that automated dynamic eco-driving can exert on traffic flow, since equipped vehicles can execute advised driving strategies with high precision. Milder safety benefits are observed with the introduction of advisory dynamic eco-driving in the fleet mix. The latter finding can also be considered valid since drivers receive speed assistance and improve anticipation levels via traffic light status and countdown information, while they might exhibit fluctuating driving behavior in the attempt to adopt dynamic eco-driving advice according to their skills and distractions from surrounding traffic. However, it is highly likely that safety risk is underestimated in our analysis when unequipped manually driven vehicles (LVs) are introduced in the fleet mix. In the case that CVs/CAVs receive and execute deceleration advice while the signal status is still green (which is possible since they cannot cross the intersection in the current green phase) LVs might react erratically to the latter phenomenally irrational behavior of CVs/CAVs in the real world (the latter behavior cannot be rigorously emulated in our simulation experiments). Possible lane changes and overtaking maneuvers from LV side while CVs/CAVs adopt-execute dynamic eco-driving advice might induce complex vehicle interactions and pose increased conflict risk in highly heterogenous traffic scenarios.

6 Conclusions

6.1 Overview

Constant growth of demand for vehicle trips can significantly exacerbate the adverse impacts of road traffic on the environment. On the other hand, recent technological evolution in the field of telecommunications has enabled the development of CV services that can improve traffic flow performance, road safety and sustainability of the road transport system. For example, CVs can be informed about upcoming changes to traffic signal status via I2V communication and plan energy efficient trajectories accordingly. Moreover, planning of CV maneuvering for attaining energy consumption and emissions goals (i.e. dynamic eco-driving) can encompass the actions and desires of surrounding traffic via V2V communication in a connected road vehicle environment.

In the past decade, several dynamic eco-driving models and systems have been introduced and examined for improving fuel efficiency and reducing vehicular emissions in the proximity of signalized intersections. This doctoral dissertation maps existing dynamic eco-driving technologies and identifies areas in the research domain of dynamic eco-driving for interrupted traffic flow facilities that have not received significant attention thus far. According to the research gaps identified by the literature review, a methodological framework is proposed for incorporating human factors in the modelling of dynamic eco-driving based on empirical evidence that encompasses the design of human-centered and safe dynamic eco-driving strategies, as well as the integration of driver adaptation to environmentally friendly speed advice in the control logic of dynamic eco-driving models. Additionally, a generic impact assessment framework is introduced for the evaluation of alternative dynamic eco-driving systems with the use of microscopic traffic simulation and customized software explicitly developed for the needs of this doctoral dissertation. Finally, simulation results pertaining to traffic efficiency, safety and emissions savings of different dynamic eco-driving models are analyzed, relevant implications for road transport stakeholders are discussed, and prospects for future research in the examined domain are presented.

6.2 Main Contributions

6.2.1 Mapping of Existing Dynamic Eco-Driving Technologies

This doctoral dissertation provides a detailed analysis of recent advancements in the field of dynamic eco-driving for interrupted traffic flow facilities. A comprehensive and critical review of existing literature pertinent to dynamic eco-driving systems was conducted to identify their advantages and limitations. The review showed that dynamic eco-driving systems vary in terms of their control logic, optimization objectives, vehicle dynamics and fuel consumption models, analysis boundaries, deployment readiness and other characteristics. An examination of the aforementioned elements indicated inherent limitations in the design of available dynamic eco-driving strategies and proposed a set of desirable features that could significantly enhance the performance of future dynamic eco-driving systems (cf. Section 2.3). Moreover, it was found that automated dynamic eco-driving systems had received significantly more attention compared to their advisory counterparts.

Regardless of the developments with respect to the mathematical formulation of the dynamic eco-driving modeling problem, the impacts of human factors on the efficiency of advisory dynamic eco-driving systems have not been studied thoroughly. Specifically, less focus has been placed on the design of dynamic eco-driving strategies that enhance user acceptance and road safety, while there is very little evidence on the effects of driver's adaptation to dynamic eco-driving speed advice on the performance of dynamic eco-driving systems. Considering that the transition towards a fully automated and connected vehicular fleet will last decades, and that connectivity capabilities are integrated into market ready vehicles at a slower pace compared to automation ones, it is evident that the human-centered design of dynamic eco-driving models is important for achieving sustainability goals. Thus, the development of dynamic eco-driving models that account for driver's adaptation to speed advice facilitates the evaluation of different dynamic eco-driving technologies for different market penetration rates. However, it is also noted that such developments should be based on adequate relevant data that could be collected during large-scale pilot operations of dynamic eco-driving services that account for variability in driver's behavior, traffic conditions and vehicle types.

6.2.2 Methodological Framework for Human-Centered modelling of Dynamic Eco-Driving

As aforementioned, this doctoral dissertation proposed methods that enable the integration of human factors in the development of dynamic eco-driving strategies near signalized intersections. Generic modifications were introduced to the control logic of dynamic eco-driving models that account for user acceptance of the system and road safety. The latter modifications encompass:

- provision of non-crawling speed advice, and
- vehicle acceleration commencement prior to CV arrival at signalized intersection at the end of deceleration strategies

Moreover, driver adaptation to dynamic eco-driving speed advice was examined. Initially, feature selection algorithms and data from a real-world deployment of an advisory dynamic eco-driving service were utilized to identify factors that affect driver adaptation to energy efficient speed advice. Subsequently, a DT model was developed based on the same dataset that predicts average driver adaptation (i.e. speed divergence) to speed advice according to the message type, distance to signalized intersection, and remaining duration of running traffic signal status. The latter DT model enabled the evaluation of advisory dynamic eco-driving strategies when the driver is responsible for the execution of the energy efficient speed advice.

It is noteworthy, that this is the first research effort that utilizes data from the pilot operation of an advisory dynamic eco-driving system along an urban arterial corridor to investigate the effects of human factors on dynamic eco-driving. Specifically, 200 taxis were equipped with OBUs, and RSUs were installed on 12 traffic light controllers along the signalized arterial corridor. Data were collected via a monitoring system throughout the 11-month pilot operation period and included information pertaining to CVs' dynamic status, signal timing plans, and speed advice messages (cf. Section 4.1.3).

6.2.3 Impact Assessment Framework for Dynamic Eco-Driving Technologies

An impact assessment framework based on microscopic traffic simulation was introduced for the evaluation of different dynamic eco-driving technologies. The microscopic traffic simulator Aimsun was used for the simulation of traffic operations along an urban arterial corridor. The simulated network was calibrated against field traffic measurements based on appropriate statistical tests. An Aimsun API was developed for emulating dynamic eco-driving in the proximity of signalized intersections (cf. Appendix A). The Aimsun API is capable of emulating both advisory and automated dynamic eco-driving models, but it also features a modular structure that facilitates the integration of new dynamic eco-driving models. Safety analysis was performed with the use of SSAM, while a custom web-based application (cf. Appendix B) was developed for analyzing vehicle trajectory data generated via Aimsun. Moreover, two sets of simulation experiments were devised to assess the proposed generic enhancements to the control logic of existing dynamic eco-driving models, and compare the performance of advisory against automated dynamic eco-driving for different market penetration rates of the two technologies. Overall, the impact assessment framework exhibits a versatile design that facilitates future developments via the simplified integration of alternative dynamic eco-driving models and the analysis of simulation results with the use of multiple robust tools in a streamlined fashion.

6.2.4 Performance of Dynamic Eco-Driving Technologies

Microscopic traffic simulation experiments were conducted to compare a dynamic eco-driving model that accounts for user acceptance and road safety (EVPA) against its naïve counterpart (VPA) that does not consider the latter objectives. The latter experiments encompassed different penetration rates of the examined dynamic eco-driving technologies and multiple traffic demand levels corresponding to a wide range of possible traffic conditions. Simulation results indicated that EVPA can generate CO_2 emissions savings on the order of 13% along individual intersection approaches and 2.5% on a network scale, without substantially escalating travel times. Moreover, EVPA ensures increased speed advice comfort and safety due to its inherent control logic. However, it was also identified that EVPA's efficiency is dependent on roadway characteristics, distance of the dynamic eco-driving service zone, traffic signal plans and traffic conditions. Thus, the deployment scheme of dynamic eco-driving on urban networks plays a significant role in warranting environmental benefits and traffic efficiency. It was also identified that speed advice estimation should consider signal plans from consecutive traffic lights on urban arterial corridors with closely spaced signalized intersections to increase dynamic eco-driving performance. Additionally, evidence was provided that dynamic eco-driving can affect traffic patterns in areas of road networks that lie beyond the dynamic eco-driving service zones.

Microscopic traffic simulation analysis was also conducted to evaluate advisory dynamic eco-driving (EVPA-DT) in the context of simulation experiments that also encompassed different penetration rates of unequipped legacy vehicles and CAVs equipped with automated dynamic eco-driving (EVPA). In this case, simulation results indicated that performance of advisory dynamic eco-driving in terms of GHG emissions, traffic efficiency and safety cannot exceed that of automated dynamic eco-driving but at most instances is superior to that of unequipped manually driven vehicles. Advisory dynamic eco-driving performance may also vary among different service zones given specific geometrical and operational characteristics of the corresponding road sections which can influence driver's adaptation to energy efficient speed advice. Moreover, maximum reduction of stop events, CO_2 emissions and severe conflicts can be explicitly achieved when vehicle fleet is fully equipped with automated dynamic eco-driving technology (EVPA) that enables CAVs to execute energy-efficient driving strategies with high degree of precision.

The latter simulation findings have profound implications for road transport stakeholders. Automakers and service providers can easily adapt the design of future dynamic eco-driving models to attain comfort and safety goals without adversely impacting energy and traffic efficiency. Moreover, they can develop advisory dynamic eco-driving systems that can foresee driver adaptation to energy efficient speed advice and enact accordingly (i.e. adjust advice to achieve increased compliance or terminate advice provision). Road authorities and road operators can estimate impacts from dynamic eco-driving deployment both within and beyond service zones, while they can also warrant deployment on different road network areas according to prevailing geometrical, operational and traffic signal plan characteristics. Given that advisory dynamic eco-driving can yield substantial emissions savings when deployment conditions are favorable, they can accelerate deployment of relevant road-side communication equipment on selected signalized intersections prior to the transition towards a fully connected and automated road environment. Subsequently, the latter equipment can be upgraded to enable the realization of higher emissions savings when vehicular fleet will be fully automated and automated dynamic eco-driving maneuvers could be orchestrated more efficiently via cooperation. Moreover, policy makers can advocate for prompt introduction of dynamic eco-driving technology, since empirical and simulation evidence indicates the significant environmental benefits of dynamic eco-driving.

6.3 Limitations and Future Research Directions

This doctoral dissertation proposed enhancements to the control logic of dynamic eco-driving models so that energy efficient speed advice in the proximity of signalized intersections becomes more comfortable and safer. However, these enhancements entail adjustments to energy efficient driving strategies that are made subsequent to their initial estimation. In the future, integration of comfort and safety constraints in the estimation process of energy efficient speed advice could concurrently increase performance and robustness of dynamic eco-driving models.

Development of advisory dynamic eco-driving models could become more sophisticated depending on the richness of data collected during real world testing of dynamic eco-driving technologies. Availability of traffic count data from dynamic eco-driving service zones that are contemporaneous to speed advice data can enable the development of refined DT model versions which can capture variations in driver adaptability to dynamic eco-driving advice according to prevailing traffic conditions (uncongested, near-congested, congested). Moreover, information about lane-wise position of CVs during pilot operation of advisory dynamic eco-driving could further enhance realism of DT modelling since driver adaptation to speed advice could be rendered lane-dependent. The latter possibility would be of particular interest for dynamic eco-driving service zones including exclusive lanes for specific vehicle types. Future research could also focus on modelling time varying instantaneous speed divergence considering its dependability on driver behavior during previous update intervals of speed advice assistance. Thus, dynamic eco-driving episodes that possibly yield inferior performance compared to unequipped manually driven vehicles can be also examined.

Decentralized CAV cooperation based on V2V communication can significantly increase the performance of automated dynamic eco-driving in mixed traffic flows. However, existing studies focus on the longitudinal cooperation of CAVs to increase energy consumption and emissions savings. The integration of cooperative lane changing in the optimization problem of dynamic eco-driving could further minimize the environmental footprint of vehicular traffic near signalized intersections. Benefits could further escalate in a fully connected and automated road environment where centralized coordination could enable system optimum performance.

Moreover, guidelines could be developed that warrant the deployment of alternative dynamic eco-driving technologies according to their computational performance, road geometry and operational characteristics, traffic signal control, and prevailing traffic conditions. The methodologies and software developed in the context of this dissertation can facilitate and expedite the latter task, since they enable low-cost and safe testing of different dynamic eco-driving systems for different types of road sections (number of lanes and length), green and red signal durations for different signal phases, passenger car characteristics, and traffic conditions (uncongested, near-congested, congested). In the case of advisory dynamic eco-driving, the latter elements can be used in conjunction with driver profile and CV dynamic status upon entrance to dynamic eco-driving service zone in order to decide on the provision of dynamic eco-driving advice.

Finally, it has to be mentioned that this dissertation explicitly focuses on dynamic eco-driving systems that have been developed for ICE vehicles. Recently, the substantial shift to electromobility, which is experienced worldwide, has led to the development of dynamic eco-driving models for hybrid electric vehicles (Zhu et al. 2022), plug-in hybrid electric vehicles (Li et al. 2021), fuel cell hybrid electric vehicles (Liu et al. 2022), and purely electric vehicles (Zhang et al. 2021). However, the dynamic eco-driving systems examined in the context of this dissertation can be rendered compatible with the latter vehicle types via the appropriate substitution of vehicle dynamics and energy consumption models according to vehicle powertrain.

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Appendix A

The EVPA Aimsun API enables the emulation of dynamic eco-driving near signalized intersections in the microscopic traffic simulator Aimsun. The source code of the API can be found in the corresponding EVPA GitHub Repository, where instructions are provided with respect to building the EVPA Dynamic-link library (DLL) and loading it to Aimsun. When the EVPA DLL is loaded in Aimsun and a Simulation Experiment is executed, the EVPA GUI pops up (**Figure A.1**) that enables the setup of EVPA along multiple areas of the simulated road network and the manipulation of its behavior.

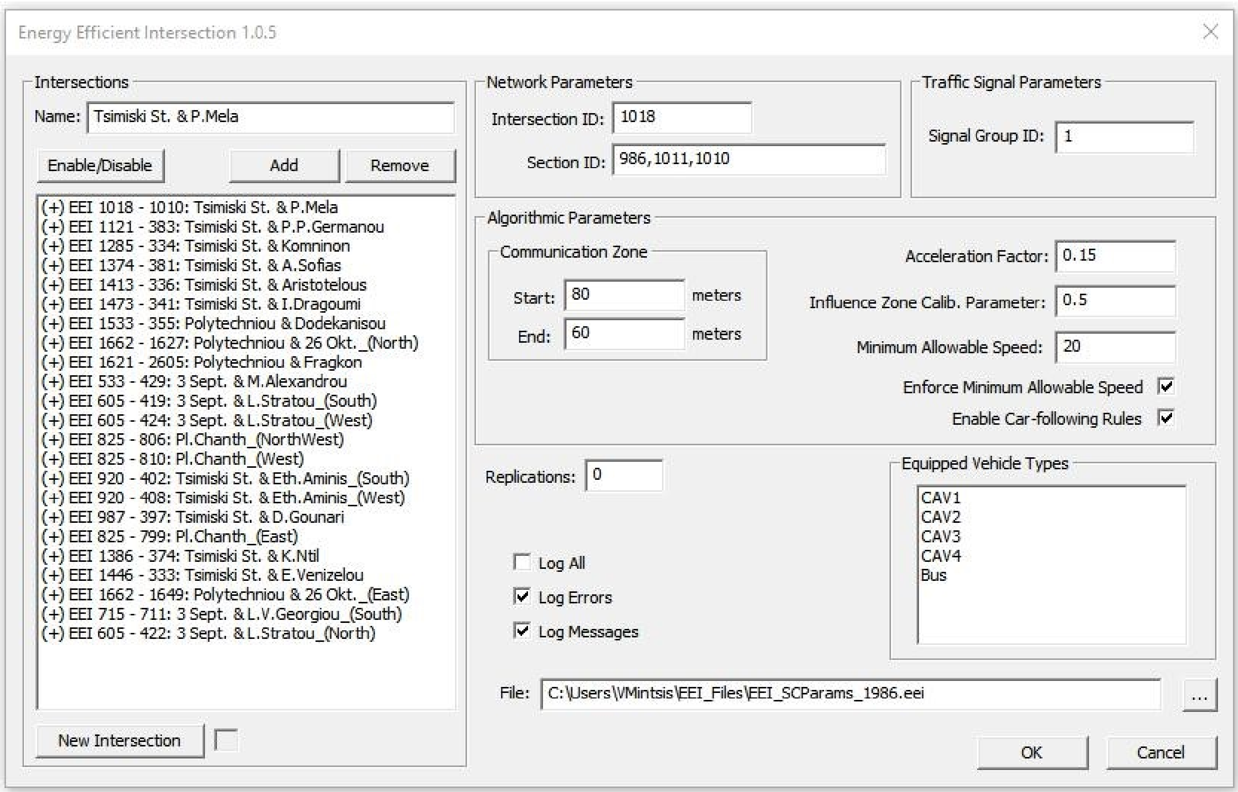

Figure A.1. EVPA GUI

Specifically, the EVPA GUI allows a user to initialize and manipulate the following elements of the EVPA API:

- add/remove an intersection approach where dynamic eco-driving is implemented,
- enable/disable the dynamic eco-driving service along selected intersection approaches,
- specify the road sections that constitute an intersection approach (from farthest to closest),

- specify the intersection that the coded intersection approach leads to,
- specify the signal group for which speed advice is estimated,
- specify the zone upstream of the intersection where speed advice execution starts,
- specify algorithmic parameters of dynamic eco-driving,
- specify vehicle types that receive and execute speed advice,
- specify number of replications for which EVPA API will be run automatically,
- specify log files that will be output, and
- upload text file that contains the aforementioned information.

To explicitly emulate manually driven CVs operated by EVPA-DT throughout dynamic eco-driving maneuvers, a dedicated vehicle type entitled "NC_Car" needs to be specified in Aimsun. Moreover, visualization of vehicle types that implement dynamic eco-driving during simulation animations requires the definition of a new vehicle parameter entitled "Advised" and the relevant View Style (**Figure A.2**) and View Mode (**Figure A.3**) in Aimsun. Different labels and relevant symbols (i.e. vehicle colors) defined within the newly created View Style imply different vehicle behavior within dynamic eco-driving service zones and are explained below:

- **Not Tracked – Not Advised:** manually driven vehicle enters the dynamic eco-driving service zone but is not equipped with connectivity capabilities and cannot receive speed advice,
- **Tracked:** CV enters the dynamic eco-driving service zone where its behavior can externally be manipulated via the EVPA API (becomes tracked), but does not receive speed advice due to unfavorable conditions (distance to intersection, remaining phase time, speed on entry to service zone, interactions with surrounding vehicles),
- **Advised:** CV enters the dynamic eco-driving service zone and receives speed advice without becoming tracked via the EVPA API (status serving debugging purposes),
- **Tracked – Advised – Non-Compliant:** manually driven CV enters the dynamic eco-driving service zone, becomes tracked and executes speed advice based on EVPA-DT, and
- **Tracked – Advised:** automatically driven CV enters the dynamic eco-driving service zone, becomes tracked and executes speed advice based on EVPA.

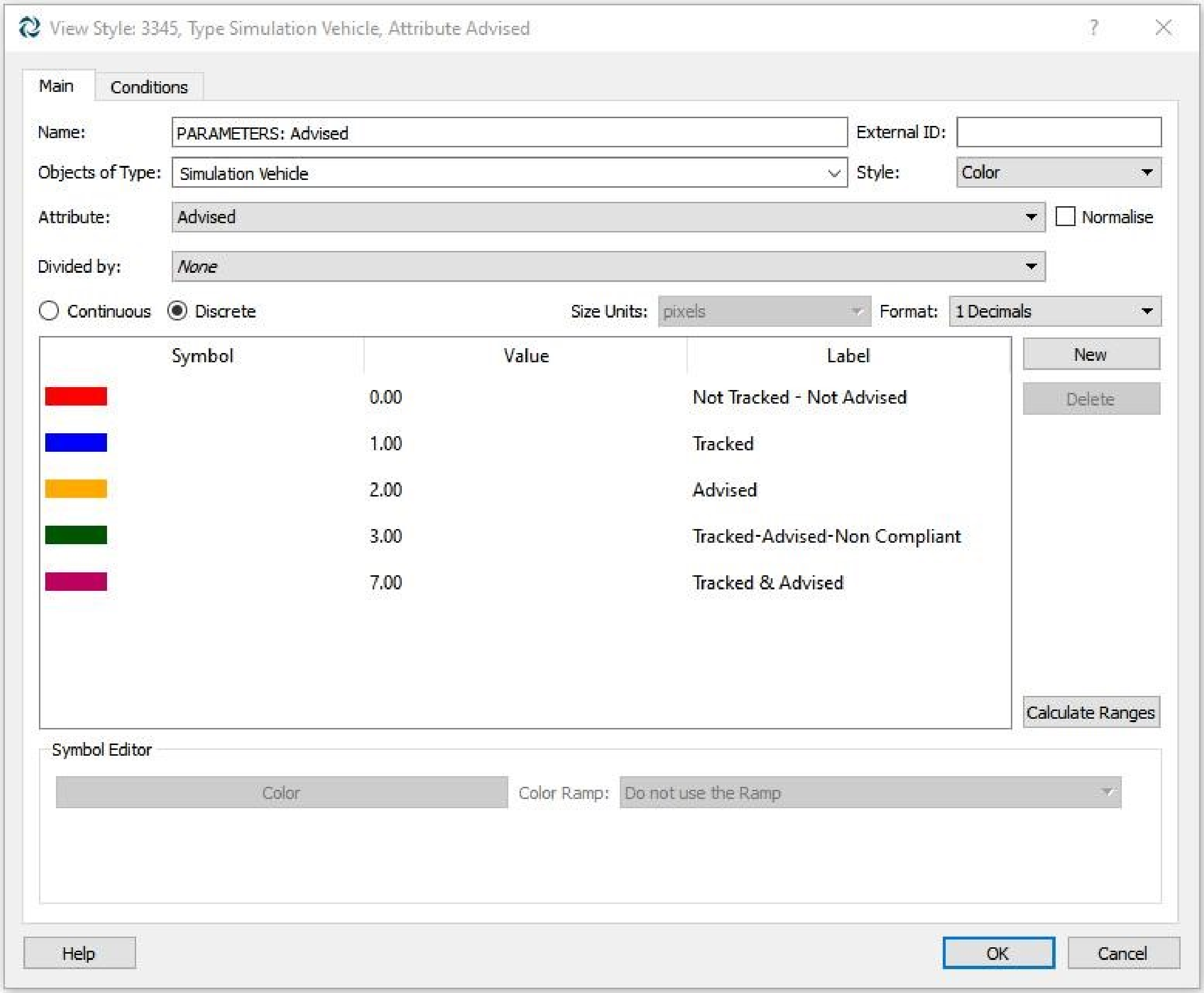

Figure A.2. View Style required for visualizing dynamic eco-driving capable vehicles in Aimsun

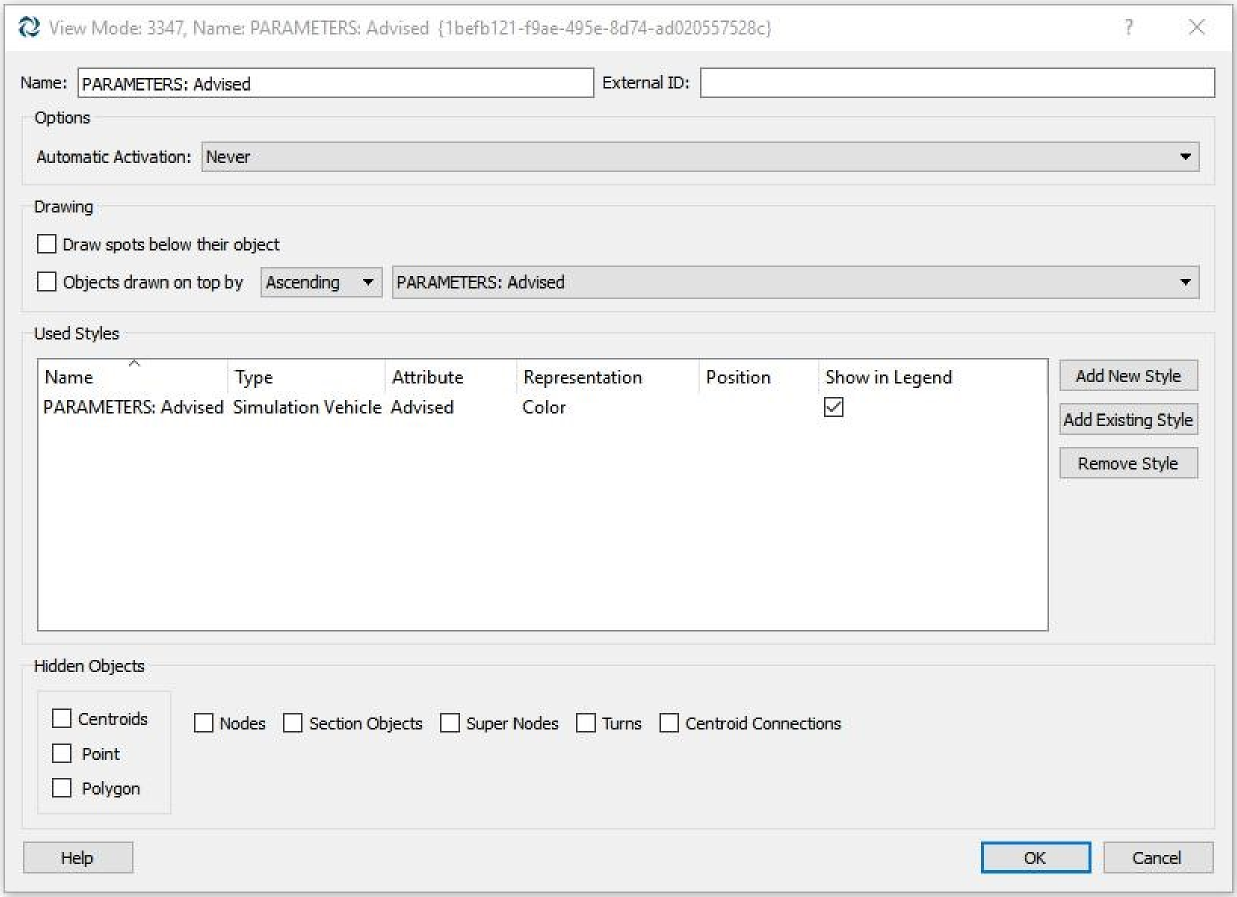

Figure A.3. View Mode required for visualizing dynamic eco-driving capable vehicles in Aimsun

Appendix B

TrajAIM (Trajectory Analysis for Microsimulation) is a web-based application that enables the visualization and analysis of vehicle trajectories produced by the microscopic traffic simulator Aimsun. The application code can be found in the corresponding TrajAIM GitHub Repository along with relevant installation instructions.

TrajAIM can process and visualize vehicle trajectories and other dynamic vehicle characteristics that are output as ".fzp" files from Aimsun. Moroever, it enables the comparison of the latter vehicle attributes that have been produced from different Aimsun Experiments. Upon opening TrajAIM the user encounters two separate tabs ("Tables" and "Analysis") that offer different functionalities.

Via the "Tables" tab the user can browse and upload the output files that contain information about vehicle dynamic characteristics (".fzp" files must be converted to ".txt" files prior to uploading to TrajAIM). In order to upload an output file the "Initialize" button should be clicked. In case of comparison of trajectories from different simulation experiments, the user should check the "Advise" option and click the "Merge" button to upload the second output file. **Figure B.1** depicts the "Tables" Tab and its functionalities.

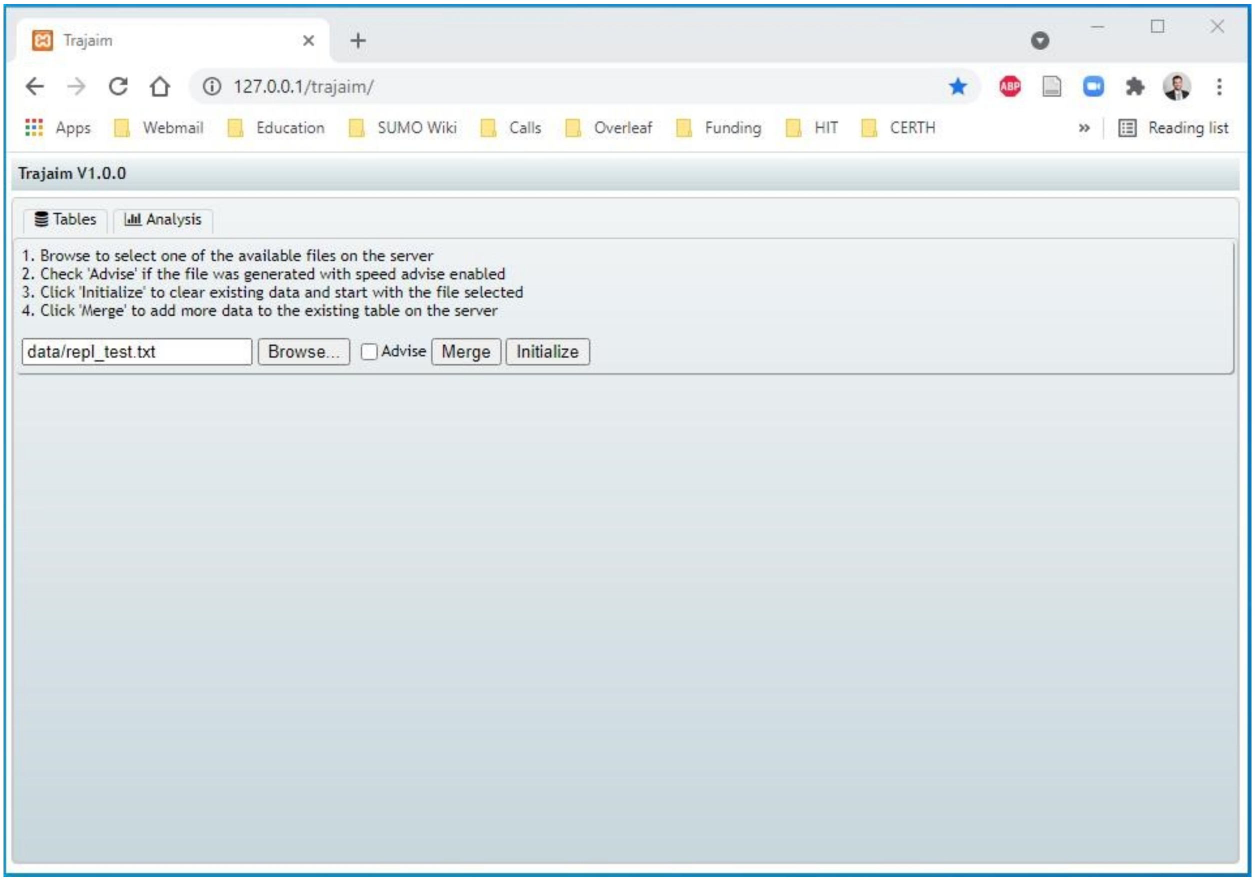

Figure B.1. The "Tables" tab in TrajAIM enables the uploading of simulation output in a SQL database

Via the "Analysis" tab the user can specify the vehicles (types and ids) for which plots can be created. The following types of plots can be generated by TrajAIM according to vehicle dynamic characteristics (i.e. position, speed, acceleration):

- distance vs time,
- speed vs time,
- speed vs distance,
- acceleration vs time,
- acceleration vs distance, and
- acceleration vs speed.

By checking the option "Export", the data used for generating the selected plots are also exported in csv format in the corresponding csv project folder. **Figure B.2** depicts the "Analysis" Tab and its functionalities.

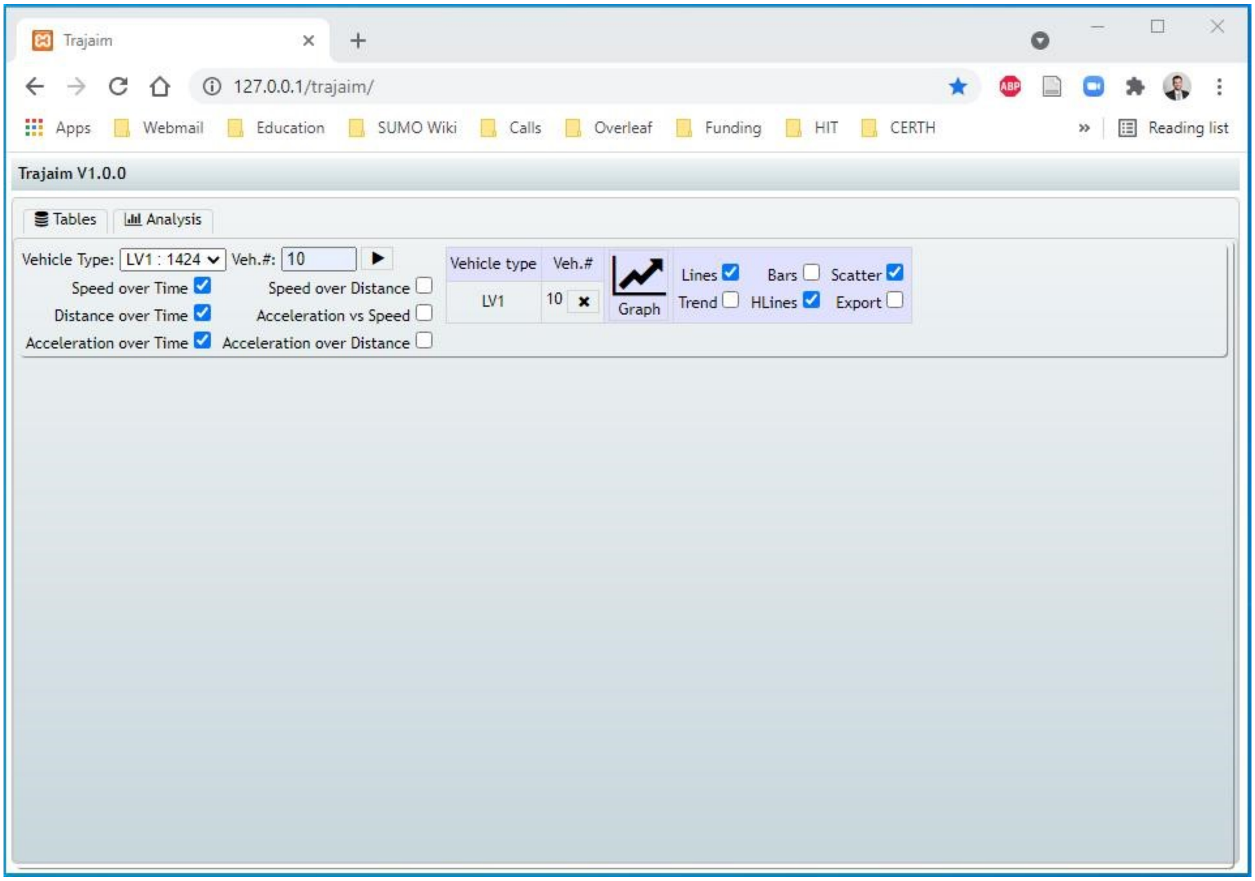

Figure B.2. The “Analysis” tab in TrajAIM enables the processing, visualization and export of simulation output for selected vehicles simulated in Aimsun Experiments

List of Publications

Journal Articles

- Mintsis, E., Vlahogianni, E. I., and E. Mitsakis. 2020. "Dynamic Eco-Driving near Signalized Intersections: Systematic Review and Future Research Directions." Journal of Transportation Engineering, Part A: Systems, 146(4), 04020018. https://doi.org/10.1061/JTEPBS.0000318
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- Mamarikas, S., Mintsis, E., Doulgeris, S., Ntziachristos, L., Vlahogianni, E. I., and E. Mitsakis. 2019. "Impacts of Dynamic Eco-driving on the Energy Consumption of Electric Vehicles and Hybrids." In Proc., 9th International Congress on Transport Research. Athens, Greece.
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