POLITECNICO DI TORINO

Master's Degree in Automotive Engineering

Master's Degree Thesis

Eco-Approach & Departure (EAD) Application in Real-World Urban Traffic

Supervisors:

Prof. Carlo NOVARA

Prof. Angelo BONFITTO

Prof. Michele PAGONE

Eng. Stefano FAVELLI

Candidate:

Mohammed

KHAIRI MOHAMMED KHAIRI

MARCH 2024

Summary

When driving on urban roads, repetitive braking, acceleration and idling at traffic signals result in loss of the energy produced by the engine in conventional vehicles, by the battery in Battery Electric Vehicles (BEV), or both in Hybrid Electric Vehicles (HEV). Some of these stops are due to the lack of information about the state of traffic lights. So if the drivers have a pre-knowledge about the traffic condition ahead, unnecessary stops can be avoided. Such pre-knowledge is now possible to be provided through Vehicle-to-Infrastructure (V2I) connectivity.

In an ideal connected urban area with V2I connectivity, Eco-Approach and Departure (EAD) application is one of the most promising solutions, in which drivers are guided to approach, travel through and depart from signalized intersections in an eco-friendly manner using the Signal Phase and Timing (SPaT) information broadcast by the traffic signals. With the knowledge of incoming signal information, connected vehicles can improve their energy consumption efficiency by following well-designed speed profiles that guarantee a timely arrival at a green light.

This thesis is an implementation of the EAD application using the SPaT information broadcast by the traffic signals. Aiming to test this application in Real-World Urban Traffic, a velocity profile recorded in Torino, Italy, is used as the velocity profile of a Lead vehicle, which is followed by an Ego vehicle (i.e. the test vehicle) with two strategies:

1. An Adaptive Cruise Control (ACC) strategy only, which will be the reference vehicle; (i.e. the uninformed vehicle with no V2I communication).
2. An ACC combined with the EAD strategy. The ACC is active when there is no SPaT coverage, and the EAD is active when there is SPaT coverage.

The thesis is structured as follows; the first chapter is an introduction, the second chapter provides a theoretical background about the work previously done, followed by a chapter discussing the methodology followed in this thesis. Chapter 4 is the application, followed by a brief conclusion about the framework.

Acknowledgements

I would like to express my deepest gratitude to the following individuals for having played a crucial role in the completion of this thesis:

- After more than 7 years of his absence, I dedicate this thesis to the loving memory of my dear father, and I offer this work as a tribute to his soul. May his spirit continue to inspire and guide me in all my endeavors.

- My sincere appreciation goes to my mother, whose unwavering support, boundless love and prayers have been a source of strength throughout my academic journey and life.

- On an academic level, a genuine appreciation goes to my supervisor, [Pro. Carlo NOVARA], for his unwavering guidance, invaluable insights and continuous support throughout the research process. His expertise and encouragement have been instrumental in shaping the direction of this study.

- Numerous thanks go to my co-supervisors, [Pro. Angelo BONFITTO], [Pro. Michele PAGONE] and [Eng. Stefano FAVELLI] for their weekly meetings and guidance, without which, this research would not have been possible.

- An extended gratitude goes to my family and friends for their unwavering support, understanding, and encouragement during the ups and downs.

Mohammed KHAIRI MOHAMMED KHAIRI

Table of Contents

List of Tables

List of Figures

Acronyms

EAD
Eco-Approach and Departure

SPaT
Signal Phase and Timing

DSRC
Dedicated Short Range Communication

ACC
Adaptive Cruise Control

SAE
Society of Automotive Engineers

BEV
Battery Electric Vehicle

V2I
Vehicle-to-Infrastructure

V2V
Vehicle-to-Vehicle

EDM
Electric Drive Modules

SOC
State of Charge

Chapter 1

INTRODUCTION

Transportation activities, (i.e. the movement of goods and people), are a key contributor to fuel consumption and the release of various air pollutants, including greenhouse gas (GHG), carbon monoxide (CO), nitrogen oxides (NOx), particulate matter (PM) and many others, and vehicle emissions often stand out as the primary source of these pollutants in many regions [1]. Transportation practices were reported by the U.S. Environmental Protection Agency (USEPA) as the responsible for approximately 26% of the total U.S. greenhouse gas (GHG) emissions in 2014 [2]. Approximately 97.5 quadrillion British Thermal Units (BTUs) (i.e. Quads) of energy were consumed by the United States in 2015, and 28% of which was used for transportation purposes [3].

Increasingly stringent standards and regulations have been implemented as a powerful driving force to encourage fuel efficiency, aiming to conserve energy and decrease vehicle exhaust emissions. On the other hand, the rapid advancements in vehicle and communication technologies are fostering the experimental implementation of eco-driving prototypes. These prototypes, through the adoption of more intelligent driving styles, aim to enhance transportation energy efficiency.

A notice of proposed rule-making was issued in 2016 by the US Department of Transportation that, if implemented, would require Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) connectivity on all new light-duty vehicles, with the intention of reducing the number of car accidents [4]. A percentage of 20 to 40% of vehicle sales will be automated by 2030 and a full penetration could be seen in several stages over the next few decades [5]. With the implementation of such rules, access to information and data by connected vehicles will rapidly increase. This level of connectivity and autonomy will transform transportation of people and goods in a green way with important positive impacts, socially and economically, such as, improved safety, increased comfort, reduced travel time, and more efficient road utilization.

Connected and automated vehicles offer huge potentials for boosting road safety, capacity, and efficiency, because of their ability to process data from many sources and their precise ability for positioning and control compared to human drivers, and with Vehicle-to-Infrastructure (V2I) connectivity, it is possible to provide vehicles with much more information, as to facilitate that vehicles form groups and act cooperatively, with the aim of improving traffic flow, increasing safety, and reducing energy consumption and emissions. Some of the frameworks are addressed below.

1.1 Anticipating the State of the Road

More energy efficient velocity transitions can be obtained if the change in velocity constraints is anticipated by having a prior knowledge of road speed limits, safe speeds on curved roads, and an estimate of average traffic speed. Speed limit is a standard feature on modern onboard navigation units, and road curvature can be extracted from navigation maps to calculate the likely safe speed on a curve. Not only can speed limit, curve and traffic speeds be used to optimize velocity transitions, but also to inform its predictive power-train control functions.

Road incline, especially on steep terrain, is another predominant factor influencing vehicle power demand, and more so for heavier vehicles, as it influences velocity, torque and gear selection constraints. Therefore, prior knowledge of the road grade, obtained from 3D road maps, is very helpful in predictive power-train control. Moreover, prior knowledge of road grade will allow more wise use of available velocity band and better gear selection; for instance, a vehicle can slow down in anticipation of a steep descent, or speed up in preparation for a climb. A predictive cruise control function is in production by Daimler, that is able to adjust a heavy duty truck speed and gear in anticipation of upcoming road grade for 3% increase of energy efficiency on a highway.

1.2 Anticipative Car Following

Human drivers' view, when following other cars, is often blocked by the preceding vehicle, and their event horizon is therefore very limited. As a result, they frequently neglect to take into account the vehicles approaching from behind when they abruptly decelerate. Not only is this disruptive to traffic flow and unsafe, but also, this can lead to the inefficient slowing down of multiple vehicles, ultimately causing an unavoidable queue in a brief period.

Despite the fact that experienced drivers do exercise anticipation to some extent in driving as they pay attention to clues and drive accordingly; for instance, if a lead vehicle is observed to be accelerating and decelerating erratically, or the following vehicle is tail-gating him/her, an experienced driver tends to increase the gap or change the lane, thanks to better sensing capabilities, today much more can be done. Connected vehicles with Vehicle-to-Vehicle (V2V) communication are capable of anticipating the motion of their preceding vehicle and therefore adjust their speed for a more steady and smooth motion. In a connected and automated vehicle environment, each vehicle can pass on its intended action to the following vehicles, and this allows the ego vehicle to know, with more certainty, the position of the preceding vehicles over its planning horizon.

While the primary goal is to robustly maintain a safe gap between the ego vehicle and preceding vehicle, this gap can be wisely used to filter abrupt slow-downs and application of brakes, which will result in smoother velocity transitions and increased energy efficiency of not only the ego vehicle but more, the entire queue of upstream traffic.

1.3 Anticipative Lane Selection and Merging

In multi-lane roads, practical driving observations indicate that the choice of lane is a complex decision-making challenge, potentially attributed to the absence of information about the average speed and intentions of vehicles in adjacent lanes. When merging into a highway from an on-ramp or exiting to an off-ramp, for example, lane selection can be a much bigger problem and safety-critical decision.

In an ideal scenario, when all vehicles communicate, Vehicle-to-Vehicle (V2V) communication is used to provide more information about the intention of neighboring vehicles, and the speed of each lane can be broadcast from roadside sensors, resulting in a more wise and smooth lane changing.

1.4 Anticipating Signal Phase and Timing

Numerous empirical studies demonstrate a positive correlation between vehicle emissions and energy consumption when experiencing delays at traffic signals. In urban roadways which have traffic control infrastructure (e.g. traffic lights), traffic suffers from increased delays due to idling at the traffic signals on red and increased energy consumption and emissions due to inherent acceleration and deceleration required at the signals. To minimize delays and therefore lowering energy consumption and emissions, infrastructure control is most focused on in the research, such as developing better traffic signal control algorithms that are both dynamic and adaptive, using information such as vehicle queue lengths.

However, there are a variety of strategies that are now being considered to reduce fuel consumption and carbon dioxide emissions from the transportation sector concerning the vehicle and the driver, one of which is the “eco-driving” strategy, which is garnering increased interest in recent years. Eco-driving typically consists of changing a person’s driving behavior based on general (static) advice to the driver, such as driving gently, accelerating slowly, reducing high speeds and idling, etc. Taking this one-step further, it is possible to provide real time advice to drivers based on changing traffic and infrastructure conditions for even greater fuel and emission savings.

Eco-driving at signalized intersections is one of the most promising solutions for fuel saving and emission reduction in urban areas. Applying this approach, drivers would effectively reduce stops and idling and avoid unnecessary acceleration and deceleration by receiving Signal Phase and Timing (SPaT) information in advance. The Eco-Approach and Departure (EAD) application is one primary example in which drivers are guided to approach, travel through and depart from signalized intersections in an eco-friendly manner using the Signal Phase and Timing (SPaT) information broadcast by the traffic signals. With the knowledge of incoming signal information, connected vehicles can improve their fuel efficiency by following well-designed speed profiles that guarantee a timely arrival at a green light as shown schematically in Figure 1.1 [6]. Furthermore, the burden of speed adjustments can be taken away from human drivers if vehicles are autonomously driven.

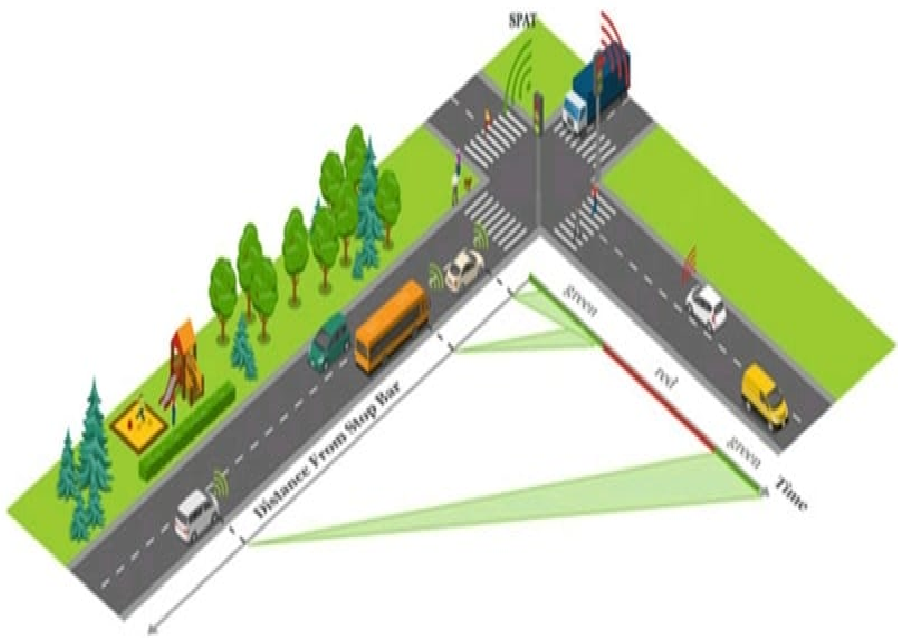

Figure 1.1: Schematic of eco-driving with SPaT preview. Shaded triangles contain feasible paths to green intervals of the traffic light for the three vehicles moving from bottom left to top right [6].

The SPaT information can be broadcast in many ways, directly transmitted to vehicles within range using Dedicated Short Range Communication (DSRC) technology or may become available via cellular networks provided by the traffic control center. Alternatively, inferring SPaT information is possible via on-board cameras and via crowd-sourcing.

Not only does using SPaT information by connected and automated vehicles improve the energy efficiency, but also, more is the penetration of these vehicles on urban roads, more is the reduction of the energy consumption of conventional vehicles as well, as conventional vehicles are more likely to smoothly follow the connected and automated vehicles, and this will therefore result in reducing the chance of stopping at intersections as well.

Energy efficient driving at signalized intersections and its impact on energy use has been the topic of much research and development in recent years. Experimental results in isolated environments and in real-world traffic conditions show that considerable fuel saving (5–15%) is possible with human drivers in the loop. Even more energy saving is expected in automated driving (or with Adaptive Cruise Control (ACC)) where vehicles can adjust their speeds more precisely and effortlessly.

The following chapters of this thesis will focus on the latest framework, as this thesis is an implementation of the Eco-Approach and Departure (EAD) application using the Signal Phase and Timing (SPaT) information broadcast by the traffic signals. The application is tested in Urban Traffic using a velocity profile recorded in Torino, Italy as a driving cycle. This velocity profile is modified using the EAD approach aiming to pass the intersections during a Green Signal Phase.

Chapter 2

THEORETICAL BACKGROUND

In this chapter, a theoretical background of the work previously done is presented, starting with a scientific paper titled "Dynamic Eco-Driving for Arterial Corridors" and published in 2011 [7], followed by "Developing a Framework of Eco-Approach and Departure Application for Actuated Signal Control", published in 2015 [8], and ending with "Eco-Approach and Departure (EAD) Application for Actuated Signals in Real-World Traffic", published in 2019 [9].

In "Dynamic Eco-Driving for Arterial Corridors" [7], a dynamic eco-driving system for signalized corridors that consists of an arterial velocity planning algorithm was developed aiming to minimize vehicle fuel consumption and emissions. The overall arterial velocity planning algorithm block diagram is shown in Figure 2.1

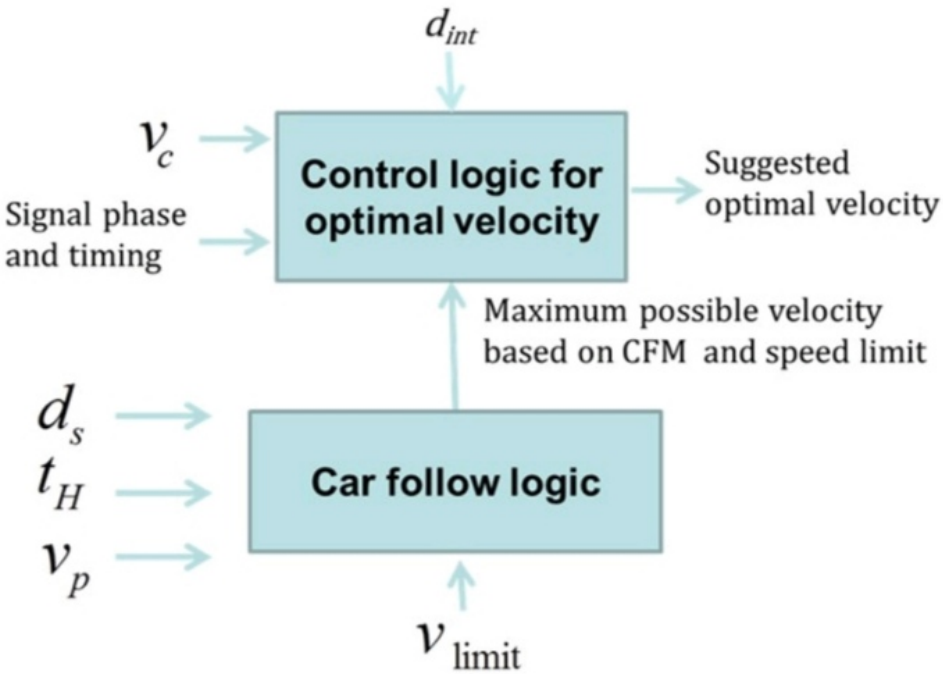

Figure 2.1: Block Diagram of the Arterial Velocity Planning Algorithm [7].

As shown in Figure 2.1, several input parameters are required for the velocity planner control logic; the distance from the vehicle to the intersection (d_{int}), the current vehicle speed (v_c), the Signal Phase and Timing (SPaT) information from the signal (t_r, t_g), where (t_r) is the time until the light changes to red, and (t_g) is the time until the light changes to green, and the target maximum speed on the roadway link that is dictated by the link speed limit and/or the car following logic (v_h), which also depends on other input parameters, such as, the headway distance (d_s), headway time (t_h), and the current vehicle speed (v_c). This optimal velocity control logic tries to minimize the fuel consumption by minimizing the idling time (i.e. ensuring that the vehicle reaches the intersection during a green phase) and the total tractive power demand, yet ensuring an optimal velocity less than or equal to (v_{limit}).

The described dynamic eco-driving velocity planning algorithm for arterial corridors was applied to a typical mid-sized sedan car traveling on a hypothetical 10-signalized intersection corridor with 500 m to 600 m length between the intersections, and 70 km/h as speed limit, and the Signal Phase and Timing (SPaT) information was set randomly between 200 m and 300 m prior to the intersection.

The results show that 12% less fuel was consumed by vehicles with velocity planning, and the travel time on an average is approximately 2% shorter, compared to vehicles without velocity planning. Also, [7] concluded that, driving style with hard acceleration and deceleration velocity profile that quickly gets a vehicle up or down to a target speed and then hold a steady state cruise speed till specific location at a specific time is reached is less fuel consuming, compared to a driving style with velocity profile that takes a longer period of time to accelerate and decelerate to reach the same point, as in the earlier, it takes less energy to accelerate back up to typical speed, compared to starting from a stop.

However, “Developing a Framework of Eco-Approach and Departure Application for Actuated Signal Control” [8] proposes a framework for the eco-approach and departure application for actuated signals. This framework has been evaluated with numerical experiments taking into account information uncertainties, preceding vehicle’s dynamics from radar detection and potential distraction issues. Also, the display of the recommended speed was being governed in this framework by including a state machine to mitigate any induced distraction to the driver.

The aim of the paper was to develop an Eco-Approach and Departure (EAD) application that is compatible with actuated signals, and the proposed system was designed to acquire information from four sources as illustrated in Figure 2.2, which are:

1. Signal Phase and Timing (SPaT) information from the signal controller.
2. vehicle position from an on-board GPS receiver.
3. vehicle dynamics from the on-board diagnostics (OBD) port.
4. preceding vehicle’s state from a forward looking automotive radar.

Then, a vehicle trajectory planning algorithm takes all of these into account and determines an eco-friendly speed profile in response to the dynamic Signal Phase and Timing (SPaT) information of the actuated signal.

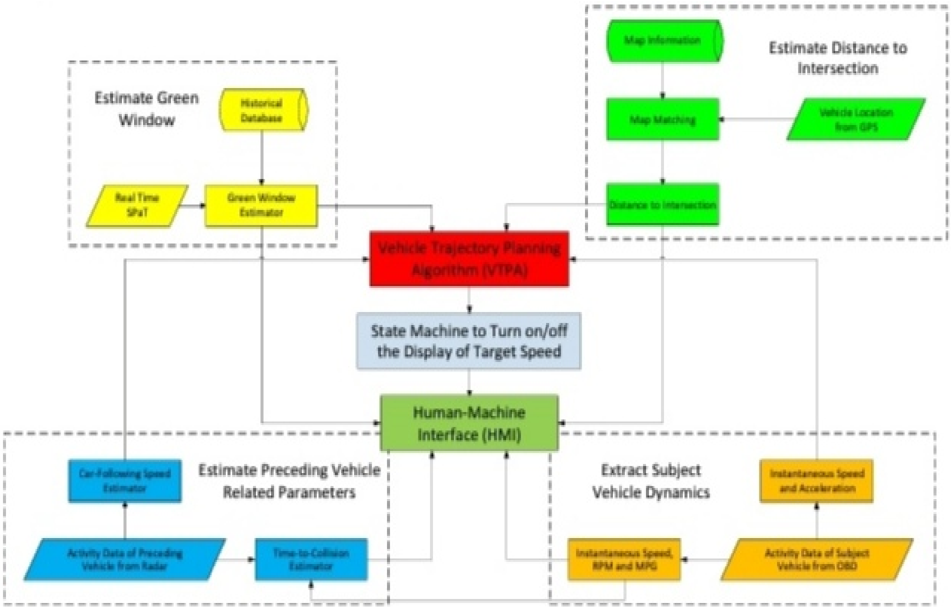

Figure 2.2: EAD System Architecture [8].

Piece-wise sinusoidal acceleration and deceleration profile based algorithm was proposed to ensure that the vehicle is able to reach a certain location within a certain time window with the objective of keeping a safe headway while not exceeding the speed limit and not crossing on red (basic requirement for a safe driving), avoiding or minimizing unnecessary idling, acceleration and deceleration (reducing energy and emissions).

The proposed EAD algorithm was applied to simulate vehicle trajectories of a single passenger car at a hypothetical signalized intersection with different entry times. The SPaT information was collected at the El Camino Real Connected Vehicles test bed in the Bay Area, California, and it is assumed that it becomes available when the vehicle is 300 m away from the intersection, as this is the range of Dedicated Short Range Communication (DSRC) transceivers in the current market. The DSRC signal covers 400 m, (300 m upstream of the intersection to 100 m downstream). The road grade of the study area is assumed to be zero, and 40 mph as a speed limit. A set of uninformed baseline vehicle trajectories were generated for comparison purposes. The uninformed drivers were assumed to attempt to cruise around the speed limit until close to the intersection, then, they may stop or not depending on the current traffic signal phase.

The results indicate that the proposed framework is effective, especially when the initial entry speed is relatively low (i.e. lower than or equal to 30 mph), at reducing energy consumption and emissions of the equipped vehicles. The emissions of the EAD-equipped vehicle were 11% - 30% less, and because some of these vehicles were able to pass the intersection without stopping, the average travel time was also slightly better.

"Eco-Approach and Departure (EAD) Application for Actuated Signals in Real-World Traffic" [9] however, was a real-world experimental work conducted along the El Camino Real corridor in Palo Alto, CA, USA, aiming to evaluate the system performance discussed in [7] and [8] in terms of energy savings and emissions reduction, taking into account that strategies and algorithms were designed to be adaptive to the dynamic uncertainty for actuated signal and real-world traffic.

The field test was conducted in Palo Alto, CA in November 2015 with a length of about 1.7 *miles*. Figure 2.3 shows the test corridor and the positions of all the Dedicated Short Range Communication (DSRC) enabled intersections. Two drivers of similar driving styles were chosen to drive along the El Camino Real corridor.

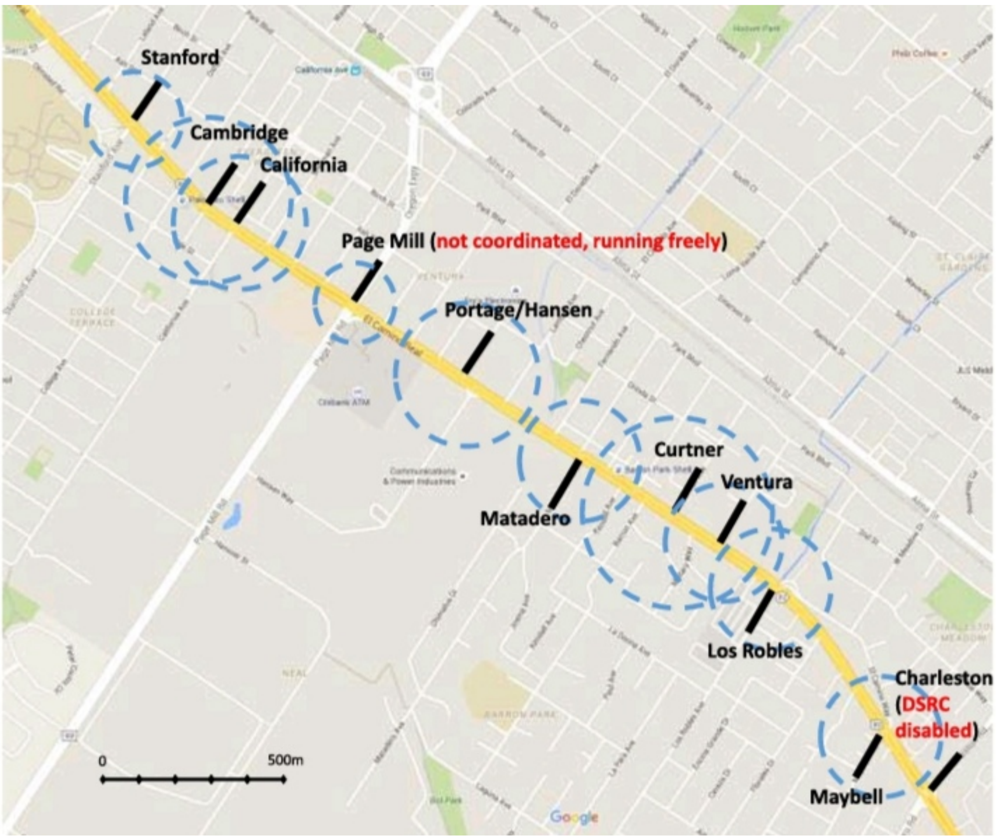

Figure 2.3: Test corridor and DSRC positions [9].

A research test vehicle set up for the field test is shown in Figure 2.4. A real-time automotive radar system was set up at the front of the vehicle to identify the relative distance and speed of the preceding vehicle. The on-board system received position information via GPS and vehicle dynamics data through on-board diagnostics (OBD). Additionally, a Dedicated Short Range Communication (DSRC) modem, an on-board computer, and a 7-inch automotive-grade display functioning as an artificial dashboard were also installed in the research test vehicle. The vehicle's distance to intersection was estimated based on the GPS location and a developed algorithm.

The recommended vehicle trajectory was calculated integrating data from multiple sources by the EAD algorithm, then, the driver received the information for EAD through the artificial dashboard display, and archived in the database every second. For comparison reasons, another vehicle with similar size and engine condition was selected as the baseline vehicle for the uninformed driver.

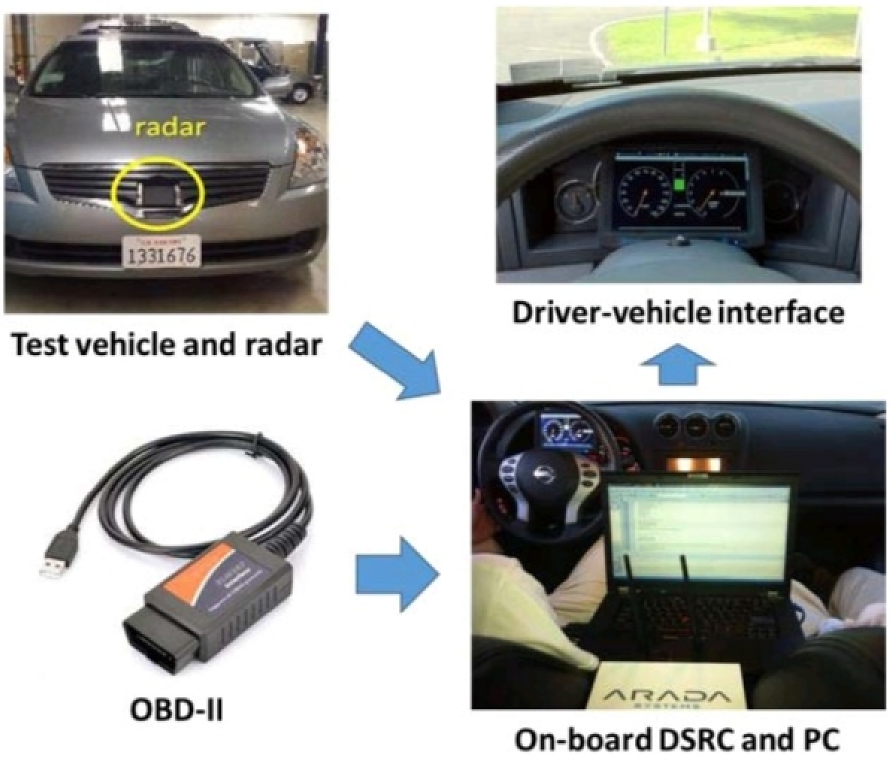

Figure 2.4: Test vehicle and on-board devices [9].

A graphic user interface (GUI) was proposed as represented in Figure 2.5, aiming to present a number of items to the driver mainly for test and development purposes, such as: the vehicle's current speed, the engine RPM, The SPaT countdown information for the current signal phase, and the most important, an "advisory" speed as calculated from the velocity planning algorithm. Figure 2.5 (a) shows the case when there was no preceding vehicle nearby in the same lane. The target speed estimated from the trajectory planning algorithm was then displayed at the speedometer. Figure 2.5 (b) shows the case when the radar detected a preceding vehicle which was 28 m in front, and to avoid any distraction, the display of target speed was turned off.

As previously mentioned, the nominal communication range of DSRC transceivers in the current market is around 300 m. In practice, however, and due to weather or obstruction of buildings and vehicles, the effective DSRC range may diminish. Thus, tests were performed to know the range around each intersection, resulting in a range varying from 113 m in Page Mill to 269 m in Curtner as illustrated in Figure 2.3. by the radii of dashed circles.

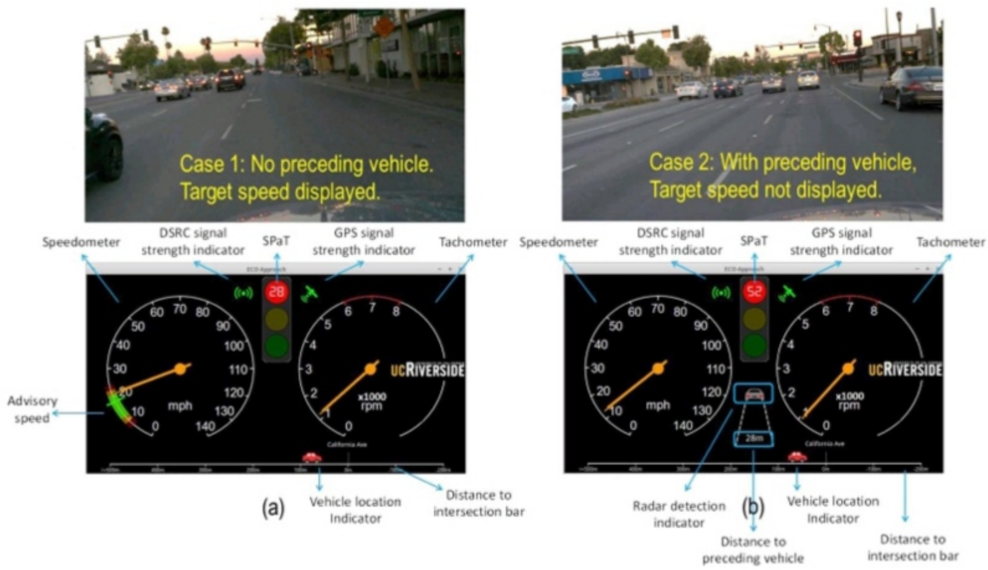

Figure 2.5: Human-Machine Interface under different traffic conditions [9].

It is worth mentioning that, The signal state data-grams were transmitted from Caltrans 2070 controller via AB3418 protocol over serial RS-232 communications. They were encoded into SPaT messages (in compliance with Society of Automotive Engineers (SAE) J2735 standard [10]) which were broadcast over DSRC at 10 Hz.

In [11], a generalized trajectory planning algorithm was developed for the EAD application that is compatible with actuated signals, in which multiple data sources, such as SPaT information broadcast by Road-side DSRC Unit (RSU), GPS location, vehicle dynamics and preceding vehicle information from radar, were integrated in this system. The proposed EAD framework also works well with fixed signals, as fixed signals can be regarded as actuated signals with equal minimum and maximum time to change for each phase.

A speed recommendation based on the state of the subject vehicle, preceding vehicle, and upcoming traffic signal was provided by the vehicle trajectory planning algorithm as described in Figure 2.6, and the development of the EAD algorithm, various objectives were taken into account to ensure a secure, comfortable, time-efficient, and environmentally friendly journey during the approach and departure stages in real-world traffic; Numerous rules were implemented to ensure the vehicle maintains a safe distance from preceding vehicles while adhering to traffic regulations, (e.g. not speeding and not crossing on red), as safety is the primary goal and fundamental requirement for any Connected Vehicle (CV) application, and the second objective is to avoid or minimize idling, acceleration and deceleration at the intersection to reduce fuel consumption and emissions.

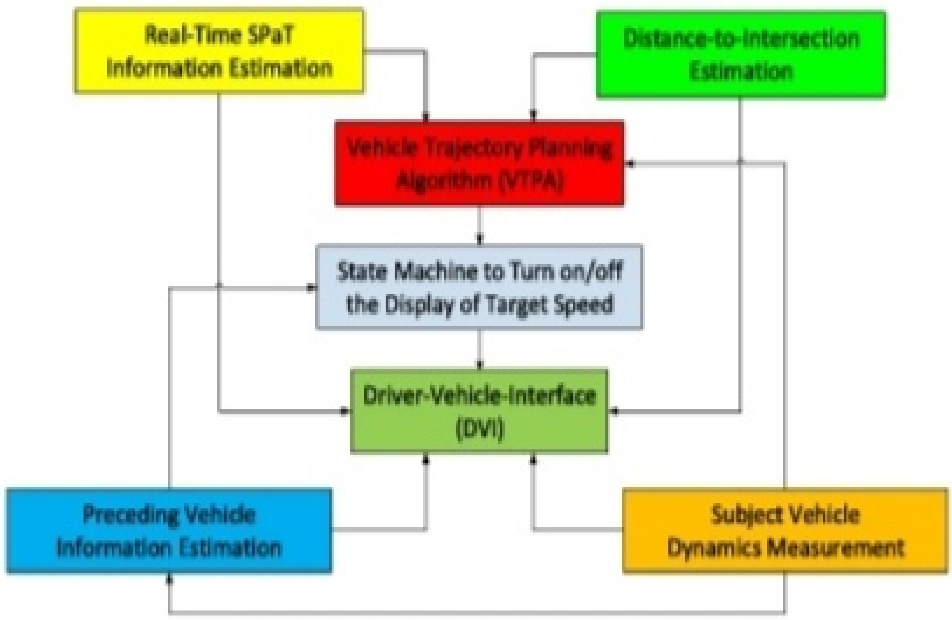

Figure 2.6: System Architecture [9].

How the EAD algorithm impacted vehicle dynamics and driving behavior was first analyzed. With the assistance of the EAD system, the percentage of low-speed mode (i.e. speed between 0 - 15 *mph*) decreased significantly, and specifically, the idling or near-idling cases (i.e. speed between 0 - 5 *mph*) for the vehicle with informed driver was 22% less, proving that the proposed EAD system can diminish unnecessary idling, even when the signal is actuated and the traffic condition is uncertain. The percentage of relatively high speed (i.e. speed between 30 *mph* - speed limit) was reduced, proving that the vehicle speed was controlled wisely avoiding unnecessary acceleration and deceleration.

Fuel consumption and air pollutant emissions derived from real-time trajectory data collected from both vehicles (research test vehicle and baseline vehicle) were estimated to evaluate the energy and environmental impact of EAD. It turned out that 6% of the energy was saved in the proposed EAD system for the trip segments when activated within DSRC ranges and 2% energy for all trips, and 7% reduction of CO, 18% of HC, and 13% of NOx for all trips. Also, as the driver was notified of the time if the remaining green time was short by the proposed HMI, the driver, in such a case, may accelerate to avoid the stop, which resulted in a 2% less average trip time compared to that of the uninformed driver.

With respect to the state of art, the contribution of this thesis is that the EAD approach is tested in Urban Traffic using a velocity profile recorded in Torino, Italy, as the velocity profile of a Lead vehicle, which is followed by the Ego vehicle (i.e. the test vehicle) with an Adaptive Cruise Control (ACC) strategy only; which will be the reference vehicle; (i.e. the uninformed vehicle with no V2I communication), and an Adaptive Cruise Control (ACC) combined with the Eco-Approach and Departure (EAD) strategy. The ACC is active when there is no Signal Phase and Timing (SPaT) coverage, and the EAD is active when there is SPaT coverage.

The Ego vehicle equipped with ACC strategy only is compared with the Ego vehicle equipped with the ACC combined with the EAD strategy. Results are shown as a comparison in the Used Battery Energy, Electrical Efficiency and Battery State of Charge (SOC).

Chapter 3

METHODOLOGY

In this chapter, the methodology followed in this thesis is described, and all the equations and diagrams are based on the scientific paper “Dynamic Eco-Driving for Arterial Corridors” [7]. The chapter discusses three major points; Velocity and Fuel Consumption/Emissions Relationship, Vehicle Trajectory Planning, and Velocity Planning Algorithm.

3.1 Velocity and Energy Consumption/Emissions Relationship

Extensive research has been done at a microscopic and physical level to study the relationship between energy consumption (i.e. fuel consumption) and/or emissions and vehicle velocity [12]. Generally speaking, when considering fuel and emissions normalized by distance traveled, the fuel-speed function takes on a general shape as depicted in Figure 3.1.

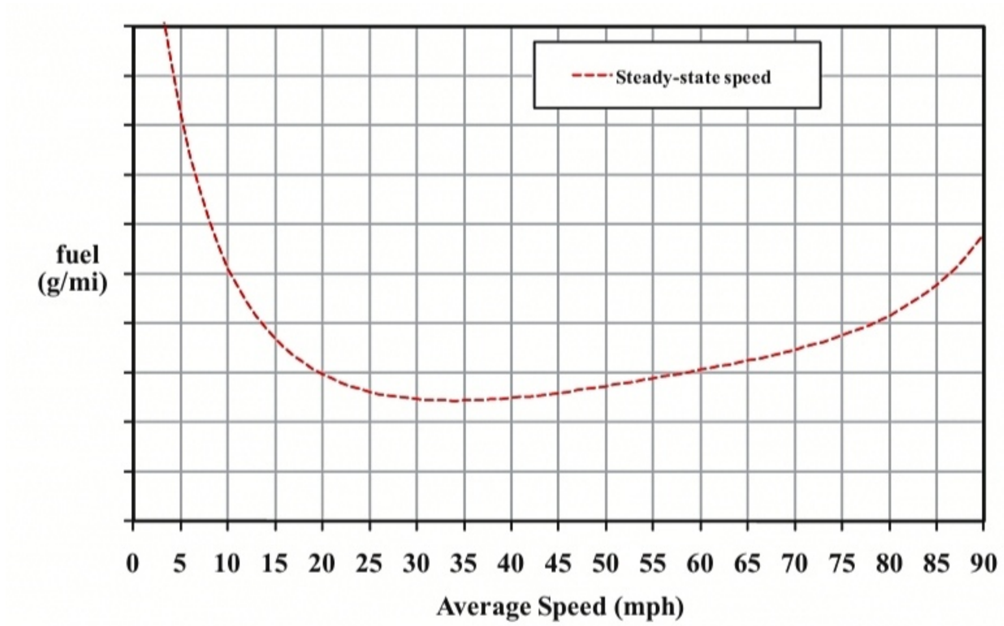

Figure 3.1: Fuel consumption versus average cruise speed [7].

As demonstrated by Figure 3.1, at lower speeds, vehicles have a high fuel/distance value due to spending a greater time on the roads. In contrast, emissions are higher at higher speeds, as the engine needs to work harder to overcome aerodynamic resistance. In between these extreme cases lies the middle ground as the fuel consumption and emissions are minimized, (around 60 *kph*), depending on the vehicle type. This concludes that it is best to maintain a steady-state velocity at these mid-range speeds, if overall fuel consumption and emissions are to be minimized.

3.2 Velocity Planning Algorithm

A single traffic light scenario and its corresponding time-distance diagram is described in Figure 3.2 and discussed below.

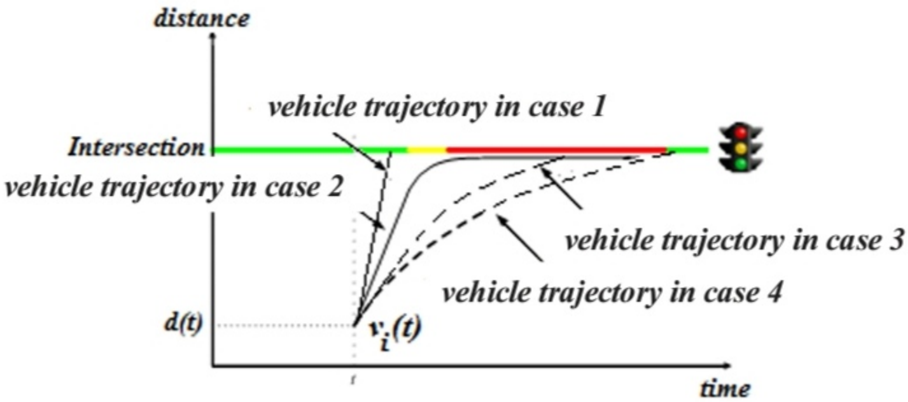

Figure 3.2: Time-space diagram representing four different velocity profiles to approach an intersection [7].

A traffic light in a fixed location with its phase changing in time (green, yellow, and red lines), and several vehicle velocity profiles that all have the same initial velocity ($v_i(t)$) and position ($d(t)$) is shown in Figure 3.2. At time (t), the vehicle receives Signal Phase and Time (SPaT) information, and then, four cases are considered:

1. The vehicle increases its speed and manages to make it through the green light with no slowing or idling. In this case, even though the vehicle does not have to idle at the red light, the fuel consumption and emissions are high since the vehicle had to accelerate to make it in the green signal phase.

2. The vehicle continues to drive at speed ($v_i(t)$), and slows down quickly and stops rather suddenly when the traffic light turns yellow then red. In this case, fuel/emissions are also high due the fact that the vehicle holds the original velocity for a certain amount of time, and then goes into idling mood for a long period.

3. The driver of the vehicle takes their foot off from the gas pedal and coasts to

a stop at the intersection. Here instead, the fuel/emissions are less, since very low fuel is being consumed as the vehicle coasts up to the intersection.

4. The vehicle actively slows down (i.e. braking) and then travels at a lower speed until the traffic light turns green, after which the vehicle increases its speed, all without stopping. This case has the lowest fuel consumption and emissions, due to the fact that the vehicle does not accelerate after the intersection from a dead stop, but rather from a moving velocity, resulting in a reduced energy, as the energy required to accelerate back up to speed is significantly less.

This concludes the following; as a vehicle travels through a signalized corridor, it is best to travel at a mid-range speed when possible, adjusting the velocity to minimize fuel consumption and emissions, while obeying these requirements:

1. maintaining a steady state speed around the speed limit.
2. maintaining a safe headway distance to vehicles in front.
3. never crossing the intersection on red.
4. minimizing idling time at the traffic signals.

The optimal velocity control logic aims to minimize the energy consumption by minimizing the total traction power demand obeying the aforementioned requirements and ensuring that the optimal velocity is less than or equal to the road speed limit. The overall arterial velocity planning algorithm block diagram was previously shown in Figure 2.1

Aiming to avoid idling, the vehicle should reach the intersection during a green signal phase, and depending on the current phase of the signal, the travel time to the intersection is given as Equation (3.1) if the signal phase is Green, and as Equation (3.2) if the signal phase is Red.

$$t \in [0, t_r) \cup [t_g, t_r) \tag{3.1}$$

$$t \in [t_g, t_r) \tag{3.2}$$

Thus, given the distance to the intersection (d_{int}), the possible velocities of the vehicle fall into a range given by ($v_{\mathrm{lo}} = d_{\mathrm{int}}$ / t_h) and ($v_{\mathrm{ho}} = d_{\mathrm{int}}$ / t_l) , where (t_l) and (t_h) are the low and high values respectively from Equation (3.1) and Equation (3.2) above.

The overall velocity selection algorithm is represented in Figure 3.3, in which one of two velocity profiles (acceleration velocity profile or deceleration velocity profile) is followed, aiming to reach the intersection at a green single phase. Those velocity profiles are described below in more detail.

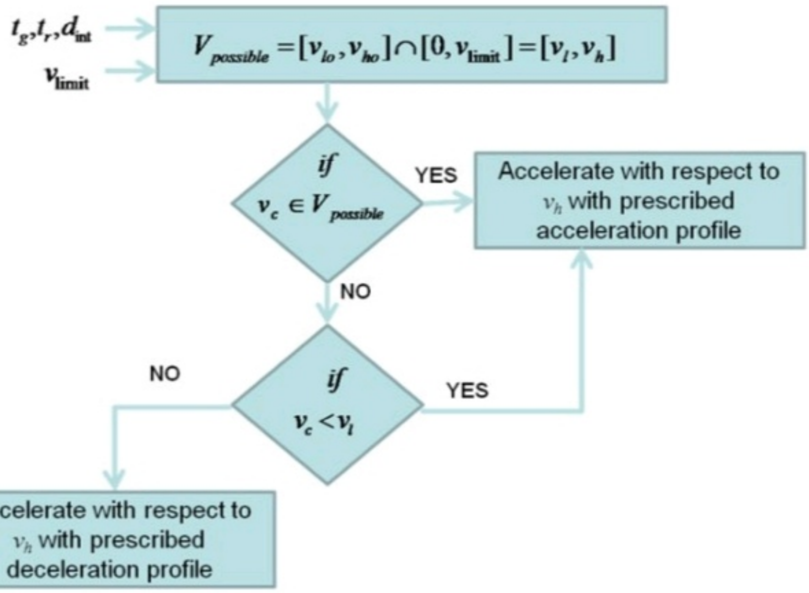

Figure 3.3: Arterial Velocity Planning Algorithm Block Diagram. You have to put reference if you took this diagram for another book or paper [7].

3.2.1 Acceleration Profile Design

The vehicle needs the ability to accelerate at specific times aiming to stay within the targeted range of velocity, or to achieve a velocity by which the vehicle can reach the intersection at a green signal phase. An infinite number of ways are there to accelerate from one speed to another (e.g. using a constant acceleration, linear-acceleration or constant-throttle acceleration), however, the acceleration profile that minimizes energy consumption and emissions, yet, takes into considerations the passengers' comfortable (i.e. low jerk) is the one to be chosen. Acceleration profiles from current vehicle velocity (v_c) to a velocity that ensures that the vehicle reaches a point (e.g. the intersection) at a specific time are shown in Figure 3.4.

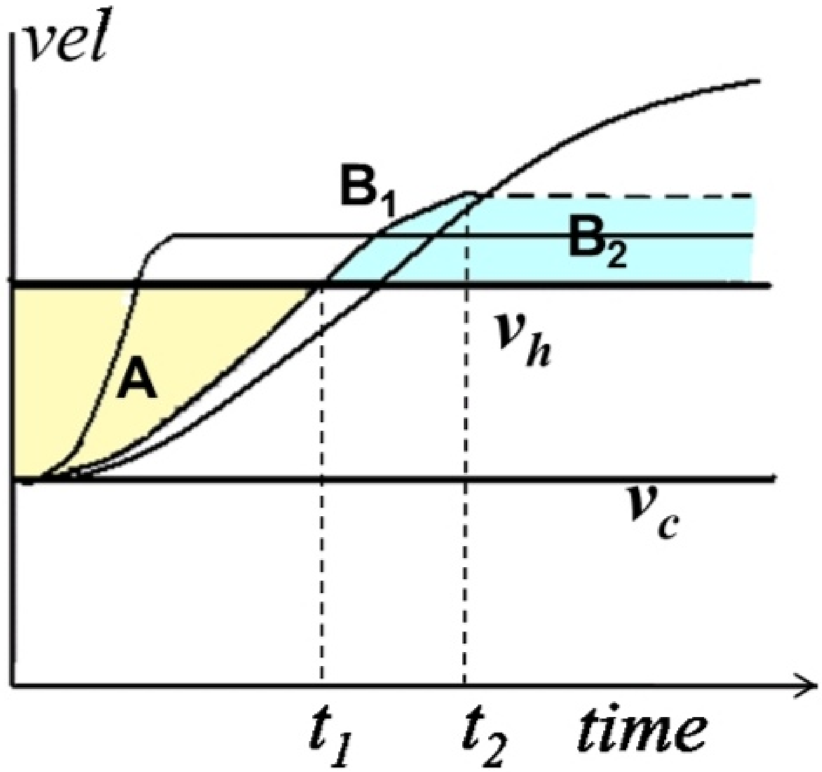

Figure 3.4: Different acceleration profiles for reaching a specific location at a specific time [7].

A family of velocity profiles with a trigonometric increase in velocity to ensure a smooth trajectory, is given by Equation (3.3) for $t = 0$ to $(\pi/2s)$, by Equation (3.4) for $t = (\pi/2s)$ to $((\pi/2a) + (\pi/2s))$, and by Equation (3.5) for $t = ((\pi/2a) + (\pi/2s))$ to (d/v_h):

$$v = v_h - v_d cos(st) \tag{3.3}$$

$$v = v_h - v_d(s/a)cos((a)(t - (\pi/2s) + (\pi/2a))) \tag{3.4}$$

$$v = v_h + v_d(s/a) \tag{3.5}$$

where (d) is the target distance, (v_h) is the higher limit of the velocity range, and (v_d) is the difference between the current vehicle velocity and the higher limit of the velocity range (i.e. $v_d = v_h$ - v_c).

The parameters (s) and (a) define the family of velocity profiles and different values of (s) and (a) correspond to different acceleration and jerk profiles. Parameter (s) controls the rate of change of acceleration in region A and parameter (a) controls the rate of change of acceleration in region B shown in Figure 3.4. Among the family of velocity profiles for different values of (s) and (a), the velocity profile that minimizes the traction power requirements (i.e. fuel consumption) is thus chosen.

The traction power requirement of a vehicle depending on the vehicle velocity and acceleration is given by Equation (3.6):

$$P_{\text{traction}} = Av + Bv^2 + Cv^3 + M(a + g\sin(\theta))v \tag{3.6}$$

where (M) is the vehicle mass with appropriate inertial correction for rotating and reciprocating parts, (v) is the speed, (a) is the acceleration , (g) is the gravitational constant, (θ) is the road grade angle, and (B), (C), and (D) are coefficients involving rolling resistance and air drag factors and are determined empirically.

The standard eco-driving approach advises that drivers should always accelerate slowly. Counter-intuitively, here it can be seen that to minimize fuel consumption for the total acceleration maneuver, (s) should be chosen as large as possible, and larger is (s), the sharper the acceleration will be, yet, (s) is limited by the power of the vehicle, safety, and the ride pleasure (i.e. constrained jerk). Therefore, when given a time and distance constraint, the best trajectory will be with a quick acceleration till reaching a target velocity, then remain at a constant velocity until the desired position is reached.

3.2.2 Deceleration Profile Design

In a very similar approach to the acceleration profile design, a fuel efficient deceleration profile is designed, and also there are an infinite number of ways to perform this deceleration, as the vehicle needs to decelerate to a known speed at a known point (e.g. stopping at an intersection), and this is depicted in Figure 3.5.

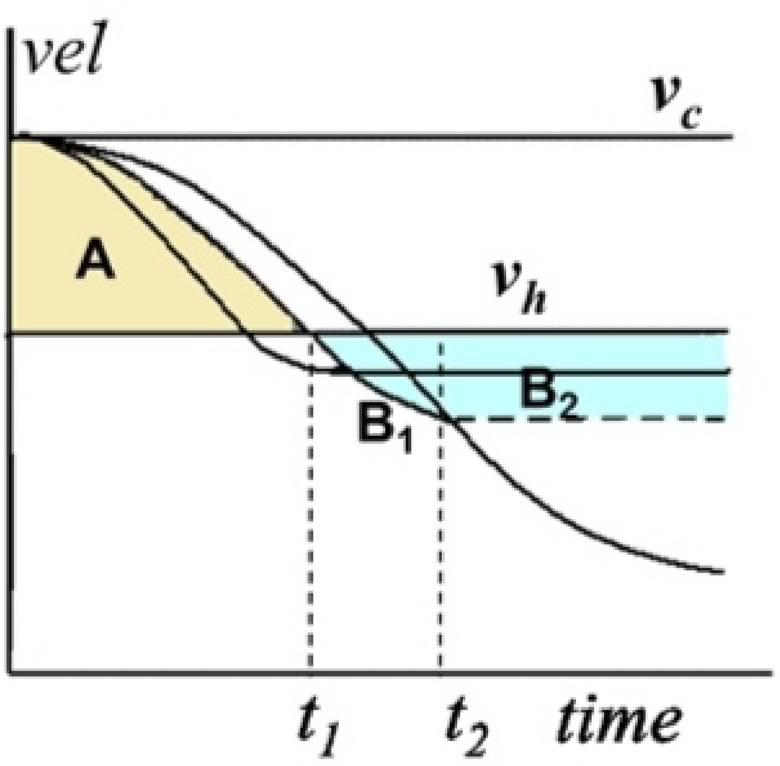

Figure 3.5: Different deceleration profiles for reaching a specific location at a specific time [7].

Also a trigonometric family of curves is chosen and given by Equation (3.7) for $t = 0$ to $(\pi/2s)$, by Equation (3.8) for $t = (\pi/2s)$ to $((\pi/2a) + (\pi/2s))$, and by Equation (3.9) for $t = ((\pi/2a) + (\pi/2s))$ to (d/v_h):

$$v = v_h + v_d cos(st) \tag{3.7}$$

$$v = v_h + v_d(s/a)cos((a)(t - (\pi/2s) + (\pi/2a))) \tag{3.8}$$

$$v = v_h - v_d(s/a) \tag{3.9}$$

where (d) is the distance to a specific location (e.g. an intersection), (v_h) is the upper limit of the possible uniform velocity range required to reach the target location at a specific time, (v_d) is the difference between the current vehicle velocity and the upper limit of the possible velocity range (i.e. $v_d = v_c$ - v_h).

As discussed before, the parameters (s) and (a) define the family of deceleration profiles and different values of (s) and (a) correspond to different deceleration and jerk profiles. Parameter (s) controls the rate of change of deceleration in region A and parameter (a) controls the rate of change of deceleration in region B shown in Figure 3.5.

Similar to the acceleration profile design, (s) is chosen as large as possible as the energy requirement (i.e. fuel consumption) for the vehicle to accelerate back to the speed limit after crossing the intersection will be less if an initial sharper deceleration is performed, as this will result in a greater final velocity at the intersection. Also the same constraints for (s) explained in the acceleration profile design applies for deceleration profile design.

Chapter 4

APPLICATION

In this chapter, the methodology discussed previously in 3 is applied on two applications, the first one is a simple application with a simplified model, while the second one is a real application applied on a real scenario using a high fidelity model. All the equations and diagrams are based on the scientific paper "Dynamic Eco-Driving for Arterial Corridors" [7].

4.1 Simplified Model Application

In this application, the algorithm provided in [7] is designed and tested using two vehicles compared against each other; an informed vehicle (e.i. the one provided with the Signal Phase and Timing (SPaT) information through Dedicated Short Range Communication (DSRC)), and an uniformed one.

4.1.1 Application Constraints

As this technology is to be equipped in new vehicles, many constraints are to be considered. These constraints are to be verified in the simulation that they are met, and they are:

1. Taking into consideration the traffic regulations, the maximum allowed speed (v_{limit}) on the road is 80 Km/h.

2. Taking into consideration the ride comfort, the maximum allowed acceleration/deceleration is 2.5 m/s^2, as shown in previous research results [13] that a driver can tolerate up to this maximum acceleration/deceleration with a gradually increasing jerk profile.

3. Also taking into consideration the ride comfort, the maximum allowed jerk is 3 m/s^3.

4.1.2 Application Assumptions

Two assumptions are introduced, one for each vehicle. For the informed vehicle, and as previously mentioned, Signal Phase and Timing (SPaT) information is assumed to be available when the vehicle is 300 m away from the intersection as this is the range of Dedicated Short Range Communication (DSRC) transceivers currently available in the market. As for the uninformed one, the traffic signal phase is assumed to be seen by the driver when he/she is 75 m away from the intersection.

4.1.3 Application Setup

The environment in which the simulation is carried is a 700 m road with an intersection 500 m from the beginning. The road width is set to be 10 m and the traffic signal is set to be in the middle of the intersection with only two phases (e.i., green and red). The Signal Phase and Timing (SPaT) information sent via Dedicated Short Range Communication (DSRC) identifies the current signal phase (e.i., green or red), and its duration (i.e. t_l, t_h), and the duration of the next signal phase, where (t_l) and (t_h) are the low and high values of the phase (e.i., the duration of the phase) respectively.

Both vehicles; the informed vehicle and the uniformed one, have the same initial velocity (v_c) which is assumed to be 50 Km/h. As for the uniformed vehicle, the driver will maintain the initial velocity till 75 m away from the intersection, when he/she sees the traffic signal phase, as previously assumed. Intuitively, if the traffic signal phase is green, the driver maintains the same speed and crosses the intersection, and if the traffic signal phase is red, the driver brakes and stops the vehicle 5 m away from the intersection (e.i. in 70 m) and waits the remaining time of the red traffic signal phase till it changes to green, then accelerates in 70 m back to the initial speed and maintains it until the end of the simulation.

On the other hand, the informed vehicle receives the Signal Phase and Timing (SPaT) information 300 m away from the intersection as previously assumed. The vehicle velocity planning algorithm, making use of the SPaT formation and satisfying the aforementioned constraints, designs and decides whether to follow an acceleration velocity profile or a deceleration velocity profile. The designed and decided velocity profile is then tuned aiming to minimize the fuel consumption and emotions.

Given the SPaT information as; the current signal phase is green and the duration is ($tg1_l$) to ($tg1_h$), and the next signal phase is red and the duration is (tr_l) to (tr_h) and the upcoming signal phase is green and the duration is ($tg2_l$) to ($tg2_h$); the low and high velocities (v_{lo} and v_{ho}) are calculated as follows:

$$v_{\text{lo}} = d_{\text{int}}/tg1_h \tag{4.1}$$

$$v_{\text{ho}} = d_{\text{int}}/tg1_l \tag{4.2}$$

where (d_{int}) is the DSRC coverage (assumed to be 300 m).

Then, satisfying the aforementioned constraints, the boundaries of the allowed velocities (v_l and v_h) within which the vehicle velocity should be, for timely arrival to the intersection at a green phase are calculated:

$$v_l = max(0, v_{\text{lo}}) \tag{4.3}$$

$$v_h = min(v_{\text{ho}}, v_{\text{limit}}) \tag{4.4}$$

meaning that; if (v_{lo}) is negative, zero is considered as the lower velocity boundary, and if (v_{ho}) is higher than (v_{limit}), (v_{limit}) is considered as the upper velocity boundary. However, if the vehicle is not able to maintain a speed within this boundary satisfying the aforementioned constraints, or the current signal phase is red, the next green signal phase is then considered.

As the intersection is 500 m from the beginning of the road, the informed vehicle will maintain the initial speed of 50 Km/h for 200 m. At the position of 200 m , the vehicle receives the SPaT information as the DSRC coverage is 300 m from the intersection. Then, as described in Figure 3.3, the velocity planning algorithm, following an if condition, decides to follow an acceleration velocity profile if the vehicle initial velocity (v_c) is less than the upper possible velocity boundary (v_h), otherwise, a deceleration velocity profile is followed.

As discussed previously in 3.2, the acceleration velocity profile is designed using Equations (3.3), (3.4) and (3.5), and the deceleration velocity profile is designed using the Equations (3.7), (3.8) and (3.9).

The parameters (s) and (a) are then tuned to obtain the acceleration/deceleration velocity profile that satisfies the aforementioned constraints, and as this application is a simple application, a simplified model representing the vehicle traction power requirement depending on the vehicle velocity and acceleration is considered and given by Equation (3.6), and the following values are considered:

$M = 1200$ $[kg]$
$g = 9.81$ $[m/s^2]$
$\theta = 0$ (assumed to be null)
$A = 100$ $[N]$
$B = 0.1$ $[Ns/m]$
$C = 0.001$ $[Ns^2/m^2]$

4.1.4 Simulation Results

Two cases are considered in order to test the aforementioned algorithm as followers:

Case 1

In this case, the Signal Phase and Timing (SPaT) information is received by the informed vehicle as the current traffic signal phase is green with a duration of 15 seconds, (i.e. $tg1_l = 0$ sec, $tg1_h = 15$ sec), and the following traffic signal phase is red with a duration of 20 seconds, (i.e. $tr_l = 15$ sec, $tr_h = 35$ sec).

Calculating the aforementioned parameters, the initial vehicle velocity (v_c) results in being less than the upper possible velocity boundary (v_h), thus, an acceleration velocity profile is designed and followed as shown in the simulation result in Figure 4.1

Initially, both vehicles; the informed vehicle and the uniformed one, maintain the same initial velocity (v_c) which is 50 Km/h for the first 200 m. At the position of 200 m, the informed vehicle receives the SPaT information and the algorithm (based on the information and satisfying the constraints) decides and designs an acceleration velocity profile, thus, the vehicle accelerates to 66 Km/h for timely arrival at a green traffic signal phase before the phase changes to red, and maintains the same speed till the end of the simulation.

On the contrast, the driver of the uniformed vehicle maintains the initial speed till 75 m away from the intersection when he/she sees the traffic signal phase, which happens to be red, thus, decelerates to a complete stop in 70 m and waits the remaining of the red phase and accelerates back to the initial speed as the traffic signal phase changes to green and maintains the same speed till the end of the simulation.

The presented result is obtained after tuning the parameters (s) and (a) (0.5 and 0.8 respectively), aiming to find the optimal velocity profile that satisfies the constraints.

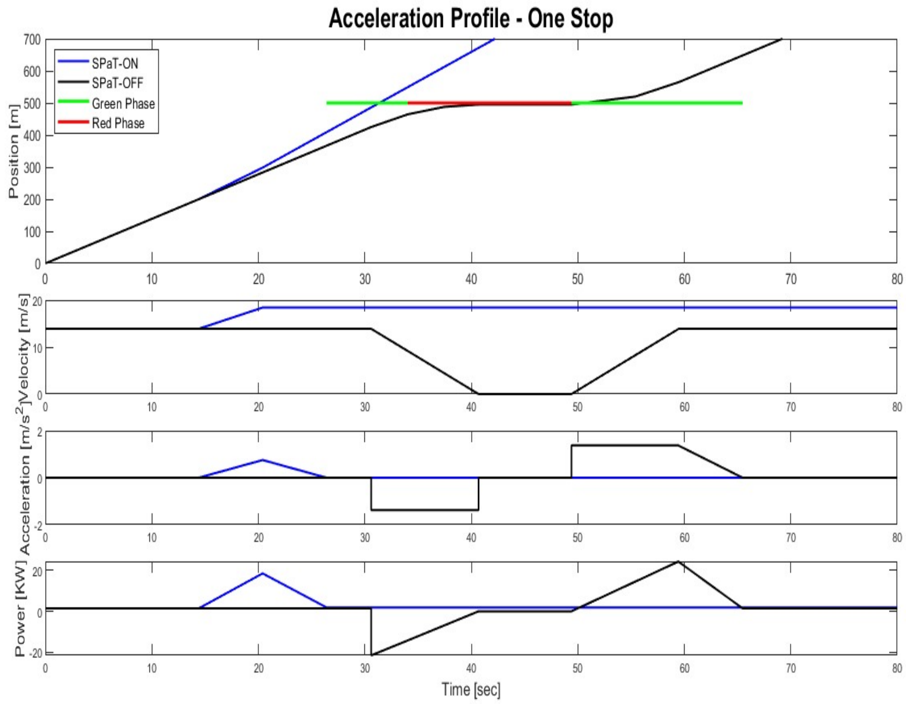

Figure 4.1: Acceleration velocity profile.

Case 2

In this case instead, the Signal Phase and Timing (SPaT) information is received by the informed vehicle as the current traffic signal phase is red with a duration of 35 seconds, (i.e. $tr_l = 0$ sec, $tr_h = 35$ sec), and the following traffic signal phase is green with a duration of 15 seconds, (i.e. $tg1_l = 35$ sec, $tg1_h = 50$ sec).

Calculating the aforementioned parameters, the initial vehicle velocity (v_c) results in being greater than the upper possible velocity boundary (v_h), thus, a deceleration velocity profile is designed and followed instead as shown in the simulation result in Figure 4.2.

Initially, both vehicles; the informed vehicle and the uniformed one, maintain the same initial velocity (v_c) which is 50 Km/h for the first 200 m. At the position of 200 m, the informed vehicle receives the SPaT information and the algorithm (based on the information and satisfying the constraints) decides and designs a deceleration velocity profile, thus, the vehicle decelerates to 19 Km/h for timely arrival at a green traffic signal phase, and maintains the same speed till the end of the simulation.

On the contrast, the driver of the uniformed vehicle, similar to Case 1, maintains the initial speed till 75 m away from the intersection when he/she sees the traffic signal phase, which happens to be red, thus, decelerates to a complete stop in 70 m and waits the remaining of the red phase and accelerates back to the initial speed as the traffic signal phase changes to green and maintains the same speed till the end of the simulation.

Similar to Case 1, and aiming to find the optimal velocity profile that satisfies the constraints, the presented result is obtained after tuning the parameters (s) and (a) (0.5 and 0.8 respectively).

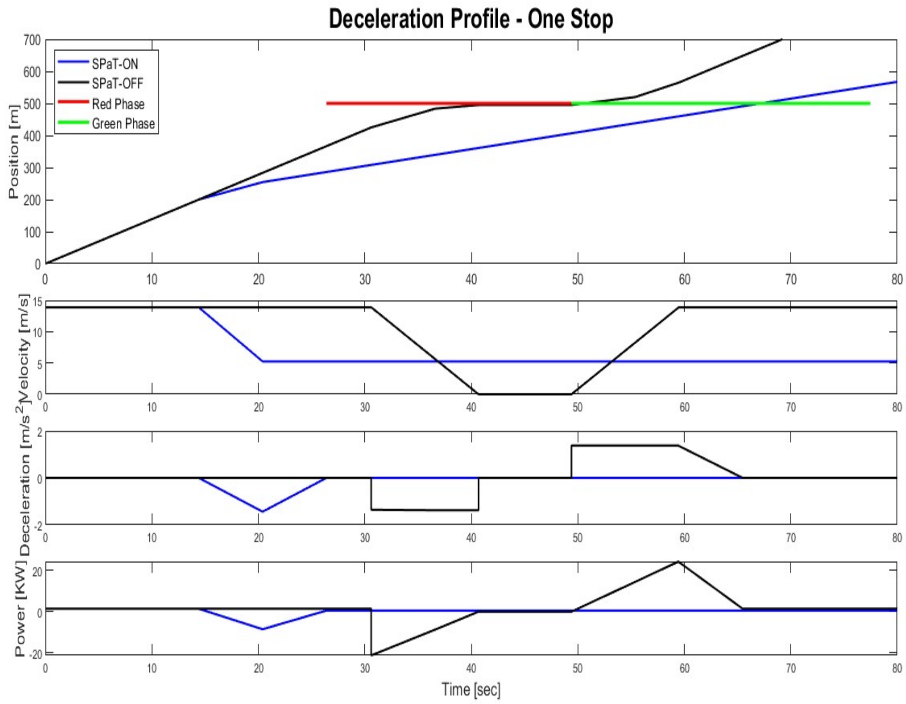

Figure 4.2: Deceleration velocity profile.

One step ahead, after testing the algorithm and tuning the parameters (s) and (a), a simulation of three stops is presented. The simulation setup is a road of 1.5 Km with three equally spaced intersections, and only the informed vehicle is considered.

First Stop

The Signal Phase and Timing (SPaT) information is received by the informed vehicle as the current traffic signal phase is green with a duration of 15 seconds, (i.e. $tg1_l = 0$ sec, $tg1_h = 15$ sec), and the following traffic signal phase is red with a duration of 20 seconds, (i.e. $tr_l = 15$ sec, $tr_h = 35$ sec).

Calculating the aforementioned parameters, the initial vehicle velocity (v_c) results in being less than the upper possible velocity boundary (v_h), thus, an acceleration velocity profile is designed and followed as shown in the simulation result in Figure 4.3.

Initially, the informed vehicle maintains the same initial velocity (v_c) which is 50 Km/h for the first 200 m. At the position of 200 m, it receives the SPaT information and the algorithm (based on the information and satisfying the constraints) decides and designs an acceleration velocity profile, thus, the vehicle accelerates to 66 Km/h for timely arrival at a green traffic signal phase before the phase changes to red, and maintains the same speed till 300 m before the second intersection.

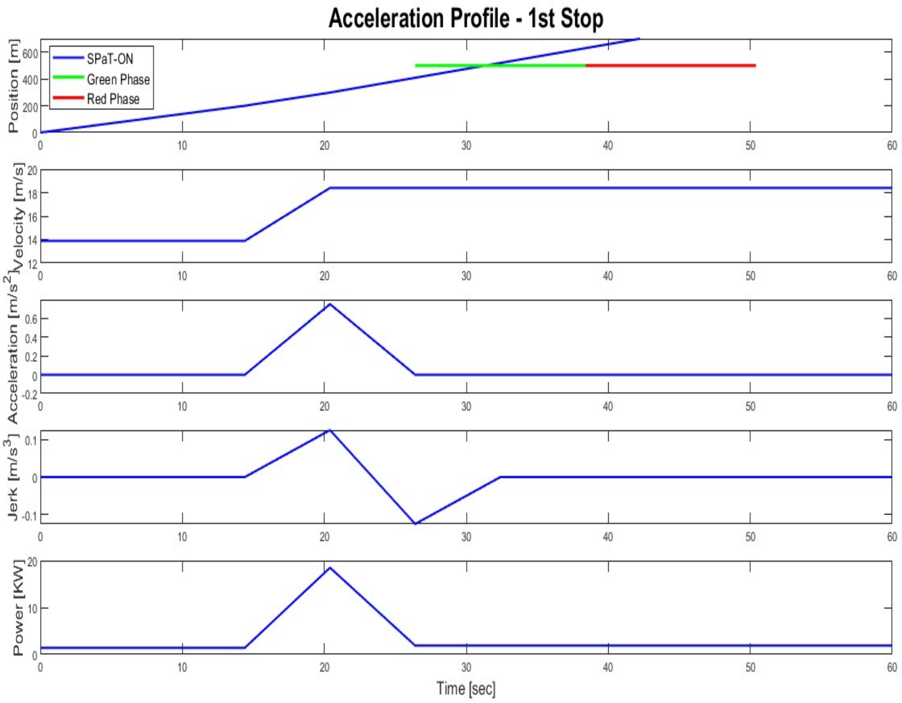

Figure 4.3: Acceleration velocity profile - First Stop.

Second Stop

The Signal Phase and Timing (SPaT) information is received by the informed vehicle as the current traffic signal phase is red with a duration of 20 seconds, (i.e. $tr_l = 0$ sec, $tr_h = 20$ sec), and the following traffic signal phase is green with a duration of 10 seconds, (i.e. $tg1_l = 20$ sec, $tg1_h = 30$ sec).

Calculating the aforementioned parameters, the initial vehicle velocity after passing the first intersection (v_{c1}) results in being greater than the upper possible velocity boundary (v_h), thus, a deceleration velocity profile is designed and followed as shown in the simulation result in Figure 4.4.

Initially, the informed vehicle maintains the same initial velocity (v_{c1}) which is 66 Km/h for the first 200 m after passing the first intersection. At the position of 700 m, it receives the SPaT information and the algorithm (based on the information and satisfying the constraints) decides and designs a deceleration velocity profile, thus, the vehicle decelerates to 46 Km/h for timely arrival at a green traffic signal phase just after the the phase changes to green, and maintains the same speed till 300 m before the third intersection.

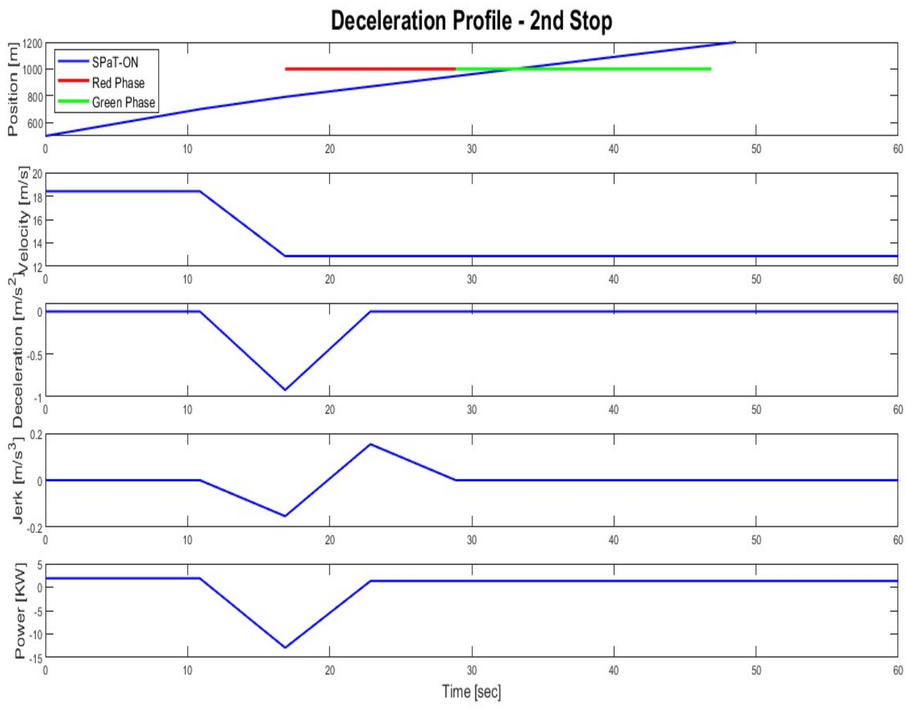

Figure 4.4: Deceleration velocity profile - Second Stop.

Third Stop

The Signal Phase and Timing (SPaT) information is received by the informed vehicle as the current traffic signal phase is green with a duration of 10 seconds, (i.e. $tg1_l = 0$ sec, $tg1_h = 10$ sec), and the following traffic signal phase is red with a duration of 20 seconds, (i.e. $tr_l = 10$ sec, $tr_h = 30$ sec).

Calculating the aforementioned parameters, the initial vehicle velocity after passing the second intersection (v_{c2}) results in being less than the upper possible velocity boundary (v_h), thus, an acceleration velocity profile is designed and followed as shown in the simulation result in Figure 4.5.

Initially, the informed vehicle maintains the same initial velocity (v_{c2}) which is 46 Km/h for the first 200 m after passing the second intersection. At the position of 1200 m, it receives the SPaT information and the algorithm (based on the information and satisfying the constraints) decides and designs an acceleration velocity profile, thus, the vehicle accelerates to 68.5 Km/h for timely arrival at a green traffic signal phase before the phase changes to red, and maintains the same speed till the end of the simulation.

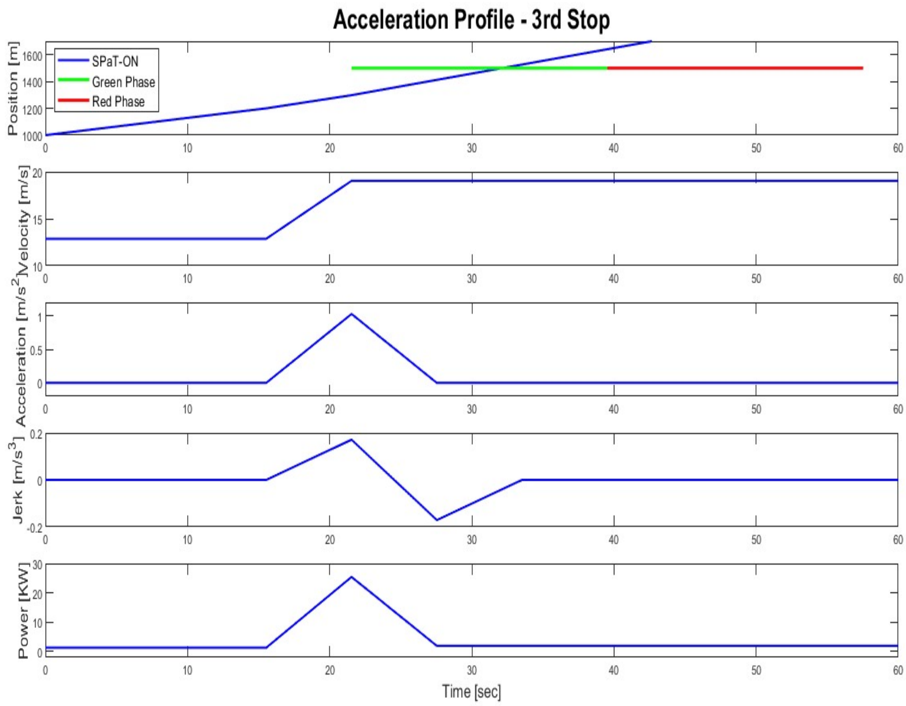

Figure 4.5: Acceleration velocity profile - Third Stop.

4.2 High Fidelity Model Application

In the previous section (i.e. section 4.1), a simplified model was considered, while in this section instead, a high fidelity model, which is more representative, not only in terms of the vehicle, but also of the scenario, is considered.

4.2.1 Application Constraints

The same constraints presented for the previous application are also considered for this one, as the road constraints and ride pleasure constraints still exist, and they are to be verified in the simulation that they are met, and they are:

1. Taking into consideration the traffic regulations, the maximum allowed speed (v_{limit}) on the road is 60 Km/h.

2. Taking into consideration the ride pleasure, the maximum allowed acceleration/deceleration is 2.5 m/s^2, as shown in previous research results [13] that a driver can tolerate up to this maximum acceleration/deceleration with a gradually increasing jerk profile.

3. Also taking into consideration the ride pleasure, the maximum allowed jerk is 3 m/s^3.

4.2.2 Application Assumption

As previously mentioned regarding the range of Dedicated Short Range Communication (DSRC) transceivers currently available in the market, Signal Phase and Timing (SPaT) information is assumed to be available when the vehicle is 300 m away from the intersection.

4.2.3 Application Setup

In this application, aiming to test the algorithm in real life, a velocity profile recorded in Torino, Italy, is used. Using a commercial software on a smartphone along with GPS, the velocity profile was recorded driving a vehicle from Politecnico di Torino - Cittadella Politecnica del Design e della Mobilità Sostenibile to Politecnico di Torino - Main Campus, following the corridor shown in Figure 4.6

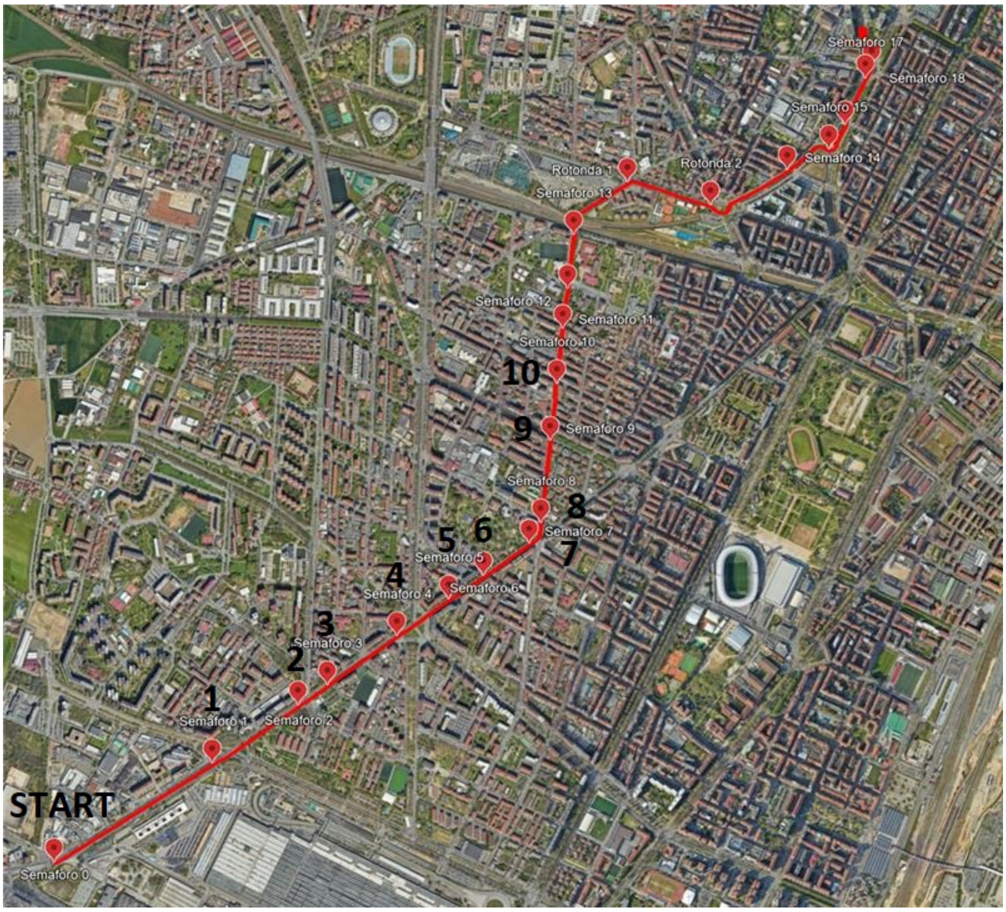

Figure 4.6: Test corridor and intersections.

This recorded velocity profile is representative of an urban driving cycle and is used as the velocity profile of the Lead vehicle. On the other hand, the Ego vehicle follows the Lead vehicle with two strategies:

1. An Adaptive Cruise Control (ACC) strategy only; which will be the reference vehicle; (i.e. the uninformed vehicle with no V2I communication).

2. An Adaptive Cruise Control (ACC) combined with the Eco-Approach and Departure (EAD) strategy. The ACC is active when there is no Signal Phase and Timing (SPaT) coverage, and the EAD is active when there is SPaT coverage, as shown schematically in Figure 4.7.

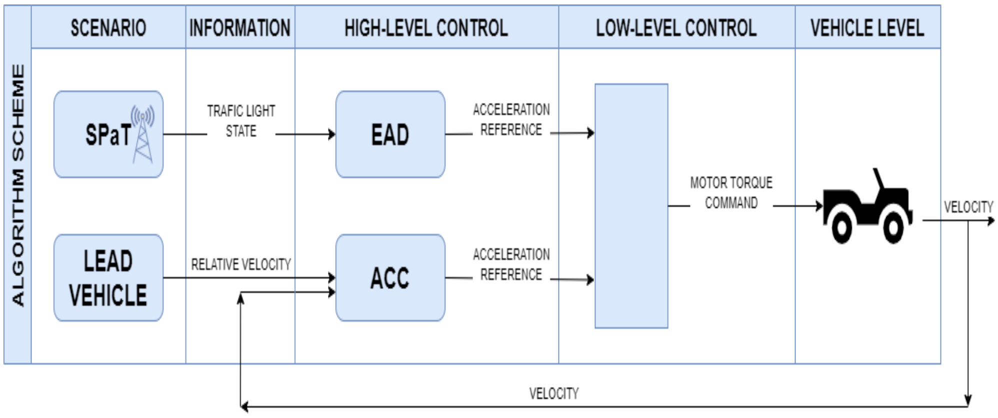

Figure 4.7: Algorithm Scheme.

4.2.4 The High Fidelity Model

The simplified model was intended for purposes of testing the functionality of the algorithm and basic tuning, (i.e. tuning the parameters (s) and (a)). Instead, the presented model in the loop shown in Figure 4.8 is a forward longitudinal model of a 52 V Battery Electric Vehicle (BEV) built in MATLAB®/Simulink™, where the vehicle is modeled as a full electric front-wheel drive passenger vehicle with one electric motor coupled with a single gear transmission system, and together with the inverter, these three components constitute the target Electric Drive Modules (EDM) [14]. The BEV main specifications are listed in Table 4.1.

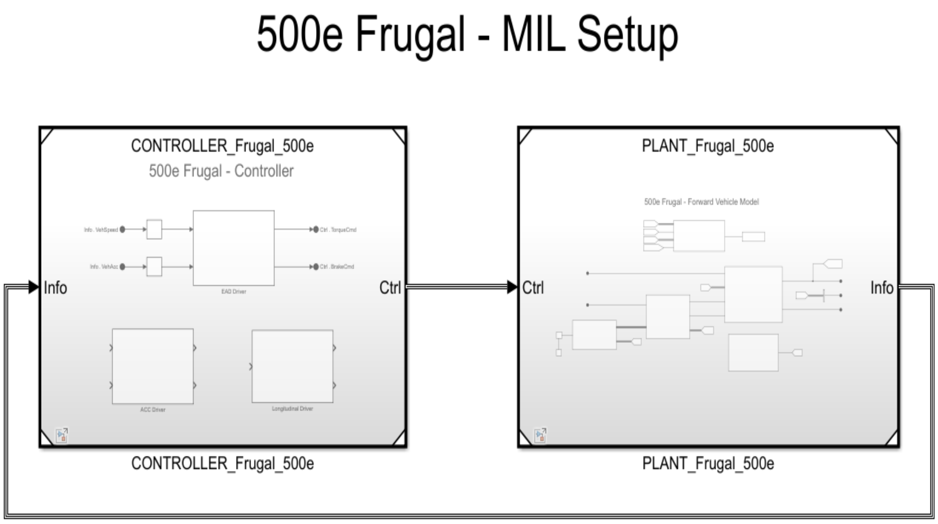

Figure 4.8: Model in the loop [14].

Parameters	Symbol	Value	Unit
Total vehicle mass	M_{veh}	1000	$[kg]$
Front axle - CoG distance	l_{f}	0.989	$[m]$
Rear axle - CoG distance	l_{r}	1.311	$[m]$
Static rolling coefficient	f_{r0}	5.3	$[N/kN]$
Wheel radius	R_0	0.3	$[m]$
Drag coefficient	C_{d}	0.33	$[-]$
Gear ratio	τ_{gb}	11	$[-]$
Gearbox efficiency	η_{gb}	0.97	$[-]$
Max motor power	P_{max}	20	$[kW]$
Motor peak torque	T_{max}	120	$[Nm]$
Max vehicle speed	v_{max}	90	$[km/h]$
Auxiliary Loads	P_{aux}	250	$[W]$

Table 4.1: BEV Specifications [14].

Longitudinal Dynamics Modeling

Figure 4.9 is a representation of how the vehicle components are modeled in Simscape. Figure 4.10 represent the longitudinal dynamics modeled as a two-axle vehicle body, accounting for all the forces experienced during driving, and their equilibrium determines the equation of motion (and consequently the vehicle speed). The mass is concentrated in the vehicle Center of Gravity (CoG) where all the contributions are applied, and the resulting equation of motion is modeled by Equation (4.5), and the traction force (F_{trac}) in the equation should be provided by the vehicle power-train to satisfy the driving cycle.

$$M_{\text{veh}}(dv/dt) = F_{\text{inertia}} = F_{\text{trac}} - F_{\text{aero}} - F_{\text{roll}} - F_{\text{grade}} \tag{4.5}$$

The aerodynamic drag is expressed by Equation (4.6):

$$F_{\text{aero}} = 0.5\rho_{\text{air}}A_{\text{f}}C_{\text{d}}v^2 \tag{4.6}$$

where (ρ_{air}) is the air density, (A_{f}) is the vehicle front surface, (C_{d}) is the aerodynamic drag coefficient and (v) is the vehicle speed.

On tarmac roads, the rolling resistance, depending on tire load, is mainly due to the flexing losses of the wheels. Thus, the rolling resistance force is defined as Equation (4.7):

$$F_{\mathrm{roll}} = f_{\mathrm{r}} F_{\mathrm{z}} \tag{4.7}$$

where (f_{r}) is the rolling resistance coefficient and (F_{z}) is the tire load. (f_{r}), in classical forward modeling approach, is assumed to be constant or a linear function of the vehicle speed.

On inclined road, the vehicle must overcome the force due to gravity, modeled as Equation (4.8):

$$F_{\mathrm{grade}} = M_{\mathrm{veh}} g sin(\alpha) \tag{4.8}$$

where (M_{veh}) is the vehicle mass and (α) is the road gradient.

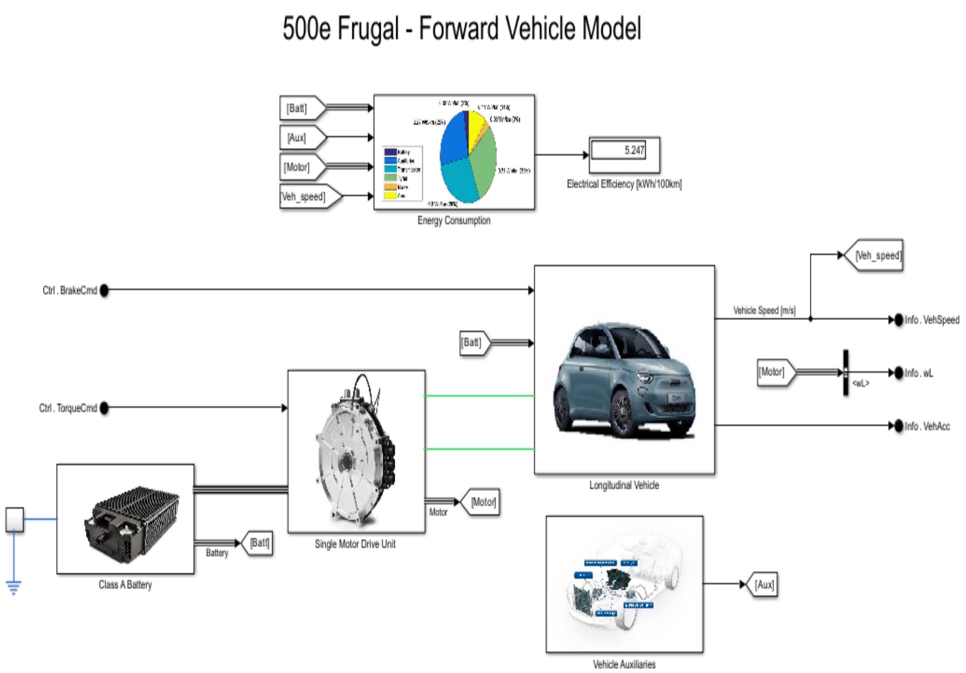

Figure 4.9: Vehicle Model in Simscape [14].

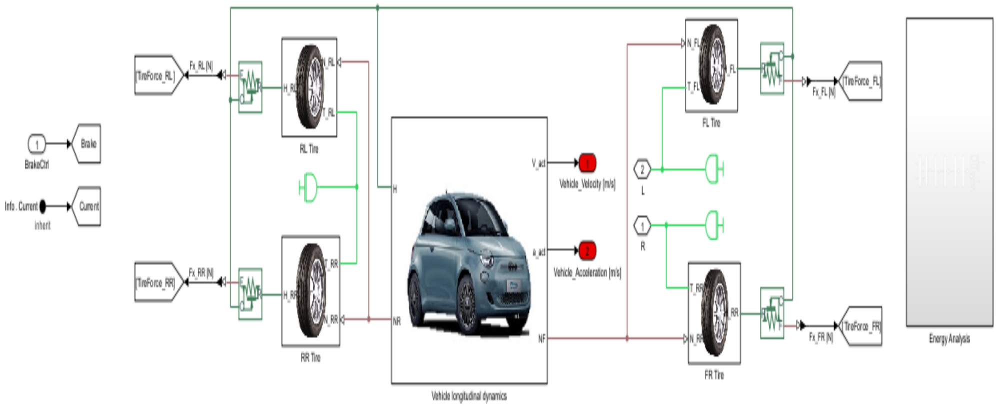

Figure 4.10: Vehicle Longitudinal Dynamics [14].

Battery Modeling

The battery (i.e. Class A Battery in Figure 4.9) is modeled as an electrical equivalent circuit with no dynamics. The circuit consists of an internal resistance (R_i) and an ideal voltage source (V_0). (I_{batt}) is the load current while (V_{batt}) is the terminal voltage. The electrical equivalent circuit is represented in Figure 4.11 and is governed by Equation (4.9).

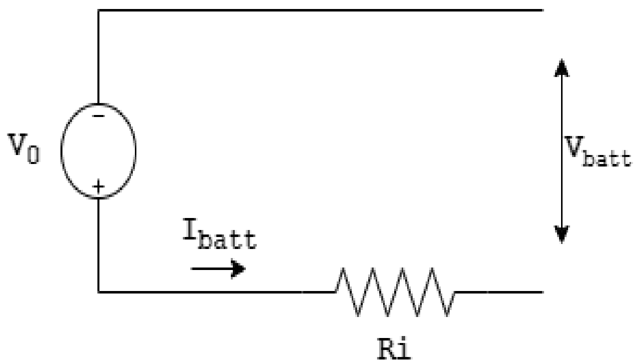

Figure 4.11: Battery electrical equivalent circuit.

$$V_{\text{batt}}(t) = V_0 - R_i I_{\text{batt}}(t) \tag{4.9}$$

Figure 4.12 represents how the battery electrical equivalent circuit is modeled in Simscape.

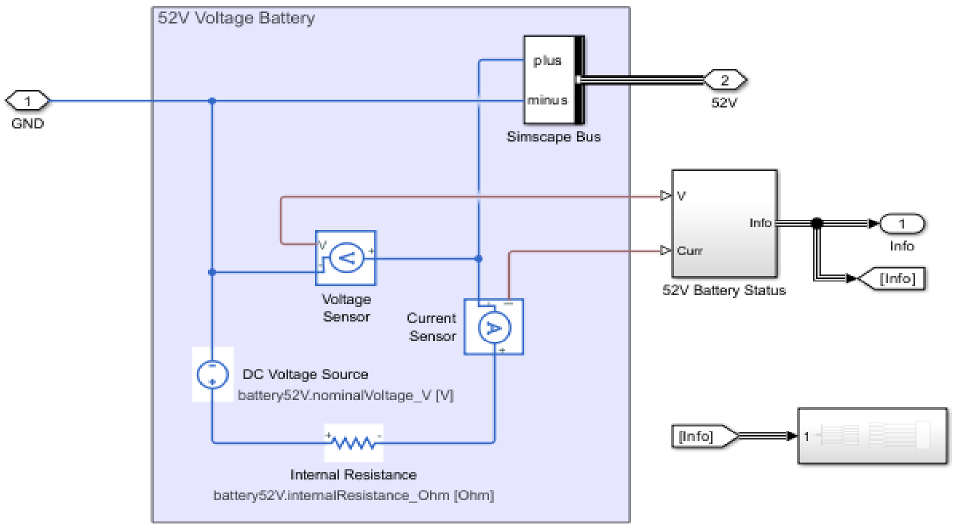

Figure 4.12: Battery Model [14].

Performance Indexes

The Battery State of Charge (SOC) is used as one of the performance indexes, and it is defined as the ratio of the available charge ($Q(t)$) and the maximum possible charge that can be stored in the battery, (i.e. the nominal charge (Q_n)) as represented by Equation (4.10) and modeled in Simscape as shown in Figure 4.13.

$$SOC(t) = (Q(t)/Q_n)100\% \tag{4.10}$$

The available charge is calculated using Equation (4.11).

$$Q(t) = \int_{t_0}^{t} I_{\text{batt}}(t)dt \tag{4.11}$$

Another performance index is the Battery Energy which is given by the Battery Power integrated over time as given by Equation (4.12).

$$E(t) = \int_{t_0}^{t} P(t)dt \tag{4.12}$$

The Battery Power is given by Equation (4.13) and modeled in Simscape as shown in Figure 4.13.

$$P(t) = V_{\text{batt}}(t)I_{\text{batt}}(t) + R_i I^2_{\text{batt}}(t) \tag{4.13}$$

The Electrical Efficiency (EE) is another performance index, and is calculated by Equation (4.14).

$$EE(t) = (E(t) + E_{\text{aux}}(t))/D \tag{4.14}$$

where $(E(t))$ is the Battery Energy calculated in (4.12), $(E_{\text{aux}}(t))$ is the Auxiliary Energy and (D) is the Distance Travelled.

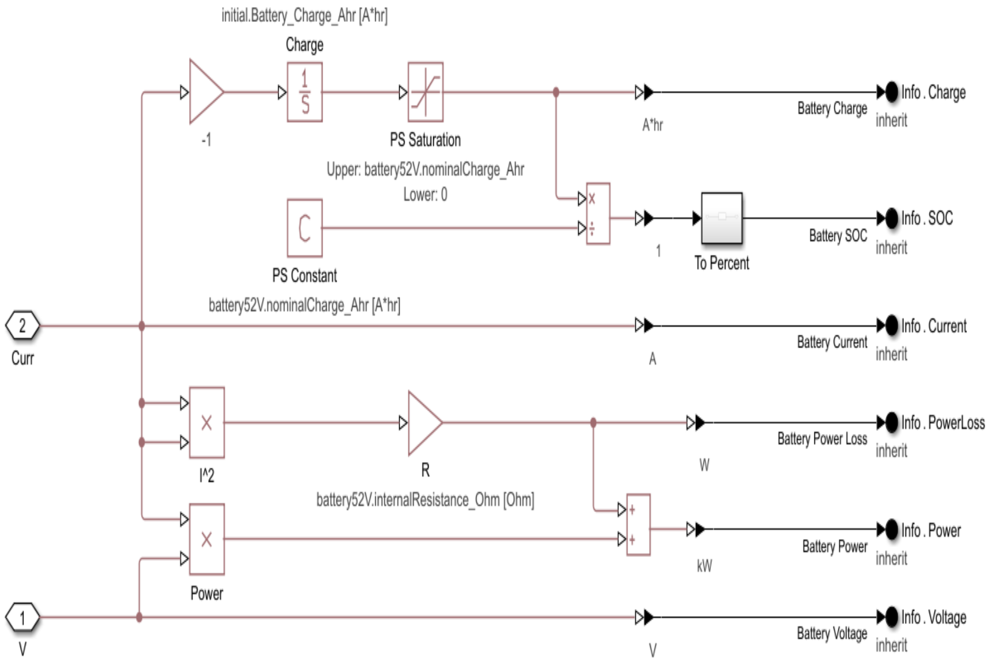

Figure 4.13: Battery Parameters [14].

The nominal data used for modeling the Battery is given in Table 4.2.

Parameters	Symbol	Value	Unit
Nominal cell voltage	V_{cell}	3.7	$[V]$
Nominal voltage source	V_0	51.8	$[V]$
Nominal internal resistance	R_i	0.0112	$[\Omega]$
Nominal battery charge	Q_n	315	$[Ahr]$

Table 4.2: Battery nominal data [14].

Forward Modeling Approach

The forward modeling approach is a comparison between the vehicle speed received as feedback from longitudinal dynamics and the reference speed set by the driving cycle, and this comparison is done by the driver model, and the generated command is a torque demand fed to the EDM. By doing so, it is possible to analyze the command from an energy consumption point of view, subsequently, fine tune the command to obtain the minimum energy consumption.

The controller shown in Figure 4.8 contains the EAD Driver represented in Figure 4.14 which contains the scenario, high-level controller and the low-level controller as shown in Figure 4.15. The high-level controller determines the desired vehicle acceleration, while the low-level controller provides the throttle/brake inputs to have the desired acceleration.

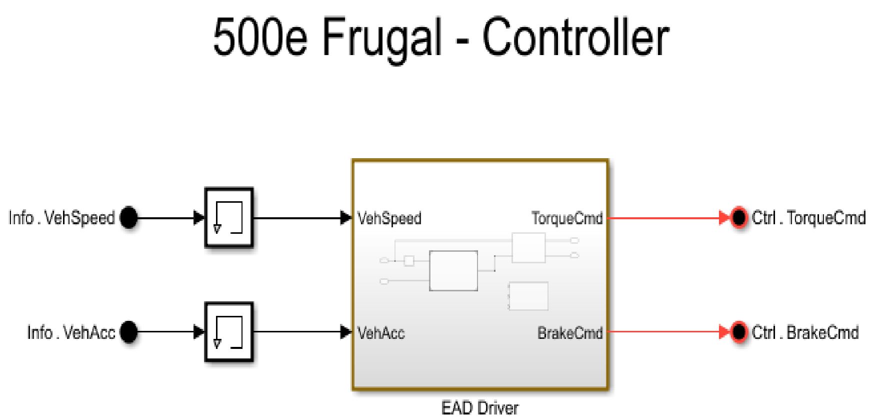

Figure 4.14: The Forward Modeling Approach [14].

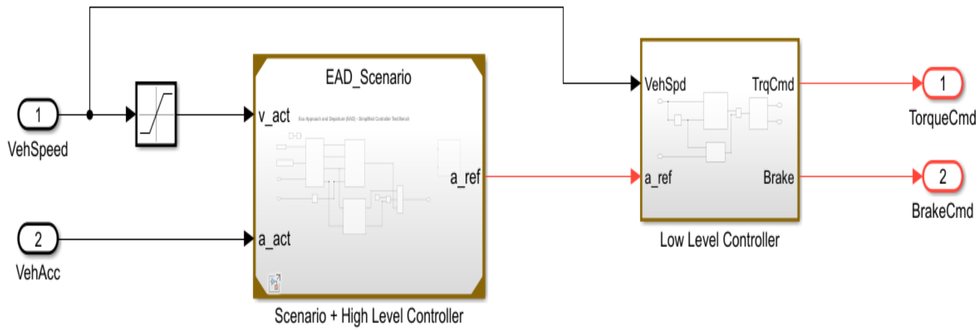

Figure 4.15: Scenario, high-level controller and the low-level controller [14].

Eco-Approach and Departure (EAD)

The strategy described in the application setup in section 4.2.3 is modeled as shown in Figure 4.16. A reference acceleration profile is generated using an Adaptive Cruise Control (ACC) strategy alone or combined with the Eco-Approach and Departure (EAD) strategy. Eco-Approach and Departure (EAD) strategy, according to the SPaT information, uses Equations (3.3), (3.4) and (3.5) to generate an acceleration velocity profile, or instead, uses Equations (3.7), (3.8) and (3.9) to generate a deceleration velocity profile.

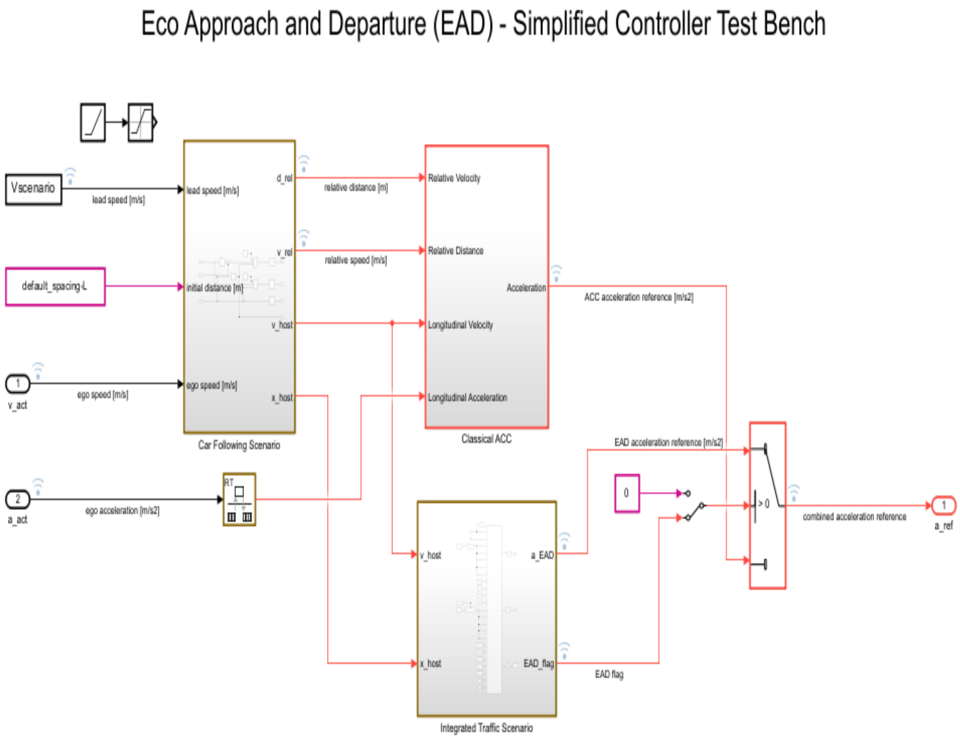

Figure 4.16: Eco-Approach and Departure (EAD) strategy [14].

Adaptive Cruise Control (ACC)

The Ego vehicle is equipped with a Constant Time Gap (CTG) Adaptive Cruise Control (ACC), which implies that the relative distance (D_{rel}) and relative velocity (V_{rel}) to the Lead vehicle are measured through a sensor, (e.g. radar). The ACC system operates in the following two modes:

- Speed control: The Ego vehicle travels at a driver-set velocity (V_{set}).
- Spacing control: The Ego vehicle maintains a safe distance (D_{safe}) from the lead car.

Based on real-time radar measurements, the ACC system decides which mode to use. For instance, if the Ego vehicle is too close to the Lead vehicle, the ACC works on spacing control mode. If the Ego vehicle is far to the Lead vehicle, the ACC system works on speed control mode instead. In other words, the ACC system makes the Ego vehicle travel at a driver-set speed as long as it maintains a safe distance from the Lead vehicle.

Thus, the following rules are used to determine the ACC system operating mode:

- If $(D_{\text{rel}}) \geq (D_{\text{safe}})$, then the speed control mode is active, (i.e. the control goal is to track the driver-set velocity (V_{set})).
- If $(D_{\text{rel}}) < (D_{\text{safe}})$, then the spacing control mode is active, (i.e. the control goal is to maintain the safe distance (D_{safe}).

The ACC system operating modes are graphically demonstrated by Figure 4.17

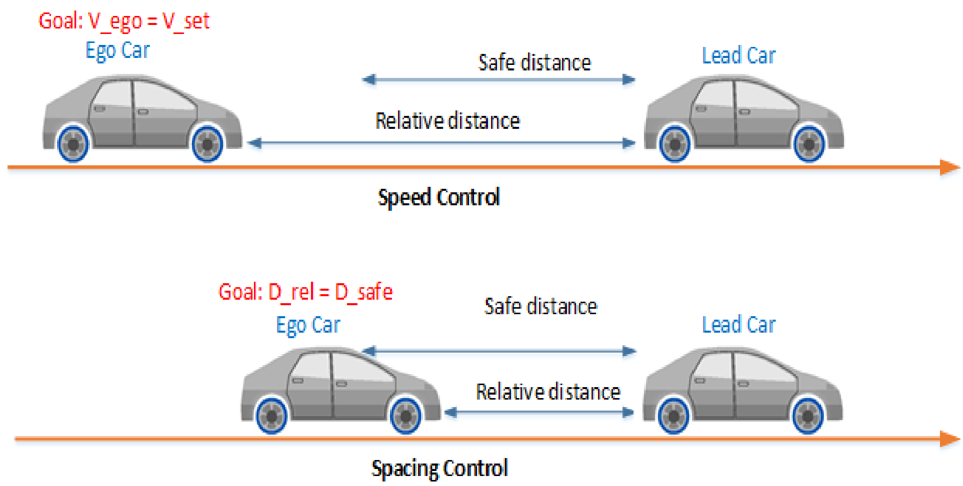

Figure 4.17: Adaptive Cruise Control (ACC) operating modes.

The safe distance (D_{safe}) between the Lead vehicle and the Ego vehicle is given by Equation (4.15).

$$D_{\text{safe}} = D_{\text{default}} + T_{\text{gap}} V_{\text{ego}} \tag{4.15}$$

where (D_{default}) is the standstill default spacing, (T_{gap}) is the time gap between the Ego vehicle and the Lead vehicle and (V_{ego}) is the Ego vehicle velocity.

The output for the ACC system is the Ego vehicle acceleration, and for the spacing control mode, it is given by Equation (4.16).

$$a_{\text{ego}} = V_{\text{rel}} G_{\text{relv}} - (D_{\text{safe}} - D_{\text{rel}}) G_{\text{x}} \tag{4.16}$$

where (G_{relv}) is the ACC relative velocity gain and (G_{x}) is the ACC spacing error gain.

And for the speed control mode, it is given by Equation (4.17).

$$a_{\text{ego}} = min(V_{\text{rel}} G_{\text{relv}} - (D_{\text{safe}} - D_{\text{rel}}) G_{\text{x}}, (V_{\text{set}} - V_{\text{ego}}) G_{\text{v}}) \tag{4.17}$$

where (G_{v}) is the ACC velocity error gain. Considering the physical limitations of the vehicle dynamics, the acceleration is constrained to the range [-3,2] m/s^2.

Table 4.3 shows the parameters used for designing the ACC control.

Parameters	**Symbol**	**Value**	**Unit**
The standstill default spacing	D_{default}	5	$[m]$
Time gap	T_{gap}	3	$[sec]$
Driver-set velocity	V_{set}	20	$[m/s]$
Relative velocity gain	G_{relv}	0.5	$[N/A]$
Spacing error gain	G_{x}	0.3	$[N/A]$
Velocity error gain	G_{v}	0.1	$[N/A]$

Table 4.3: ACC parameters [14].

The Adaptive Cruise Control (ACC) algorithm is modeled in Simulink as shown in Figure 4.18.

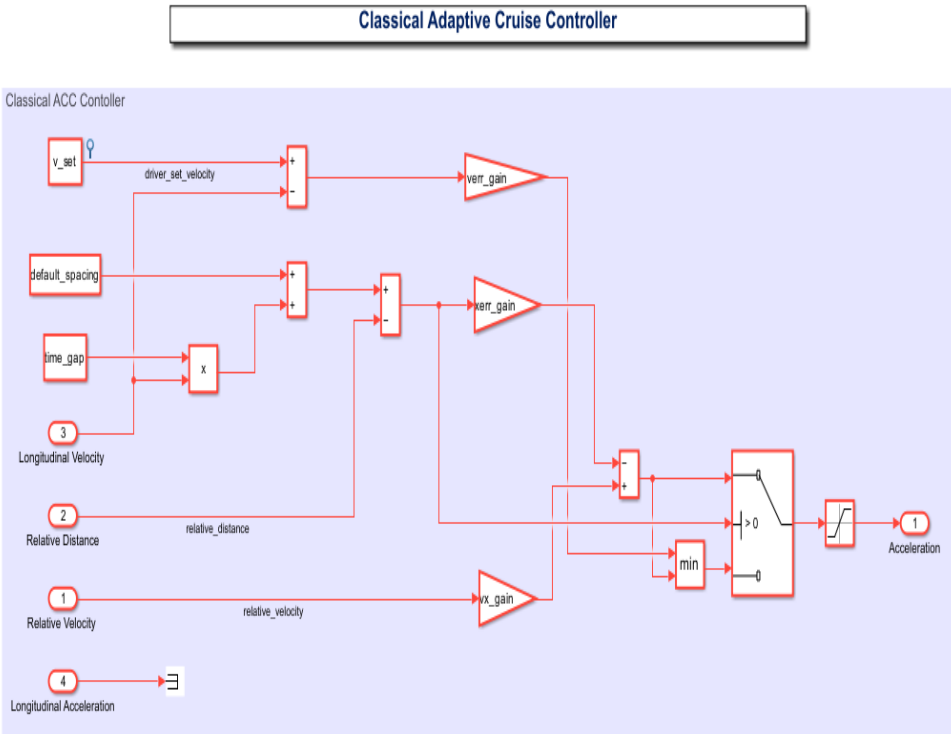

Figure 4.18: The Adaptive Cruise Control (ACC) algorithm [14].

4.2.5 Simulation Results

The velocity profiles, covering the first 10 intersections of the test corridor, comparing the original driving cycle, the ACC and the EAD is represented in Figure 4.19 against time, and in Figure 4.20 against the traveled distance. In the original driving cycle and thus using only the ACC strategy, the Ego vehicle managed to precisely follow the Lead vehicle, but it stopped in 5 intersections; number 2, 6, 8, 9, and 10 as it reached these intersections during a Red Signal Phase, while, using the ACC combined with the EAD strategy (i.e. the EAD vehicle in the fingers), all 10 intersections were passed during a Green Signal Phase, as the vehicle was informed about the SPaT information in advance, thus, it managed to adjust its speed for a timely arrival at Green Signal Phase. It is worth mentioning that the simulation was of a duration of 7 minutes and 15 seconds, covering around 3 km.

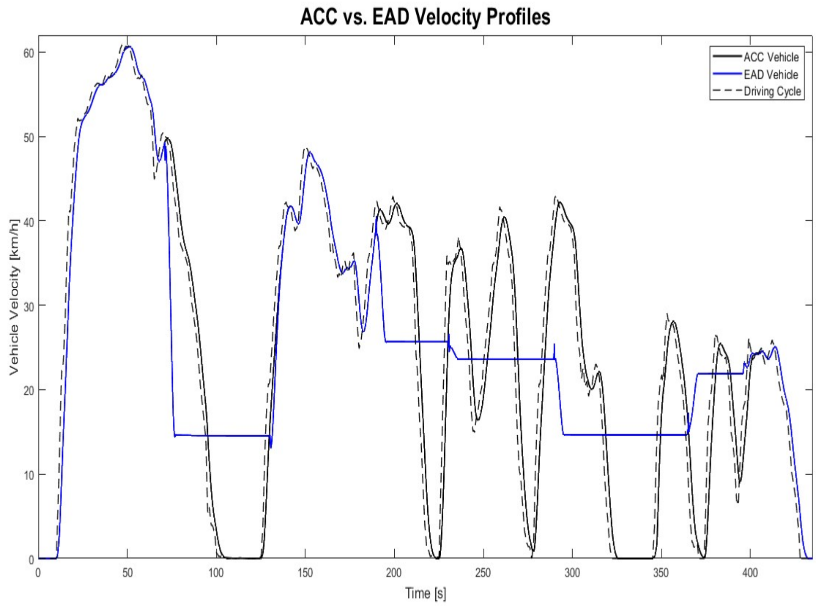

Figure 4.19: Velocity profiles against time.

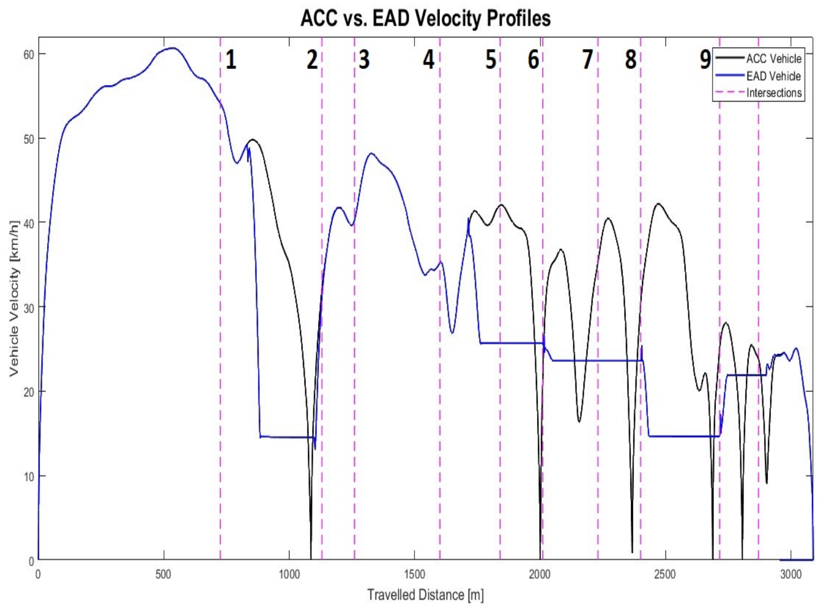

Figure 4.20: Velocity profiles against traveled distance.

Figure 4.21 better represents the differences in position between the ACC vehicle and the EAD one (by EAD, it is meant the ACC combined with the EAD strategy), and better shows the intersections and their phases. In intersections number 2, 6, 8, and 9, the algorithm, provided with the SPaT information, decided to decelerate, while for the intersection number 10, decided to accelerate instead.

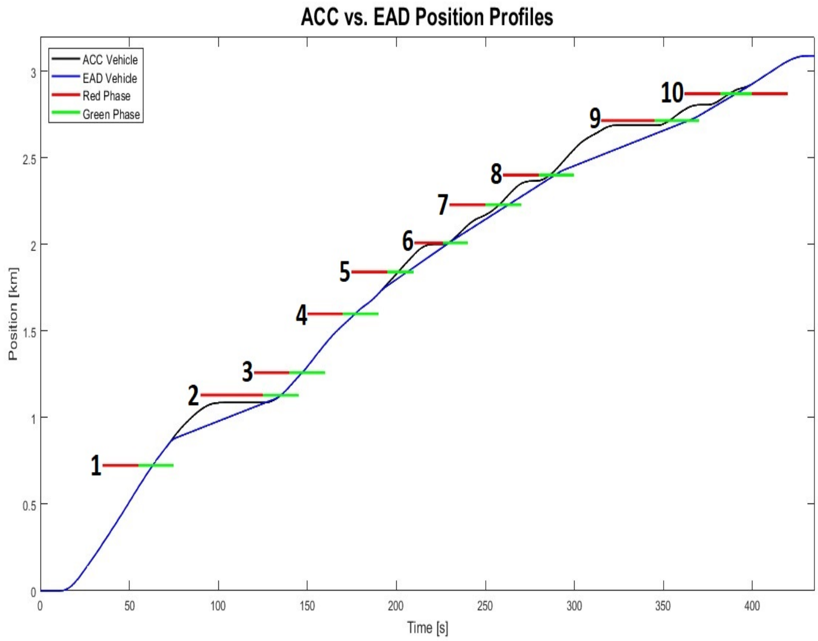

Figure 4.21: Position profiles.

Figure 4.22 shows a comparison between ACC and EAD acceleration profile. The EAD acceleration profile is smoother, containing less fluctuation than ACC one, as the EAD strategy is based on the fact that, from an energy consumption point of view, it is better to accelerate/decelerate sharply, then hold a constant speed until the vehicle passes the intersection.

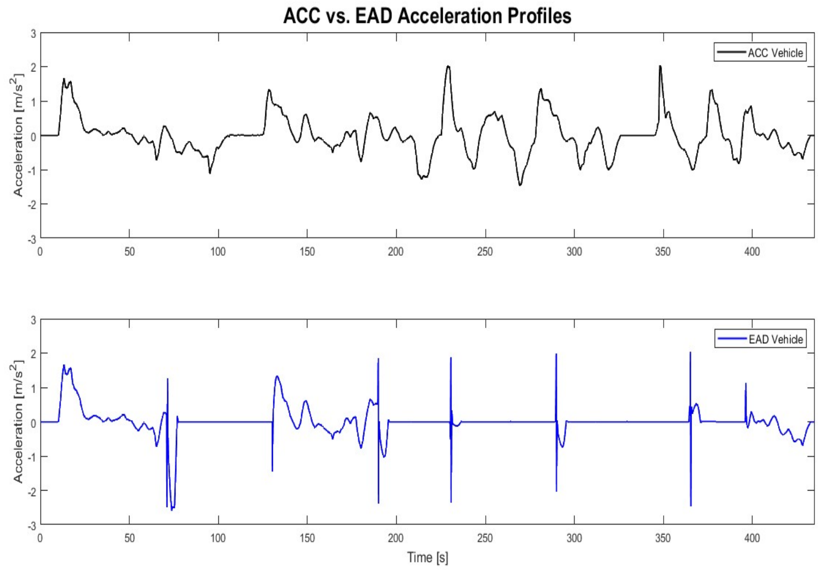

Figure 4.22: ACC vs EAD acceleration profiles.

The need for smooth velocity and acceleration profiles is achieved with smother motor torque, as represented in Figure 4.23.

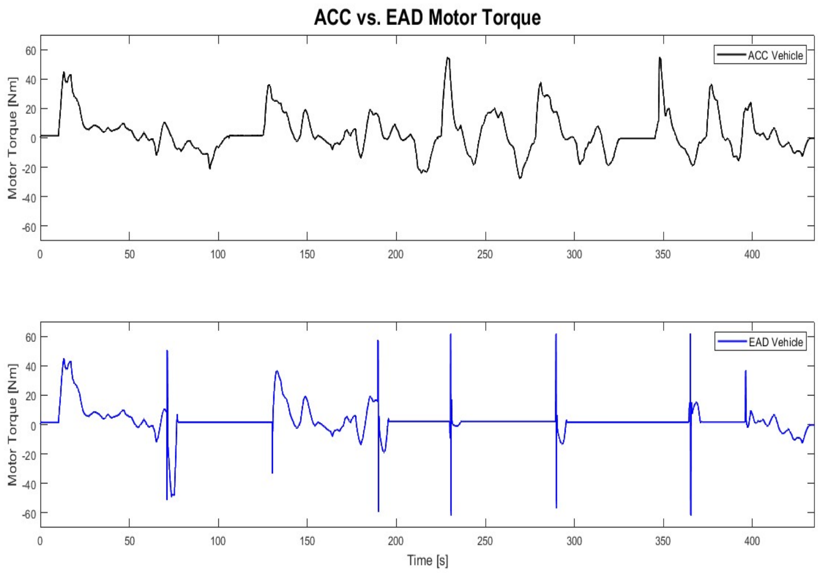

Figure 4.23: ACC vs EAD Motor Torque.

In Figure 4.22 and Figure 4.23, sharp peaks are noticed in the acceleration and motor torque profiles, which happen to be when the controller switches from one strategy to another; (e.g. from ACC to EAD or the vice versa). A possible solution to this problem is to better tune the controllers and have a middle ground controller to smooth the switching between strategies.

Figure 4.24 shows a comparison between the ACC and the EAD in terms of the relative distance and the relative speed, and intuitively, the EAD relative distance and relative speed are higher, due to the fact that the velocity profile and thus the the position profile are adjusted according to the SPaT information, and the Ego vehicle does not strictly follow the Lead vehicle.

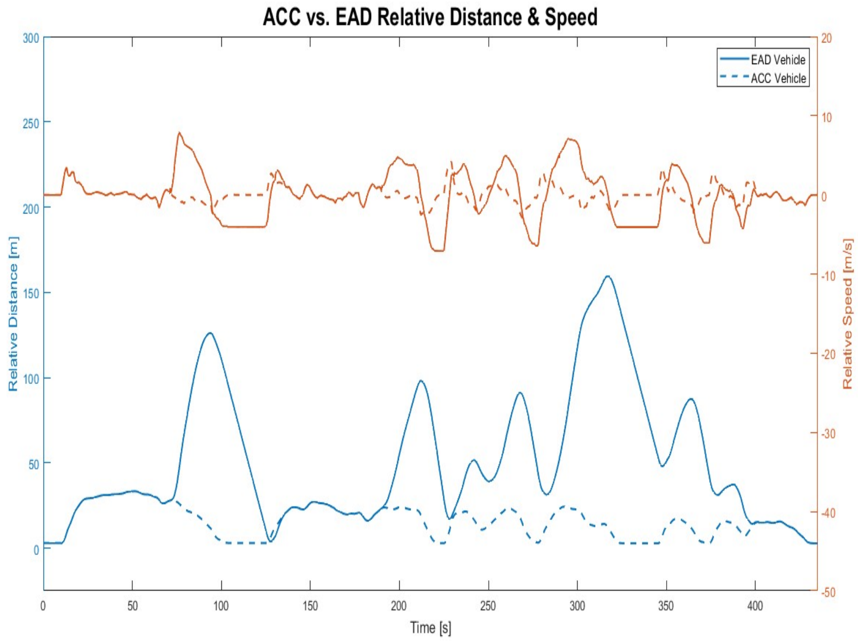

Figure 4.24: ACC vs EAD Relative distance and Relative speed.

Using Equations (4.10), (4.12) and (4.14), and aiming to test the algorithm from an energy point of view, a simulation was run using a Lead Vehicle with the recorded urban driving cycle. The Lead Vehicle consumed 0.181 $[KWh]$ Battery Energy with 6.697 $[kWh/100km]$ Electrical Efficiency. The Battery State of Charge (SOC) at the end of the simulation was 88.92 [%] and the vehicle crossed the 10$^{\text{th}}$ intersection in 385 $[sec]$. Using the first strategy described in 4.2.3; (i.e. following the Lead Vehicle with the Ego Vehicle using the ACC only), the Ego Vehicle consumed 0.165 $[KWh]$ Battery Energy with 6.173 $[kWh/100km]$ Electrical Efficiency. The Battery State of Charge (SOC) at the end of the simulation was 89.02 [%] and the vehicle crossed the 10^{th} intersection in 387 [sec]. Using the second strategy instead described in 4.2.3; (i.e. following the Lead Vehicle with the Ego Vehicle using the ACC combined with the EAD), the Ego Vehicle consumed 0.136 [KWh] Battery Energy with 5.248 [$kWh/100km$] Electrical Efficiency. The Battery State of Charge (SOC) at the end of the simulation was 89.19 [%] and the vehicle crossed the 10^{th} intersection in 390 [sec].

Using the ACC combined with the EAD strategy instead of using the ACC strategy only, there was a notable decrease in the used Battery Energy (i.e. saving 0.029 [KWh]), and a notable increase in the Electrical Efficiency (i.e. saving 0.925 [$kWh/100km$]). As a result, the Battery State of Charge (SOC) at the end of the simulation was higher (i.e. an increase of 0.17 [%]). These results are graphically represented in Figure 4.25 and Figure 4.26 and numerically in Table 4.4.

A noticeable result is that, the EAD vehicle crossed the 10^{th} intersection 3 seconds after the ACC vehicle, as the EAD vehicle followed the ACC vehicle in one strategy, and used the SPaT information and adjusted the velocity profile accordingly in the other. Although this may result in an increased travel time, yet, it is balanced by the reduction of the idling time as the EAD vehicle, least likely, stops at the intersections.

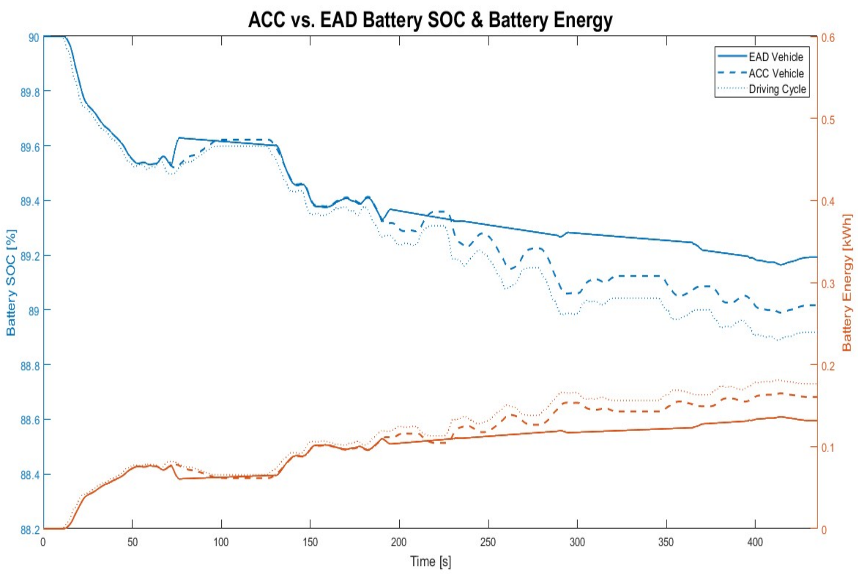

Figure 4.25: Battery SOC and Battery Energy.

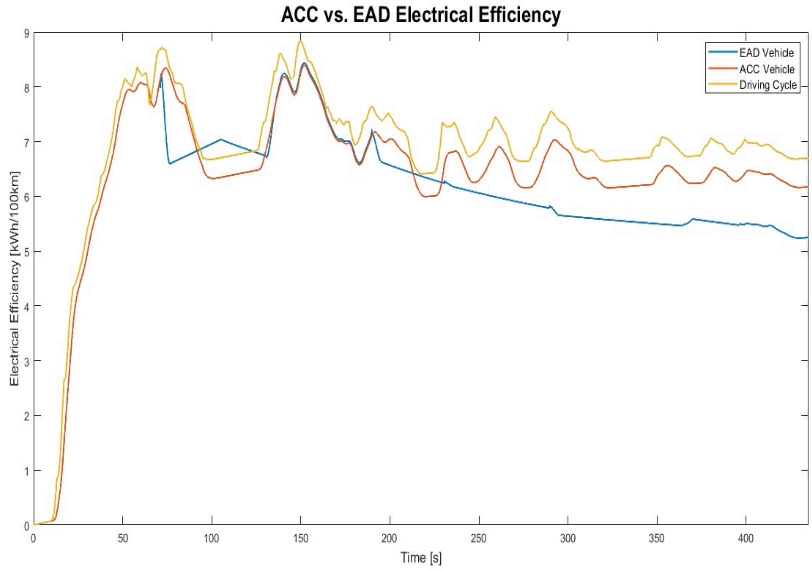

Figure 4.26: Electrical Efficiency.

	Electrical Efficiency $[kWh/100km]$	**Battery Energy** $[kWh]$	**Battery SOC** [%]	**Time @ the** 10^{th} **stop** [sec]
Driver	6.697	0.181	88.92	385
ACC	6.173	0.165	89.02	387
EAD	5.248	0.136	89.19	390
Δ	$+0.925$	$+0.029$	$+0.17$	-3

Table 4.4: Numerical Results.

Chapter 5

CONCLUSION

Fuel consumption and emissions are directly related to the acceleration, deceleration and idling patterns at traffic signals as the vehicles travel on urban roads, on which, unlike highways, traffic suffers from inherent acceleration and deceleration maneuvers and idling at the traffic signals while waiting for the lights to change from Red to Green. Taking advantage of the recent developments in communication between vehicles and road infrastructure (V2I), it has become possible to obtain the Signal Phase and Timing (SPaT) information from the traffic signals using Dedicated Short Range Communication (DSRC).

In this thesis, and using this real-time Signal Phase and Timing (SPaT) information, a dynamic eco-driving velocity planning algorithm is developed, and one of the key findings of this thesis is that, counter-intuitively compared to typical eco-driving advice, it has been found that hard accelerations that quickly get a vehicle up to a target speed and then have a steady state cruise speed to reach a specific location at a specific time are less fuel consuming compared to a velocity profile that takes a longer period of time of acceleration to reach the same point and time. Similarly, it is advisable to decelerate quickly, then hold a steady state cruise speed to reach a traffic signal just as it turns green, as this reduces idling and takes less energy to accelerate back up to the typical speed traversing the corridor, compared to starting from a stop.

This velocity planning algorithm is tested in real-world urban traffic, by using a recorded velocity profile, recorded in Torino, Italy, which is representative of an urban driving cycle, as the velocity profile of a Lead vehicle, and the Ego vehicle follows the Lead vehicle using an Adaptive Cruise Control (ACC) strategy when there is no Signal Phase and Timing (SPaT) coverage, and using the Eco-Approach and Departure (EAD) strategy when there is SPaT coverage.

The proposed algorithm was validated by a numerical experiment of a simulation of a duration of 7 minutes and 15 seconds, covering around 3 km urban road containing 10 intersections operated by the Dedicated Short Range Communication (DSRC). The simulation results showed that the EAD vehicle, passing all the intersections in a Green Signal Phase, consumed 0.029 $[KWh]$ less Battery Energy with 0.925 $[kWh/100km]$ better Electrical Efficiency, reducing 100% of the idling time and saving 0.17 [%] Battery SOC. These numerical results indicate that the energy saving potential would be really significant if the EAD algorithm is tested in a longer trip, and more is the penetration of such a feature, more is the energy saving and less is the emission, as the vehicles equipped with the EAD algorithm will affect the vehicles upstream, making them follow an optimized velocity profile that is more couple of letting them pass the intersections in a green signal phase.

Connected and automated vehicles have a huge potential in terms of energy consumption reductions, thanks to their enhanced control capabilities. However, to better exploit this potential, simple rule-based control strategies are often not sufficient and a more systematic approach, based on mathematical optimization, is needed. Also, the proposed EAD system is more efficient for light traffic conditions, as preceding vehicles may interrupt the predefined strategies. These points should be considered for future research.

Bibliography

[1] California Air Resources Board. *The California Almanac of Emissions and Air Quality—2013 Edition*. Online, June 2016. URL: `http://www.arb.ca.gov/aqd/almanac/almanac.htm` (cit. on p. 2).

[2] U. S. Environmental Protection Agency. *Transportation Sector Emissions*. Online, June 2016. URL: `https://www3.epa.gov/climatechange/ghgemissions/sources/transportation.html` (cit. on p. 2).

[3] U. S. Energy Information Agency. *Monthly Energy Review*. Online, June 2016. URL: `http://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf` (cit. on p. 2).

[4] US Department of Transportation National Highway Traffic Safety Administration Technical Report NHTSA-2016-0126. *NHTSA (2016) Federal motor vehicle safety standards; V2V communications* (cit. on p. 2).

[5] Victoria transport policy institute. *Litman T (2017) Autonomous vehicle implementation predictions* (cit. on p. 2).

[6] Sciarretta Antonio and Vahidi Ardalan. *Energy-Efficient Driving of Road Vehicles*. URL: `https://doi.org/10.1007/978-3-030-24127-8` (cit. on p. 5).

[7] M. Barth, S. Mandava, K. Boriboonsomsin, and H. Xia. «Dynamic Eco-Driving for Arterial Corridors». In: *The* 1^{st} *IEEE Forum on Integrated and Sustainable Transportation Systems (FISTS)* (July 2011), pp. 182–188 (cit. on pp. 8, 9, 11, 17, 18, 20, 21, 23, 26).

[8] P. Hao, G. Wu, K. Boriboonsomsin, and M. J. Barth. «Developing a framework of Eco-Approach and Departure application for actuated signal control». In: *IEEE Intelligent Vehicles Symposium* (June 2015), pp. 796–801 (cit. on pp. 8–11).

[9] P. Hao, G. Wu, K. Boriboonsomsin, and M. J. Barth. «Eco-Approach and Departure (EAD) Application for Actuated Signals in Real-World Traffic». In: *IEEE Transactions on Intelligent Transportation Systems* (Jan. 2019) (cit. on pp. 8, 11–14).

[10] SAE International. *Dedicated Short Range Communications (DSRC) Message*. Online, June 2016. URL: `http://standards.sae.org/j2735_200911/` (cit. on p. 13).

[11] X. Xiang, K. Zhou, W. Zhang, W. Qin, and Q. Mao. «A closed loop speed advisory model with driver's behavior adaptability for Eco-driving». In: *IEEE Trans. Intell. Transp. Syst.* (Dec. 2015), pp. 3313–3324 (cit. on p. 14).

[12] M. Barth and K. Boriboonsomsin. «AReal-world carbon dioxide impacts of traffic congestion». In: *Transportation Research Record* (2008), pp. 163–171 (cit. on p. 17).

[13] K. S. Yi and J. T. Chung. «Nonlinear brake control for vehicle CW/CA systems». In: *IEEE/ASME Transactions on Mechatronics* (Mar. 2001), pp. 17–25 (cit. on pp. 26, 35).

[14] Manca Raffaele, Tramacere Eugenio, Favelli Stefano, Tonoli Andrea, and Camosi Luca. «Impact of rolling resistance modeling on energy consumption for a low voltage battery electric vehicle». In: *IEEE Xplore 2023 International Symposium on Electromobility (ISEM)* (2023) (cit. on pp. 37–45, 47, 48).