Evaluation of the effect of “Energy Efficient Intersection” system on CO₂ emissions of road transport

Sokratis Mamarikas
SID: 3302130010

SCHOOL OF SCIENCE & TECHNOLOGY
A thesis submitted for the degree of
Master of Science (MSc) in Energy Systems

DECEMBER 2014
THESSALONIKI – GREECE
Evaluation of the effect of “Energy Efficient Intersection” system on CO$_2$ emissions of road transport

Sokratis Mamarikas
SID: 3302130010

Supervisor: G. Martinopoulos
Supervising Committee Members: E. Mitsakis

SCHOOL OF SCIENCE & TECHNOLOGY
A thesis submitted for the degree of
_Master of Science (MSc) in Energy Systems_

DECEMBER 2014
THESSALONIKI – GREECE
Abstract

Intelligent Transport Systems (ITS) play an important role in the effort for the reduction of energy consumption, CO$_2$ emissions and other various pollutants of the transport sector and can provide significant contributions to the achievement of the goals set by the EC White Paper of transport, for a 60% decrease of CO$_2$ transportation emissions for the period 1990-2050. The evolution in the area ITS is related to the development of systems, referred to as Cooperative ITS (C-ITS), that link the vehicle with the road infrastructure and are able to reduce vehicular energy consumption and CO$_2$ emissions. The need for the development and implementation of these systems has been recognized as one of the main priority areas in the strategies for a cleaner and more efficient transport system. The present master thesis analyzes and assesses the impacts of Cooperative Intelligent Transport Systems (C-ITS) on energy consumption and CO$_2$ emissions of road transport. The first step of this evaluation is related with the identification of the suitability of existing models to be used for the environmental evaluation of ITS and C-ITS. Emission models are classified and analyzed and their capability, in terms of the evaluation of different applications, is identified. As a next step the “Energy efficient intersection”, which is a C-ITS developed by CERTH/HIT, is examined as a case study. The system aims at the reduction of energy consumption and emissions of a vehicle when approaching a signalized intersection, through the provision of speed advices to the drivers, in order to reduce stop and go traffic. The logic of this system is evaluated and proposals regarding potential extensions are expressed. Through the use of traffic data derived by a traffic micro simulator, the effect of the system on individual vehicles’ and traffic CO$_2$ emissions is evaluated and analyzed. Moreover a parametric analysis is performed adjusting the traffic demand, the traffic lights settings and the speed advice provision distances. At the end, conclusions and proposal are outlined.
Acknowledgements

After the implementation of this thesis I would like to thank Dr. G. Martinopoulos (Academic Associate at International Hellenic University) for his supervision and for his useful advices during the implementation process of this Thesis.

I would like to thank Dr. E. Mitsakis (Researcher at Hellenic Institute of Transport) for the formulation and the commitment of the Thesis topic and for his useful advices.

I would also like to thank the researchers of Hellenic Institute of Transport, J. M. Salanova and E. Mintsis for their valuable contribution.

This Thesis was performed at the Hellenic Institute of Transport (HIT) of the Centre for Research and Technology Hellas (CERTH)

Sokratis Mamarikas
19/12/2014
Objective and Methodology

The general objective of this master thesis is to analyze and assess the effect of the Energy Efficient Intersection, which is a Cooperative Intelligent Transport Systems (C-ITS) application, on energy consumption and CO₂ emissions of road transport. The Energy Efficient Intersection (EEI) system is a service developed and simulated by CERTH/HIT. The general objective of the thesis is achieved through a number of steps. The first step is the identification of the suitability of existing emission models in order to be used for the environmental impact assessment of ITS and C-ITS. The second step is the examination of the logic of the system that is evaluated and the third is the evaluation of case study, which is used as an example of the integrated ITS evaluation modeling process. These steps are summarized on the followings:

- The identification of the suitability of emission models to be used for ITS and C-ITS evaluation, through a literature review
- Presentation of Energy efficient intersection C-ITS system through a literature review and through the implementation of specific examples using the instantaneous speed-based emission model Enviver
- Description of the adopted integrated simulation process (methodological framework)
- Presentation, analysis and evaluation of Case study results
Contents

ABSTRACT .......................................................................................................................... III

CONTENTS ........................................................................................................................ VII

1 INTRODUCTION ............................................................................................................. 1

1.1 ROAD TRANSPORT AND GREENHOUSE GAS EMISSIONS ................................. 1

1.2 ROAD TRANSPORT-ENERGY CONSUMPTION AND EMISSIONS ....................... 4

1.3 TRAFFIC VARIABLES INFLUENCING ENERGY CONSUMPTION AND
EMISSIONS OF ROAD TRANSPORT ........................................................................... 6

2 INTELLIGENT TRANSPORT SYSTEMS OVERVIEW .............................................. 9

2.1 DESCRIPTION OF ITS - COOPERATIVE ITS. APPROACH OF THEIR
ENVIRONMENTAL IMPACT. ............................................................................................. 9

2.2 ITS AND IDENTIFICATION OF THEIR IMPACT ON ENERGY CONSUMPTION AND
EMISSIONS ....................................................................................................................... 11

2.3 EMISSION MODELS .................................................................................................. 13

2.3.1 Emission Factors – Development ...................................................................... 14

2.3.2 Driving cycles ........................................................................................................ 16

2.3.3 Emission models classification & description ....................................................... 20

2.4 ITS EVALUATION CONCERNING THEIR EFFECT ON ENERGY CONSUMPTION AND
EMISSIONS ....................................................................................................................... 37

2.4.1 ITS modeling process ............................................................................................. 37

3 CASE STUDY .................................................................................................................. 39

3.1 TRAFFIC SIGNALS AND THEIR EFFECT ON ENERGY CONSUMPTION AND
EMISSIONS OF ROAD TRANSPORT ........................................................................... 39

3.2 ENERGY EFFICIENT INTERSECTION. OVERVIEW ............................................ 42

3.2.1 Literature review of Energy Efficient intersection ................................................. 43

3.2.2 Case study – Contribution ..................................................................................... 50

3.3 TRAFFIC MODELING OF ENERGY EFFICIENT INTERSECTION ............................. 54

3.4 EMISSION MODELING ............................................................................................... 56
3.5 INTEGRATED MODELLING PROCESS ................................................................. 58
3.6 CASE STUDY EVALUATION - EFFECT ON CO2 EMISSIONS ...................... 63
3.7 TRAFFIC ANALYSIS ..................................................................................... 68
3.8 RESULTS ....................................................................................................... 70
3.9 ANALYSIS ...................................................................................................... 74

4 CONCLUSIONS .................................................................................................. 84

BIBLIOGRAPHY .................................................................................................... 91
LIST OF FIGURES

FIGURE 1: ALLOCATION OF GHG EMISSIONS PER SOURCE-SECTOR IN EU IN 2012 2
FIGURE 2: GHGS FROM TRANSPORT AND ROAD TRANSPORT IN EU 3
FIGURE 3: RELATION OF CO₂ EMISSIONS AND AVERAGE SPEED 7
FIGURE 4: CO₂ AS A RELATIONSHIP OF INSTANTANEOUS SPEED AND ACCELERATION 8
FIGURE 5: THE EUROPEAN LEGISLATIVE DRIVING CYCLE NEDC 16
FIGURE 6: THE FTP-75 DRIVING CYCLE 17
FIGURE 7: THE ARTEMIS DRIVING CYCLE 18
FIGURE 8: RELATION BETWEEN AVERAGE SPEED AND CO₂ EMISSIONS 22
FIGURE 9: TRAFFIC CONDITIONS USED IN THE ARTEMIS EMISSION MODEL 26
FIGURE 10: RELATION OF NOₓ EMISSIONS WITH DIFFERENT MODES 29
FIGURE 11: NOₓ EMISSIONS AS A FUNCTION OF SPEED AND SPEED X ACCELERATION 30
FIGURE 12: THE ARCHITECTURE OF CMEM MODEL 33
FIGURE 13: SUITABILITY OF EMISSION MODELS TO BE USED FOR ITS EVALUATION 35
FIGURE 14: DELAY EVENTS AT A TIME-DISTANCE GRAPH [61] 40
FIGURE 15: ACCELERATION PROFILE 46
FIGURE 16: DECELERATION PROFILE 47
FIGURE 17: POSSIBLE UPSTREAM SPEED PROFILES 51
FIGURE 18: CO₂ EMISSIONS IN GRAMS REGARDING THE FOUR CASES 52
FIGURE 19: POSSIBLE DOWNSTREAM SPEED PROFILES 53
FIGURE 20: UPSTREAM CO₂ EMISSIONS AND TOTAL CO₂ EMISSIONS 54
FIGURE 21: THE LOGIC OF EEI AS IT HAS BEEN ADOPTED BY CERTH/HIT 56
FIGURE 22: THE VERSIT+ STRUCTURE 57
FIGURE 23: THE INTEGRATED TRAFFIC AND EMISSION MODELING PROCESS OF EEI 60
FIGURE 24: ENVIVER’S EFS OVER DIFFERENT DRIVING CYCLES 62
FIGURE 25: TYPICAL SPEED PROFILES AT TSIMISKI STR. 64
FIGURE 26: ADJUSTED SPEED PROFILE DUE TO THE EEI IMPLEMENTATION 64
FIGURE 27: COMPARISON OF SPEED PROFILES 65
FIGURE 28: TWO UPSTREAM CASES IN A SPACE-TIME GRAPH 66
FIGURE 29: CO₂ EMISSIONS FOR BOTH CASES 67
FIGURE 30: CO₂ DIFFERENCE WITH THE IMPLEMENTATION OF THE SYSTEM 71
FIGURE 31: CO₂ DIFFERENCE FOR DIFFERENT GREEN SPLITS 72
FIGURE 32: CO₂ DIFFERENCE FOR DIFFERENT SPEED LIMITS 73
FIGURE 33: CO₂ DIFFERENCE FOR DIFFERENT DEMAND LEVELS 74
FIGURE 34: TRAJECTORIES IN A TIME-SPACE GRAPH FOR THE BASE CASE SCENARIO 75
FIGURE 35: TRAJECTORIES IN A TIME-SPACE GRAPH FOR 75
FIGURE 36: SIMULATED VEHICLES BEFORE AND AFTER THE IMPLEMENTATION 76
FIGURE 37: SIMULATED VEHICLES 77
# LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE 1: SECTORS WITH THE HIGHEST INCREASE AND REDUCTION OF GHGS</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>TABLE 2: POTENTIAL IMPACT OF SEVERAL ITS ON CO2 EMISSIONS</td>
<td>10</td>
</tr>
<tr>
<td>TABLE 3: VARIOUS KINEMATIC PARAMETERS</td>
<td>18</td>
</tr>
<tr>
<td>TABLE 4: KINEMATIC PARAMETERS OF THREE URBAN DRIVING CYCLES</td>
<td>19</td>
</tr>
<tr>
<td>TABLE 5: SUMMARY OF LITERATURE REVIEW REGARDING EEI</td>
<td>49</td>
</tr>
<tr>
<td>TABLE 6: EFFECT OF THE SYSTEM ON VEHICULAR EMISSIONS AT TSIMISKI</td>
<td>63</td>
</tr>
<tr>
<td>TABLE 7: SCENARIOS THAT HAVE BEEN EXAMINED</td>
<td>69</td>
</tr>
<tr>
<td>TABLE 8: SCENARIOS WITH THE ADJUSTED GREEN SPLIT</td>
<td>69</td>
</tr>
<tr>
<td>TABLE 9: SCENARIOS WITH INCREASED SPEED LIMIT</td>
<td>69</td>
</tr>
<tr>
<td>TABLE 10: RELATIVE POSITIVE ACCELERATION</td>
<td>83</td>
</tr>
</tbody>
</table>
1 Introduction

1.1 Road Transport and Greenhouse Gas Emissions

In the European Union (EU), total Greenhouse Gas (GHG) emissions from all sectors were reduced by 19.2% between 1990 and 2012 in the EU-28 and by 15.1% in the EU-15. Despite this reduction, the transport sector remains problematic in terms of CO2 reduction.

Road transport is the leading sector among those whose emissions have increased since 1990. More specifically GHG emissions of road transport were raised by 72 million tones CO$_2$ eq. in the EU-28 [1]. Table 1 presents the sectors, in which the greatest increase and decrease was achieved respectively, as well as the total reduction of GHGs achieved by all sectors (and by those not presented in the table) accumulatively.

Table 1: Sectors with the highest increase and reduction of GHGs for the period 1990-2012. (in million tonnes CO$_2$eq.) [1]

<table>
<thead>
<tr>
<th>Source category</th>
<th>EU-15</th>
<th>EU-28</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road Transport</td>
<td>72</td>
<td>123</td>
</tr>
<tr>
<td>Consumptions of halocarbons</td>
<td>71</td>
<td>85</td>
</tr>
<tr>
<td>Households and services</td>
<td>-78</td>
<td>-137</td>
</tr>
<tr>
<td>Manufacturing industries</td>
<td>-151</td>
<td>-258</td>
</tr>
<tr>
<td><strong>Total (All sources)</strong></td>
<td><strong>-643</strong></td>
<td><strong>-1082</strong></td>
</tr>
</tbody>
</table>
In 2012, the road transport was the second larger source of GHGs after the Public Electricity and Heat Production sector [1].

Figure 1 presents the allocation of the emissions per source-sector.

Figure 1: Allocation of GHG emissions per source-sector in EU-28 in 2012. [1]

EU has developed a focused and integrated policy framework covering several aspects by introducing measures that are capable to increase the effectiveness of the sector. This framework is depicted in a number of actions and interventions (vehicle’s technological solutions, alternative fuels, transport systems, infrastructure improvement
etc.) and are described mainly in the White Paper [2] of Transport and in the major legislative initiatives (Directive 2003/30/EC for biofuels, Directive 2010/40 EC for ITS, Regulation 443/2009 on CO\textsubscript{2} emissions from cars etc.) and the respective Action Plans of the Union. In this European framework, there are reflected extensively the environmental targets that has been set and the deployment of the appropriate measures and solutions that are able to bring about positive results, both in the context of climate change mitigation and in terms of addressing urban and atmospheric pollution. The main objective for the transportation sector, as it is contained in the White Paper, incorporating all the relevant policies, is the reduction of CO\textsubscript{2} emissions by 60\% by 2050.

The implemented policy regarding the reduction of GHGs seems to be effective. Between 2011 and 2012 emissions of road transport decreased by 4\% (30 million tones) and this constituted the main reason of the overall emission reduction in the Union. This fact verifies that the transport sector is in a positive route, since a reduction is achieved for fifth consecutive year. This trend is clearly presented in Figure 2.

![Figure 2: GHGs from transport and road transport in EU for the period 1990-2012](image)

The continuation of this positive trend demands the use of various measures and the adoption of integrated solutions that can intervene on various parameters that are related with fuel consumption and emissions and therefore improve the efficiency of the sector, in a diverse way. Therefore the adoption of effective and targeted traffic management strategies and measures can be an important solution to the constantly growing problems of the urban space and to the climate change mitigation. The next section presents
the whole framework of interventions that are related to fuel consumption and emissions of road transport, while the rest of the present thesis focuses on traffic related interventions.

1.2 Road Transport-Energy consumption and emissions

The main purpose of the transport sector, in the framework of sustainable development, is the covering of mobility’s necessity, from one side, and the decrease of fuel consumption and emissions, from the other. Fuel consumption and the emissions are the result of the following factors:

- The vehicle’s operation (Internal combustion engine, power transmission, after-treatment system).
- The way in which the user operates his vehicle (driver’s behavior)
- The traffic conditions
- The road infrastructure
- Other factors (weather events)

It is clear that the reduction of energy consumption and emissions from the transportation sector is a very complicated issue, because of the large number of heterogeneous factors. Nowadays, a large part of the global research in “transport and emissions” field is covered by the improvement in the technological and operational field, of those mechanisms, which contribute to the reduction of fuel consumption and emissions. The research focuses on three main fields: on the vehicle, on the driving behavior and on the effective traffic management. For each field, specific policies, interventions and improvements aim at the formation of a cleaner transportation system.

The first field includes the interventions into the factors of the vehicle’s operation, which are the following:

- The improvement of the combustion and of the thermodynamic cycle
- The use of alternative fuels (biofuels, hydrogen) [3]
- The improvement of the technical factors of the engine and of the vehicle [4]
- The optimization of the existing after treatment systems and the development of new [5]
• The penetration of hybrids and of more clean vehicles

The second category includes the interventions which affect users’ behavior. These interventions are the following:
• The promotion of eco-driving [6]
• The change in driving behavior
• The information provision to the drivers and users
• The limitation of the vehicles’ use
• The improvement of modal split
• The route choice and the planning of the journey [7].

The third category includes the interventions which are relevant to the strategic planning, the composition and the management of traffic. These interventions are the following:
• The improvement of road infrastructure
• The existence of a complete and integrated action plan
• The reduction of the traffic congestion
• The prediction of traffic conditions
• The information provision to users
• The upgrading of the role of public transport

All the above lead to the conclusion that the effort for the reduction of energy consumption and emissions has a large number of uncertainties, as well as a number of factors which complement one another. It is a fact that the first field, this of the vehicle’s operational improvement, has a smaller number of uncertainties, as the technological achievements are the result of thorough laboratory research in the automotive sector and their results can be verified experimentally. The systems and processes associated with the first category have been evolved and are being improved continuously. The second filed has the uncertainty of the users’ behavior. Drivers use the vehicles by different ways according to their knowledge, habits and needs. So the results are the following:
• The appearance of high speeds and intense acceleration and deceleration
• The increase of fuel consumption and emissions
• The traffic safety reduction
• The use of the car, even when it is not necessary
• The use of private car, even when the use of public transport is possible

The third class has the uncertainty of the traffic condition. The continuously growing needs for mobility lead create the conditions of increased traffic volume, which has as a result:
• The increase of travel times
• The creation of stifling conditions in the cities (congestion, noise intense air pollution)
• The accident causation

It is clear that a large quantity of fuel could be saved and a high degree of CO2 and of other pollutants could be reduced through an effort of intervention to the human behavior as well as to the traffic management. ITS and C-ITS examined in the framework of the present work are integrated to the second and the third class described before.

1.3 Traffic variables influencing energy consumption and emissions of road transport

Traffic may take different characteristics depending on the area being developed. So, traffic can be divided into urban, peri-urban and interurban. Urban traffic is characterized by low speeds, intense accelerations, frequent decelerations, and increased travel times. Peri-urban traffic is characterized by higher and more steady speeds, relatively, accelerations of lower intense, smoother traffic flow with fewer stops. Interurban traffic and especially the traffic on motorways is characterized by high and very high speed, no intense accelerations, while long waiting times and congestion occur mainly in cases of accidents and inclement weather. The traffic examination can be performed on different scales:
• At the macroscopic level
• At the microscopic level
At the macroscopic level, traffic is examined in terms of flow. The variables used to describe traffic flow are the average speed (km/h), the traffic volume (Veh/h) and the density (Veh/km). Other variables include the average waiting time, the travel times, the distance traveled in vehicle-kilometers (VKM) and the length of queues.

The correlation of the average speed with energy consumption and emissions of CO\textsubscript{2} is already well known. By increasing the average speed, the emissions are reduced [8]. These exhibit a minimum at a mean traveling speed 70-80 km/h. CO\textsubscript{2} emissions are greatest at low average speeds (0-20 km/h) representing heavy traffic conditions in urban areas. Due to frequent accelerations and decelerations and the long waiting time, the emissions are particularly high. The greater the average speed (20-80 km/h), a decrease in emissions curve observed [9]. This is due to the fact that higher average speeds correspond to a more homogeneous flow (stable speed with fewer fluctuations). At high speeds (> 80 km/h) the load that the engine must overcome is very high, resulting to increased energy consumption and emissions of CO\textsubscript{2}. This trend is depicted clearly on Figure 3.

![Figure 3: Relation of CO\textsubscript{2} emissions and average speed](image)

The average speed is used as a key variable in the methodology for assessing the environmental impacts of traffic flow.
When the scale of the analysis is at individual vehicle level (microscopic), the determination of energy consumption and emissions is associated with, the speed of the vehicle, the dynamic speeds and the parameters of vehicle’s operation. At microscopic level, variables such as the instantaneous speed and acceleration, the idling time and the engine speed are the variables that influence energy consumption and emission of individual vehicles [11], [12]. Within an urban driving cycle, frequent accelerations and decelerations (because there are followed by accelerations) have the main impact on energy consumption and emissions increase. Figure 4 describes the relationship of CO₂ emissions with instantaneous speed and acceleration.

Figure 4: CO₂ in g/s as a relationship of instantaneous speed and acceleration

The implementation of systems and measures that are able to improve the performance of traffic flow and the driving pattern of individual vehicles adds benefits beyond those arising from the improvement of vehicle’s technology.
2 Intelligent Transport Systems Overview

2.1 Description of ITS & C-ITS. Approach of their environmental impact.

“Intelligent Transport Systems (ITS) are systems in which Information and Communication Technologies (ICT) are applied in the field of road transport, including infrastructure, vehicles and users, and in traffic management and mobility management, as well as for interfaces with other modes of transport” [13].

Intelligent Transport Systems (ITS) are promoted because they can play an important role in the effort for the reduction of energy consumption, CO$_2$ emissions and other various pollutants of the transport sector [14]. They can have a serious contribution to the restriction of the energy problem, to the achievement of the goal which is set by the White Paper of transport, for a 60% decrease of CO$_2$ transportation emissions for the 1990-2050 period [2] and to the improvement of local air quality.

ITS act both on the individual driving pattern as well as on the traffic in general, influencing the overall performance of the transport system, by improving traffic’s efficiency. ITS according to their reference level (micro level in terms of the individual user-vehicle and macro level in terms of the traffic as a whole) can affect both the behavior of individual users, the operation of the discrete vehicles within the traffic framework and the traffic condition and composition as a whole. “In-vehicle systems” (Gear Shift Indicator, engine Start Stop, Tyre Pressure Monitoring, Intelligent Speed Adapta-
tion, Adaptive Cruise Control, etc.) are those that predominantly contribute to changes in driving behavior by adopting an eco-driving mode that promotes optimal energy management of the vehicle and its parameters and enhances safety. Systems of the category “Information and Navigation” (Variable Message Signs, real-time route finding and navigation systems, before and after trip information systems) contribute both to changing the traffic behavior of drivers and to the broader effort of traffic management by affecting the driving pattern, promoting eco-driving, contributing to trip planning, bringing positive consequences in safety, supporting the use of public transport, helping to avoid congestion and playing an important role in the success of traffic measures. “Traffic Management systems” (Adaptive Urban Traffic Control, Access and Demand Management systems, Dynamic Speed Limits) target to smooth and efficient traffic flow by synchronizing traffic lights, by introducing low emission zones or areas of congestion charging and by dynamically adjusting speed limits in motorways. The positive environmental effect of these systems has been gathered and reported in a limited number of studies [15],[16]. Table 2 summarizes their main impacts as they have been recorded by Klunder et al. [15].

Table 2: Potential impact of several ITS on CO2 emissions and ease of implementation in EU

<table>
<thead>
<tr>
<th>System</th>
<th>Potential CO2 effect in EU-27</th>
<th>Ease of implementation</th>
<th>Compliance</th>
<th>Expected future use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eco-Driver Coaching</td>
<td>15%</td>
<td>Medium</td>
<td>Medium</td>
<td>Large</td>
</tr>
<tr>
<td>Eco-Driver Assistance</td>
<td>10%</td>
<td>Easy</td>
<td>Med./Hard</td>
<td>Large</td>
</tr>
<tr>
<td>PAYD</td>
<td>7%</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Platooning</td>
<td>6%</td>
<td>Very Hard</td>
<td>Hard</td>
<td>Small</td>
</tr>
<tr>
<td>CC/ACC</td>
<td>3%</td>
<td>Easy</td>
<td>Easy</td>
<td>Large</td>
</tr>
<tr>
<td>Fuel efficient route choice</td>
<td>2%</td>
<td>Med./Hard</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Dynamic traffic light synchronization</td>
<td>2%</td>
<td>Medium</td>
<td>No issue</td>
<td>Large</td>
</tr>
<tr>
<td>Automatic engine shutdown</td>
<td>2%</td>
<td>Easy</td>
<td>Easy</td>
<td>Large</td>
</tr>
</tbody>
</table>
### Table: Potential CO2 effect in EU-27

<table>
<thead>
<tr>
<th>System</th>
<th>Potential CO2 effect in EU-27</th>
<th>Ease of implementation</th>
<th>Compliance</th>
<th>Expected future use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trip departure planning</td>
<td>2%</td>
<td>Medium</td>
<td>Medium</td>
<td>Large</td>
</tr>
<tr>
<td>Tyre pressure indicator</td>
<td>1%</td>
<td>Easy</td>
<td>Medium</td>
<td>Large</td>
</tr>
<tr>
<td>Congestion Charging</td>
<td>0.5%</td>
<td>Medium</td>
<td>No issue</td>
<td>Medium</td>
</tr>
<tr>
<td>Slot management</td>
<td>&lt;0,1%</td>
<td>Hard</td>
<td>No issue</td>
<td>Small</td>
</tr>
<tr>
<td>Lane keeping</td>
<td>0.1%</td>
<td>Easy</td>
<td>Easy</td>
<td>Large</td>
</tr>
<tr>
<td>Emergency braking</td>
<td>&lt;0.1%</td>
<td>Easy</td>
<td>No issue</td>
<td>Large</td>
</tr>
</tbody>
</table>

ITS oriented in traffic management and travel information provision have greatly been developed and implemented in many European cities bringing particularly positive results, while vehicles recently have started to be equipped with in-vehicle systems. The new challenge for the scientific society is the development of systems, referred to as Cooperative ITS (C-ITS), that connect vehicles with the road infrastructure. This connection seems to be of great importance since it is able to increase the quality and the availability of traffic data, a key factor for the optimization of transport systems and for the successful implementation of transport strategies and measures. The bilateral data exchange is essential for the development and the application of systems that contribute to the reduction of fuel consumption and emissions. Through C-ITS, operators obtain the possibility of continuous traffic monitoring and have access to a large number of discrete driving patterns, in a high level of detail. Therefore, they can more effectively manage traffic in a dynamic and adaptive way (e.g. improvement of UTC) and develop, through the examination of the driving patterns, applications for vehicles, which are optimized in terms of fuel consumption and emissions reduction.

### 2.2 ITS and identification of their impact on energy consumption and emissions

Despite the fact that the effectiveness of all these systems in improving the operation of the transportation system has already been well examined and continues to be examined as the systems are being evolved, the recording of the impact on energy consumption
and emissions is at an early stage or is examined fragmented. The evaluation of the existing systems and their further development demand an accurate assessment methodology, which is able to capture with a high level of detail the real impact of these systems on energy consumption and emissions. However, the lack of a systematic methodology for assessing the environmental effect of ITS is a fact. This gap is fulfilled by Samaras et al. [17] in the framework of the European project ICT Emissions, where it is examined how the measures affect the driving pattern of individual vehicles, how the average driving behavior is affected by systems and what kinds of inter-modal changes such measures introduce. The methodology is accomplished identifying the missing gaps between traffic and emissions models, through the modeling of several ITS systems and through the validation of the modeling processes with real demonstration activities. Moreover, an evaluation framework for the assessment of the environmental effect of ITS has been developed by the EU-funded project AMITRAN [18].

The effectiveness of various systems and measures concerning their impact on fuel consumption and emissions is determined by the way they influence a number of parameters and variables that characterize the traffic as a whole or there are associated with the individual vehicles’ pattern and operation. Several ITS systems have been developed having a different reference scale level and affecting various parameters and traffic variables. ITS evaluation methods that can provide qualitative indicators regarding the impacts of ITS are the modeling processes and the real demonstration activities like Field Operational Tests (FOTs).

In the simulation process a traffic model is combined with an emission model. The appropriate combination is essential for the successful simulation of the tested ITS. After network’s description and calibration in a traffic simulation model (micro, macro or meso), the simulation of ITS is performed with the development of external modeling test beds, since the majority of traffic models do not contain such an option by default. Then different scenarios are identified and simulations take place. As a result exported trajectories describing discrete vehicle’s speed profiles and other more aggregated or analytic traffic variables, are fed into emission models.

“Field Operational Tests (FOT) are large-scale testing programs aiming at a comprehensive assessment of the efficiency, quality, robustness and acceptance of ICT solutions used for smarter, safer and cleaner and more comfortable transport solutions, such as navigation and traffic information, advanced driver assistance - and coopera-
tive systems” [19]. Since the present study is oriented to the modeling process, hereafter its content is oriented to this direction.

The appropriate combination and selection of a traffic emission model demands the full understanding of the variables that the system or the measure affects. Several traffic emission models were developed, which estimate emissions using different approaches and can be used in a variety of applications such as the development of national emission inventories, the monitoring of traffic pollution, and the projections regarding the impact of new vehicle technologies, fuel uses and transport demand. In the next sections, the way these models are developed and the functions they incorporate are presented extensively, always with reference to their ability to assess ITS systems and applications.

### 2.3 Emission models

The constantly growing problems of the urban space and the environmental burden, which is correlated with them, impose the constitution of targeted strategies, the adoption of policies and the implementation of measures that can deal with these problems resulting in a positive impact on the quality of life and on the environment. Road transport is a various source of air pollution and one of the main contributors to climate change phenomenon [1]. Therefore a variety of policies are prompted and several measures are implemented in order to limit the sector’s negative impact. These measures are intervening on the parameters influencing energy consumption and emissions. The complexity of the measures, the stochasticity which is enabled in the transport sector, the no uniformity between different areas and the specific need of each region imply the development and the adoption of integrated assessment processes, in order to identify accurately the effectiveness of an implemented measure or to predict the potential performance of a future policy.

These evaluation processes demand the use of analytical methodologies and specialized tools that can capture the real effect of a measure in a high level of accuracy. The most accurate way to quantify the environmental effect of a traffic measure or a vehicle technology is real measurements. Roadside pollution counters, Portable Emissions Measurement System (PEMS), chassis and engine dynamometer tests are widely used so as to monitor the environmental effect of traffic or to assess the impact of a vehicle.
technology. But it is a fact that measurements are not always an assessment cost-effective way. It is not possible and feasible to measure a large number of vehicles and also the monitoring of air pollution at the road network level cannot provide us with safe conclusions regarding the contribution of road-transport. Therefore there is a generic need for the development of tools and models that can be used in the majority of cases, they can applied at different levels (macroscale-microscale) and are capable to assess a wide variety of measures, applications and technologies. Methodologies and models come to evaluate the environmental impact of the interventions on the traffic as whole, and on the discrete movement of a vehicle within the traffic framework. So several traffic emission models were developed, which estimate emissions using different approaches and can be used in a variety of applications. Thus emission models are used for several purposes such as the following:

- Development of national emission inventories
- Traffic pollution monitoring
- New road infrastructure assessment
- Intelligent transport systems (ITS) development, implementation and evaluation
- Other transport policies assessment (Use of biofuels, alternative fuels, hybrids etc.)
- Projections regarding the impact of new vehicle technologies, fuel uses and transport demand.

### 2.3.1 Emission Factors – Development

Despite the fact that emission models estimate traffic related emissions using different approaches and having a different reference scale level (macroscale in terms of the traffic as a whole, microscale in terms of a single vehicle), the majority of them are based on the logic of Emission Factors (EFs). Emission (or consumption; in case of fuel use) factor is the estimated average rate of emission produced (or fuel consumed) per unit of activity [20].

Therefore, EFs represent the average mass of a gas emitted and are expressed in g/km when the unit of activity is the distance traveled (km), in g/s in terms of temporal activity (s), in g/kwh when the unit of activity is the energy demand by the engine (kwh) and in g/kg fuel when the activity is related with the mass of fuel (kg) burned. Total
emissions result by multiplying the emission factor with the activity related to this factor.

\[ E_{\text{total},ij} = \text{EF}_{ij} \cdot \text{Activity} \quad (1) \]

Where EF is the factor of a specific emission i, for a single vehicle or class of vehicles j and Activity can be one of the followings [21]:

- The total number of Km travelled by a single vehicle (or vehicle kilometers travelled (VKM) for a class of vehicles),
- The total time spent in a specific mode (acceleration, idle, etc),
- The total amount of fuel consumed.

In emission models, EFs are estimated independently as discrete average emission rates or as continuous functional relations [22], [10]. The suitability of a traffic emission model to be used for specific applications is strongly related to the way it estimates the appropriate EF and to the way the EFs, it contains, have been developed. The description and the analytic identification of the method EFs are developed is essential, since they incorporate the technological background of the vehicles measured and the traffic environment (urban, rural, motorway) and its characteristics (congested, free flow) they represent. The development of EFs is a result of extended measurements, which are made in the laboratory and under real conditions. The way EFs are developed is extensively described in the relevant literature [20],[22]. Their development is based mainly on emission data derived by chassis and engine dynamometer measurements and on board measurements (PEMS). Remote sensing measurements, on road (chase) measurements, and tunnel studies are mainly used for the validation of the existing models. The most common way to develop emission factors is the chassis and engine dynamometer measurements. In these, vehicles are tested over specific and predetermined driving cycles. Emissions are gathered in sample bags and analyzed or there are measured through on-line analyzers. Especially for the development of EFs that are used in traffic oriented emission models, chassis dynamometer measurements, PEMS and modal measurements derived by chassis dynamometer measurements are most commonly used. At the next section an analysis of driving cycles is performed which is essential because the fact that they simulate real driving and traffic conditions provide us with the
appropriate indicators regarding the analysis of traffic and they reveal the opportunities and the limitations regarding the suitability of emission models to be used as assessment tools for ITS.

2.3.2 Driving cycles

“A Driving cycle is a fixed schedule of vehicle operation which allows an emission test to be conducted under reproducible conditions [23]”. Driving cycles try to represent real traffic conditions. They are consisted of the four driving modes that are met in real world traffic conditions (acceleration, cruising, deceleration, idling). These modes are alternating continuously especially when heavy congestion occurs. Cycles are divided in two main categories; the “steady-state” and the “transient”. Steady-state cycles are characterized by constant engine speed and load. These are used for testing of heavy-duty diesel engines. In transient cycles, vehicle’s load varies. The type-approval cycles that are used by authorities and policy makers in order to test if vehicles exceed the emission limits, are transient cycles. Examples of type approval cycles are presented in Figure 5 and Figure 6. In Europe the type approval cycle is the New European Driving Cycle (NEDC), consisted by an urban and an extra urban part. In the US the respective one is the EPA Federal Test Procedure (FTP-75).
As it is shown in figures above the NEDC is a smooth cycle without representing real driving conditions, especially for an urban environment. The cycle has smoother speed dynamics (long time maintaining steady-state speed, smoother accelerations) compared with those found in real driving conditions. Therefore emissions and fuel consumption, resulting from the measurements over the NEDC, are not depicting the reality. Real-world fuel consumption and CO$_2$ emissions seems to be 10-20% higher compared to the NEDC while NO$_X$ and CO emissions appear to be 10 times higher [24]. Thus, either the emission factor development, or any other evaluation process can have the NEDC as a basis.

The development of accurate EFs demands the use of real-world driving cycles. The construction of these cycles is a complex process and is based on extensive field operational tests in which different types of equipped (GPS, sensors) vehicles are making multiple routes to various road types, recording their instantaneous speed (and other variables) for every second. From the data recorded, mainly the speed profiles are analyzed and their kinematic parameters are identified. The majority of driving cycles has been developed using the method of micro trips. Total recorded trips are divided in a number of “Kinematic sequences” [25]. Each sequence is defined between two temporal successive vehicle stops. Sequences are clustered in categories according to calculated kinematic parameters and variables-indicators. These clusters represent various traffic conditions (congested urban, urban free flow, rural, motorway, etc.). Finally the sequences are merged according to the type of traffic; the cycle intends to represent. Other methods are also used such as the collection of modal events and the statistical synthesis.
of them, instead of microtrips [26]. A series of cycles representing the average European driving conditions were developed in the framework of the ARTEMIS project [27]. The development of cycles was based on data collected from several European traffic environments. The cycles were constructed by clustering the kinematic sequences in bins of speed and acceleration. The frequencies of each bin were computed. Figure 7 presents the urban ARTEMIS cycle.

![ARTEMIS Urban](image)

**Figure 7: The ARTEMIS driving cycle**

Each cycle reflects a specific traffic environment and is characterized as a whole by several kinematic parameters that are indicators for its dynamics. In real traffic these parameters are taking the nature of variables. These variables affect energy consumption and emissions. The comprehension of the kinematic parameters is essential because they explain the variations encountered in emission factors and are used to evaluate the performance of real-traffic in cases where traffic data are available. The most important parameters that have significant role in fuel consumption and emissions are presented in Table 3.

<table>
<thead>
<tr>
<th>Kinematic parameter</th>
<th>Unit</th>
<th>Kinematic parameter</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive spent accelerating</td>
<td>s</td>
<td>Average positive acceleration</td>
<td>m/s²</td>
</tr>
<tr>
<td>Standing time</td>
<td>%</td>
<td>Average negative acceleration</td>
<td>m/s²</td>
</tr>
<tr>
<td>% of time accelerating</td>
<td>%</td>
<td>Average stop duration</td>
<td>s</td>
</tr>
<tr>
<td>% of time standing</td>
<td>%</td>
<td>Relative positive acceleration</td>
<td>m/s²</td>
</tr>
</tbody>
</table>
Fuel consumption and emissions are strongly related to driving dynamics. Positive acceleration is the most important factor since vehicles have to overcome the inertia resistance. Therefore a cycle which is characterized by intense accelerations leads to higher fuel consumption and emissions compared to another with a more smooth profile. Speed standard deviation is a measure of cycle dynamics but it cannot reveal the intensity of accelerations [8]. The intensity of acceleration can be described sufficiently by the Relative Positive Acceleration (RPA) which is a speed-related average of acceleration of the vehicle [24]. RPA (m/s²) is given by the following equation:

$$RPA = \frac{\int_0^T (v_i a_i^+)^{dt}}{x}$$  \hspace{1cm} (2)

Where $v_i$ (m/s) and $a_i$ (m/s²) are the instantaneous speed and acceleration of a vehicle respectively and $x$ (m) the total distance covered. RPA is an important indicator of the cycle and therefore of traffic dynamics, since the power demand of an engine due to acceleration is strongly related to the product of speed with acceleration. The kinematic parameters of the ECE (urban part of the NEDC) and FT-75 type-approval cycles and of the real world ARTEMIS cycle are presented in Table 4.

**Table 4: Kinematic parameters of three urban driving cycles [29]**

<table>
<thead>
<tr>
<th>Kinematic parameter</th>
<th>ECE</th>
<th>FTP-75</th>
<th>ARTEMIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive spent accelerating</td>
<td>278 s</td>
<td>683 s</td>
<td>357 s</td>
</tr>
<tr>
<td>Standing time</td>
<td>241 s</td>
<td>241 s</td>
<td>206 s</td>
</tr>
<tr>
<td>% of time accelerating</td>
<td>23,56</td>
<td>36,45</td>
<td>35,95</td>
</tr>
<tr>
<td>% of time standing</td>
<td>20,42</td>
<td>12,86</td>
<td>20,75</td>
</tr>
<tr>
<td>Average trip speed</td>
<td>33,6 km/h</td>
<td>39,21 km/h</td>
<td>17,7 km/h</td>
</tr>
<tr>
<td>Average positive acceleration</td>
<td>0,528 m/s²</td>
<td>0,420 m/s²</td>
<td>0,531 m/s²</td>
</tr>
<tr>
<td>Average negative acceleration</td>
<td>-0,719 m/s²</td>
<td>-0,457 m/s²</td>
<td>-0,571 m/s²</td>
</tr>
<tr>
<td>Average stop duration</td>
<td>17,21 s</td>
<td>15,06 s</td>
<td>14,71 s</td>
</tr>
</tbody>
</table>
Andre et al. [28] underlines the importance for driving cycles to represent the real-world conditions. Several driving cycles have been developed simulating driving conditions of specific cities or developed serving the scope to produce emission factors depicting actual driving and traffic conditions.

### 2.3.3 Emission models classification & description

Emission models use EFs to estimate traffic and vehicle emissions. Models have different level of detail (macroscale, microscale), take different vehicle related-parameters account in order to estimate emissions (vehicle technology, fuel type, classes, engine capacity, mileage) and demand various input data (average speed, instantaneous speed, gear shift pattern) and activity data (VKM). They calculate emissions using different methodological background (EFs as a relation of average speed, EFs as a relation of speed and acceleration, EFs as a relation of engine power), they incorporate emission calculations of different nature (discrete EFs, continuous emission functions) and they provide various types of emission estimations (cold start-hot exhaust emissions, exhaust regulated pollutants, exhaust non-regulated pollutants and gases, non-exhaust emissions, evaporative emissions). Several classifications are met in the literature such as the classification according to the type of input data [21], according to the methodological approach adopted for emissions calculations [29] and according to the reference scale of the models (traffic emission models - vehicle simulation models) [30]. In the present thesis the classification is made considering the methodological background and the approach each model adopts because for the assessment of ITS, the suitability of an emission model to be used for specific applications is mainly related to the way it estimates the appropriate EF and to the way the EFs, it contains, have been developed. Therefore the classification of Boulter et al. [29] and of the EC-METI Task force is suitable. The main categories of emission models are:

- Aggregated emission factors
• Average speed
• Adjusted average speed
• Traffic situation
• Multiple linear regression
• Simple modal
• Instantaneous, speed based
• Instantaneous, power based

Regarding the identification and the assessment of the environmental impact of ITS, the suitability of a traffic emission model to be used for specific applications is strongly related to the way each model estimates the appropriate EFs for each case, to the way the EFs it contains have been developed, the reference scale of the model (micro-macro) and the traffic data that it accepts as input.

**Aggregated emission factors**

Aggregated emission factors are expressed in g/km or in g/fuel. EFs are discrete values representing standard driving conditions and vehicles’ types. These single values that cannot be adjusted according to traffic and driving conditions express a mean mass of pollutants emitted per unit of activity. Usually they are derived from measurements over specific driving cycles and represent mean fleet emissions and specific roads (urban, rural, motorway). These types of EFs can be used only for inventorying purposes and in cases where only activity data are available. EFs of this nature can be found in the EMEP/EEA [31] emission inventory guidebook. Their ability to be used for ITS evaluation is extremely weak. The only cases that they could be applied is in a very macroscopic level where the only affected parameter is the total VKM traveled assuming no other change in traffic variables.

**Average speed emission models**
Emission models that calculate emissions using average speed-dependent EFs are gathering many advantages and are convenient for road transport emission inventorying since with only one traffic variable as an input (average speed) and with the relevant activity data (VKM), they can provide emission estimations at a macroscale level (city, regional or national). In these models, EFs are expressed as function of average speed [8] and are given in g/km. Emissions and fuel consumption are generally decreased with the increase of average speed. Average speed reflects the travel time spent at a route. Increased travel times (hence lower average speeds) are mainly caused by congestion. Congestion affects the driving pattern and this is depicted in the frequency and the intensity of accelerations and decelerations, the number and the duration of stops and the limitation of constant speeds. All these variables are determining the increase of fuel consumption and emissions.

Average speed is able to depict the variance of emissions since an increase in average speed generally depicts less driving dynamics and idling time, which are caused mainly by stop and go traffic, and consequently means a reduction in fuel consumption and emissions. Figure 8 depicts that trend and shows that for average speeds at 60-70 km/h the lower level of emissions occur.

At higher average speeds, where the aerodynamic drag is increased, fuel consumption and emissions are increased. Therefore, the expression of emissions as a function of average speed can be achieved by plotting, for a specific class of vehicles, all the average emission rates obtained by various driving cycles, which are characterized by different average speeds. Through a regression method, the function expressing the dependence
of emissions by average speed is derived. Regarding fuel consumption and CO$_2$ emissions the coefficient of determination ($R^2$) is high enough to indicate the correlation of the measured data with the statistical model that is implemented and to confirm the trend described before. Concerning other pollutants, correlation coefficient is generally lower, a fact that is not invalidate the relative dependence of them from the average speed but it can be attributed to the different vehicle and after treatment technologies. The general trend shows that PM are increased at lower speeds because of the incomplete combustion and NO$_X$ are increased at higher speeds due to higher temperatures [32]. The variability in average speed shows to play an important role in the identification of all emissions except of NO$_X$, where the specification of driving dynamics is of great importance.

However for the same average speed, different driving patterns can occur a fact that leads to different produced quantities of emissions [12]. So the way the average speed was achieved is an important factor for determination of fuel consumption and emissions [11]. A driving pattern with frequent speed fluctuations may has the same average speed with a pattern of steady speed. These two patterns present different emission levels. Also, the road type plays important role since the same average speed may represents different levels of congestion when different road types are compared. Moreover EFs have been produced with the use of specific driving cycles that differ from the actual traffic conditions of each case [33]. These indicate that the average speed approach can overestimate or underestimate emissions because of the driving dynamics. When the focus is on traffic as a whole, then the influence of stop and go on the driving pattern is partially taken account by the average speed approach [34]. The rate of influence is determined by the driving cycles that have been used for the development of the emission function. Applying the average speed methodology at a more analytical and detailed level (e.g. link level), may lead to deviations from the reality. Although, as higher the length of the trip for which the approach is applied, the lesser the deviation from the reality [30]. Moreover within a specific link driving patterns with different average speed from the average speed of the link occur. Therefore the introduction of speed distributions within the same link for specific vehicle classes can be introduced [35], [36]. The capture of driving dynamics or the effect of congestion by these models can be improved though the introduction of a variable that can represent driving dynamics. Relative positive acceleration or the standard deviation of speed could be solutions for the driving dynamics identification.
The main representative of this category is the COPERT emission model [37] which methodology also is included in the official EU’s air pollutant emission inventory guidebook (EMEP/EEA). COPERT provides estimations regarding several regulated (CO, NOx, PM, VOC), for non-regulated pollutants and for fuel consumption (CO2 emissions are derived from fuel consumption). Hot emissions are calculated with the use of speed-dependent EFs. COPERT is able to take account into calculations and the non-exhaust emissions (fuel evaporation, PM from tires and brakes) that usually do not taken into consideration by other models. In COPERT, vehicles are classified in passenger cars, light duty vehicles, heavy duty vehicles, buses and power two wheelers. Moreover the classification in each category is performed according to the European emission standards (Euro classes) and the engine capacity. The model covers a variety of fuels such except from the conventional (petrol, diesel), such as CNG, LPG, biodiesel and bioethanol. COPERT is met very frequently in the literature and is applied especially in cases of air-pollution monitoring and emission inventorying at local, regional and national level. As main input data the user enters the average speed per road type (urban, rural, motorway) and the relevant activity data (total VKM) for each road type. Regarding the air-pollution monitoring at a street level, there are limitations, which are related to the average speed approach (restrictions regarding the capture of traffic dynamics) and the ease of processing (multiple runs to simulate the links of an entire road network). A solution concerning the use of the model at link level and the combination with traffic models is provided by COPERT Micro [38].

Moreover the model calculates cold start emissions which are of great importance especially in cases where the total trip has a short length. The cold start emissions are calculated mainly with the use of empirical functions. The emissions during the cold-start phase are higher compared to the emissions during the hot-start. This is particular intensive when vehicles start from ambient temperature.

Other average speed emission models are MOBILE and EMFAC 2000. MOBILE was an average speed emission model that has been developed by US EPA and was the main inventorying tool of road transport emissions in USA. MOBILE 6 has been replaced by MOVES emission model. MOBILE initially calculated emissions as a function of average speed using emission factors of the FTP cycle implementing in parallel a correction for average speeds other than the average speed of the FTP cycle.
Average speed approaches cannot be used directly for ITS evaluation because of their weakness to capture and precisely take account driving dynamics,[34],[22] and vehicles’ transient operation which are of great importance in traffic-related emissions. These weaknesses should be considered when the approach is used to simulate an ITS. An extension of COPERT in order to take account more precisely traffic dynamics and enable different driving patterns is performed within the framework of ICT-Emissions where average speed EFs for different driving patterns derived from CRUISE (micro emission model) will be fed in the average emission model in order to distinguish different driving patterns with the same average speed and generalize the effect of ITS at a macroscale level.

**Traffic situation models**

Other macroscale modeling approaches are the traffic situation models like HBEFA [39] and Artemis [40], in which emission factors (g/VKM) are defined for different traffic situations/conditions. These models are able to take account driving dynamics since they estimate emission factors for different traffic conditions (free flow, congestion).

The Artemis model is a traffic situation model that has been developed within the framework of the European funded project Artemis with the use of an extensive database of LDV and HDV measurements. [40]. The scope of the model is to enhance emission inventorying (local, regional and national level), contribute in the evaluation of transport-related projects and create the appropriate input data for air-quality modeling and monitoring. The model can be applied down to a link level. It is able to provide estimations regarding pollutants such as CO, NOx, HC, PM, regarding fuel consumption and regarding non-regulated emissions such as CO2, CH4, NH3, C6H6, PAHs, PM and others. Vehicles in the model are classified according to their type, size, engine capacity and emission standards. The model takes account both cold start and hot exhaust emissions. The development of the traffic situation EFs was based on the analysis of the available emission measurements. The driving cycles that have been used for these measurements, were analyzed according to their kinematic parameters (two dimensional time distribution of the instantaneous speed and acceleration). These kinematic parameters were matched to specific traffic situations. Then the driving cycles were clustered according to the traffic condition they represent. A representative driving pattern, representing a specific traffic condition, was selected. The emission rates for the clustered
driving patterns were used for the development of the traffic situation EFs. This classification is depicted in Figure 9.

Figure 9: Traffic conditions used in the ARTEMIS emission model [40]

Regarding the traffic situations in Artemis model, these are described in free-flow traffic (speed at 85-100% of the free speed), heavy traffic (speed at 65-85% of the free speed), unsteady saturated traffic (variable speed with possible stops, 30 to 60% of the free speed) and stop-and-go (speed around 10 km/h) [40]. Therefore the model distinguishes different level of service in the calculation.

In the German – Austrian – Swiss Handbook Emission Factors for Road Transport (HBEFA) [39] EFs are provided as discrete functions of specific traffic situations. For the development of EFs, 4 different driving cycles (each one contains 3 sub-cycles) were used. The identification of the traffic situations is achieved through the introduction of driving patterns representing specific traffic situations and traffic environments. These driving patterns are analyzed to their kinematic parameters and each one is correlated to a number of the initial cycles and sub-cycles as their linear combination. The criterion of this combination is the minimization of the sum of squared differences of the kinematic parameters. Therefore each pattern is expressed as a linear combination of the initial sub-cycles and the estimated emissions for these patterns (emission measurements are not available) as a linear combination of the available bag measurements of the initial sub-cycles. As a result EFs for different traffic situations occur. These situations include the area type (rural, urban) the road type (main urban road, motorway etc.) the speed limit and the level of service (free flow, heavy, saturated, stop and go). During
the evolution of the model other cycles were introduced (Artemis cycle). The latter versions of the Handbook use the instantaneous model PHEM for the calculation of the EFs for HDV and LDV vehicles in order to include the latter emission standards (e.g. Euro 5 and Euro 6 standards), the gear shift pattern and the new after treatment technologies in the emission estimations).

These approaches are able to take account dynamics, in a higher level of accuracy compared to the average speed approach, but enable the difficulty from the perspective of the user to define the appropriate traffic situation qualitatively or partially quantitatively (e.g. speed limit, level of service). In the Artemis model an attempt was made to describe the different traffic situations in accordance to the definitions found in the traffic engineering practice [10]. According to [15], the traffic situation approach could be able to capture the effect of traffic management measures in a macroscale level, with the appropriate support of traffic-simulation or real-traffic data. However, the same study concludes that the existing traffic situation emission models are not considered as sufficient enough to estimate the effect of traffic management systems and measures. This conclusion is extracted also by the Carbotraf project [41], where the predefined traffic situations are considered as an obstacle in the evaluation of ITS in cases where the transmission from one level of service to another is required.

The models that have been presented above are estimating fuel consumption and emissions based on more aggregated characteristics and variables of traffic (macroscale). There models are gathering many advantages regarding the development of emission inventories at regional and national level. They are characterized by an ease of processing since they demand as input data that are easily specified. However, they present weaknesses in terms of capturing driving dynamics or defining their exact level. Since the majority of ITS affect driving dynamics, their evaluation should be based on emission models that are able to use precise and detailed traffic data (derived from traffic models or the reality) and to assign emission changes, to the affected by the systems, driving patterns. Thus the evaluation of ITS seems to need models that estimate EFs in a different way from that previously presented.

Fuel consumption and emissions are strongly related with traffic variables such as speed, positive acceleration and idling time. The identification of fuel consumption and of emissions in the cases where a measure or a system affects the individual driving pat-
tern and the vehicle’s operation, demands the imprint of the vehicle’s speed profile, since positive accelerations have the most important impact.

The way an ITS impair the efficiency of different driving modes (acceleration, cruising idling), initially lead us to understand quantitatively the potential effect of these systems on energy consumption and CO2 emissions. For example smoother accelerations or constant speed result in a reduction of fuel consumption and consequently in a reduction of CO2. However emissions like NOx, PM, HC and CO occur under different conditions and vary in different driving modes (idling, intense accelerations, higher speeds) [28]. The pattern that they exhibit is strongly affected by transient phenomena and related to the engine’s operation (combustion, fuel mix, load) and the behavior of the after treatment system. Therefore, the environmental assessment of a system that affects the speed profile of a vehicle within the traffic framework should be based on approaches that are able to produce more detailed EFs and correlate them with the instantaneous operation of a vehicle. This can be done by specific traffic-oriented approaches (representative vehicles for the entire fleet) or by vehicle simulators (discrete simulation of specific vehicles), ensuring greater or lesser level of accuracy.

**Linear regression models**

Linear regression models constitute a transition between macroscopic and microscopic models. They correlate bag emission measurements to the instantaneous speed and acceleration pattern of vehicles. This is accomplished by an analytical kinematic parameters analysis and a complex statistical process. Despite the fact that analytic driving patterns (instantaneous speed) are analyzed by the models, the emission factors are expressed in g/km and therefore there are not correlated precisely to the instantaneous driving pattern. Versit+ [42] is the major representative of this category and a more extensive analysis of its methodological background will be carried out in a following chapter of this work, since the case study’s system will be evaluated with the use of this model.

These approaches seem to be convenient for ITS modeling because they enable driving dynamics and idling phases into their calculations. The effect of systems and measures that influence traffic flow at a link level (eg. UTC systems), or of those that affect vehicles’ driving pattern (e.g. ADAS) can be simulated sufficiently by these approaches [15]. On the other hand systems that affect parameters of the vehicle’s opera-
tion like the gear shift pattern (e.g. gear shift indicator), the operation of the engine (e.g. engine start-stop) or tires’ operation cannot be simulated with the use of these approaches because models are traffic oriented and the operational parameters cannot be modified. These systems demand more vehicle oriented solutions. Moreover the fact that EFs are provided in g/km and not in g/s does not allow a detailed comprehension of the modeling results and their further analysis.

**Instantaneous speed-based models or modal models**

Instantaneous speed-based emission approaches assign emission rates to driving modes or to instantaneous variables such as speed and accelerations. In the simplest type, the modal model, vehicle operation is defined in terms of a relatively small number of modes - typically ‘idle’, ‘acceleration’, ‘deceleration’ and ‘constant speed’ [10]. Such an approach has been adopted by Cernuschi et al. [43] where instantaneous emission data were analyzed and placed in a two-dimensional map of velocity and acceleration. Emission data were grouped in classes according to their rate of acceleration (positive, negative, zero). For each group, with the use of regression, equations occurred, in which instantaneous velocity was the independent variable and instantaneous emissions the dependent. The Figure 10 presents the graphical output of these equations for different modes. The figure below is presented in order to depict indicatively the modal process. However the absolute emission values may not represent the modern vehicles emissions because there have been many changes to vehicles since this study was published.

![Figure 10: Relation of NOx emissions with different modes [43]](image-url)
More accurate approaches correlate explicitly emissions with instantaneous speed and acceleration. Joumard et al. [11] has developed an instantaneous speed based model expressing emissions as a function of instantaneous speed and the product of speed and acceleration. This approach is depicted in Figure 11.

![Figure 11: Nox emissions as a function of speed and speed x acceleration [11]](image)

A number of more detailed modal models aim to provide a more precise description of vehicle emission behavior by relating emission rates to vehicle operation during a series of short time steps (often one second) through the development of emission functions that are able to calculate discrete EFs for every second. These emission functions are produced with non-linear multiple regression techniques. An example of this type of equation is provided by Panis et al. [12]. The equation, which is a regression result is presented below, where the f parameters are regression coefficients and estimates instantaneous emissions as a function of instantaneous speed and acceleration. A similar approach has also been used by Carslaw et al [44].

\[
E_n(t) = \max\{E_o, f_1 + f_2v_n(t) + f_3v_n(t)^2 + f_4a_n(t) + f_5a_n(t)^2 + f_6v_n(t)a_n(t)\} \quad (3)
\]

The importance of the simulation of the instantaneous vehicle’s operation has already been underlined. Instantaneous speed-based approaches correlate instantaneous
emission measurements with the combination of speed and acceleration that caused them [43] taking account driving dynamics and can be used for valuation purposes at a micro level [11].

An example of this category is the VT-Micro [45], which is an instantaneous speed-based emission model, developed with regression techniques over a sample of instantaneous dynamometer measurements. VT-Micro estimates fuel consumption and HC, CO, CO₂ and NOₓ emissions. For the development of the model, instantaneous emission measurement where binned to a range of speed and accelerations and for each bin the average value was calculated. Over these values regression techniques are used forming equations that contain linear, quadratic and polynomial terms of speed and acceleration which consist the independent variables. VT-micro has been used in the evaluation of ITS [46] and can be combined with traffic micro models.

A major drawback of these models is that they cannot take account the precise effect of the gear shift pattern, the road slope and the use of accessories [47] since all these are a-priori contained in the speed profile. A drawback regarding the development of these models is the difficulty in the collection of continuous emission measurements where these are based on measurements over transient cycles. Second by second emission data from dynamometer measurements and real world emission data measured with the use of PEMS are gathered and analyzed. This approach, in order to be accurate, requires measurements in 10 Hz analysis and the use of emission signal corrections for the appropriate emission mapping [48]. These emission models are suitable for ITS evaluation since there are able to capture the dynamics of the driving patterns. An important advantage of these models is that they can be combined effectively with traffic models and quite “easily” estimate emissions for a large number of speed profiles.

**Instantaneous power based models**

Instantaneous power-based models calculate fuel consumption and emissions of a vehicle with the most accurate way (for traffic-related purposes), by translating vehicle’s speed profile in longitudinal dynamics and calculating the instantaneous power demand of the engine. The power demand in combination with the engine speed (in the majority of models) is assigned to instantaneous energy consumption and emission through the use of fuel consumption and emission maps or predefined emission rates.
MOVES is a traffic emission model developed by US EPA. Moves is a traffic-oriented model so the user is not able to adjust specific vehicles’ parameters. On the other hand MOVES combines the ability of modeling at a link level by taking into account in its calculations driving dynamics. MOVES introduces the variable of Vehicle Specific Power (VSP), in order this variable to be corelated with emissions. VSP is generally defined as power per unit mass of the source [49]. VSP represents the power demand normalized over the mass.

VSP has a physical nature as a variable representing the power demand by an engine compared with the modal or instantaneous speed based equations, which consist the output of statistical analyses. The model uses detailed driving patterns as input and the variables of speed and acceleration are used for the calculation of VSP. Then the calculated VSP values are clustered to specific predetermined bins (VSP bins). For each bin an emission rate is available. Therefore according the VSP distribution of the input pattern, its total emissions are computed. The induction of VSP gives the opportunity for road slope’s introduction in emissions’ calculation because of the power calculation. The emission rates that contained in the model are a result of modal emission measurements. MOVES consists a traffic related model and the EFs it contains have been developed through statistical process. The difference compared to the instantaneous-speed based models has to do with the fact that the model uses as variable the power demand of the engine, which a physical factor. Despite the fact that MOVES uses VSP in order to calculate emissions, remains a traffic oriented model and this creates challenges but also limitations regarding its adaptivity concerning the simulation of ITS. A potential ability by the user’s perspective to adjust the default parameters of the VSP equation can extend the model’s ability to be used for the evaluation in a variety of applications.

CMEM is an instantaneous power based emission model which development is based on a physical approach [47]. The model goes beyond the classic modal and engine map approaches and introduces a model with physical parameters and modules in order to estimate fuel consumption and emissions. Therefore different vehicle operation modules are introduced representing the engine power demand, the engine speed, the fuel air ratio, the fuel rate, the engine out emissions and the catalyst pass fraction [50]. The structure of the model is presented in a schematic way below.
Figure 12: The architecture of CMEM model

As it is shown from the structure above, CMEM is a model that tries to represent the total physical processes that are related to the energy consumption and emissions production at vehicle’s level. The model at a first level calculates fuel consumption (fuel rate) based on the power demand, the engine speed and the air-fuel ratio. After that it applies emission factors over the fuel rate in order to estimate engine out emissions. Then the operation of the after treatment system is simulated so as the exhaust emissions to occur. The EFs used and of fractions of the after treatment system and other important parameters regarding cold start and hot exhaust emissions are the result of an the model’s development through the use of bag, modal and second by second emission measurements.

PHEM is a power-based emission model that calculates emissions using engine fuel consumption and emission maps. PHEM uses the speed profile in order to calculate longitudinal dynamics and to estimate the power that is produced by the engine to overcome resistances and losses. The model also uses a gear shift pattern model to calculate the gear ratio and therefore the engine speed. The development of the model regarding the engine emission maps can be separated on two entities; the one regarding passenger cars and the other concerning heavy duty vehicles. Regarding heavy duty vehicles steady state engine maps derived by engine measurements are used and transient corrections are applied so as dynamic’s to be taken account. Concerning passenger cars, these
are tested over transient cycles and instantaneous emissions are allocated to engine power and speed. This approach takes account transient phenomena while a correction regarding how transient each point of the map was during the measurements is applied. PHEM is a vehicle simulator and is used for several purposes such as the EFs development.

Power-based models are able to enhance the gear shift pattern and the slope of the road, which are important factors concerning fuel consumption and emissions. Therefore these models are able to be used for the simulation of the majority of ITS systems ensuring a high level of accuracy. Especially for systems that affect parameters of vehicle’s operation like the engine start stop system, gear shift indicator tire pressure systems, and systems that provide advanced eco-driving advices, then these models are the only convenient. Moreover some of these models are able to provide detailed information regarding exhaust emissions correlating them to the driving pattern and therefore to facilitate the further analysis. An important element is related to their ability to be connected with traffic micro models and to handle multiple speed profiles.

Summarizing the previous description, in general systems that affect more macro scale characteristics of traffic can be assessed with more macroscopic approaches, while for systems that affect individual driving patterns, then more microscopic approaches can be used. So the findings of the previous review can be summarized in a schematic way on Figure 13.
Figure 13: Suitability of emission models to be used for ITS evaluation
2.4 ITS evaluation concerning their effect on energy consumption and emissions

Regarding ITS impact identification on energy consumption and emissions, through the combination of traffic simulation and emission models, few cases are met in literature and the majority of them is based on the examination of wider traffic management measures.

2.4.1 ITS modeling process

The effect of traffic signals control and synchronization, a traffic strategy (supported in many cases by ITS) acting in the whole traffic flow has been examined by Rahka et al. [51] with the use of an instantaneous speed-based emission approach, the methodology of which is described in [52]. The paper does not concentrate on the results of the simulation but on the importance of the integrated process. The traffic signals synchronization is examined as a case study of the integrated simulation process. In a hypothetical path, with 3 traffic signals spaced at a distance of 0.35 km, the non-signal control is compared to a poor signal coordination, to an off-line coordination and to an adaptive optimization of the signals offset. The simulation results showed that the effective signal control can lead to a reduction of 50% in fuel consumption and emissions. The limitations of the case study are related to the examination of a limited network with through-traffic in one direction. The examination of a wider network would lead to a limited benefit. Nevertheless the proposed modeling process is not only important for the evaluation of the different strategies, but also for their optimization. The synchronization of traffic lights also has been examined by Coensel et al. [53] where the traffic micro-simulation VISSIM is combined with the emission model Versit\textsubscript{micro}. The implementation of the green wave is simulated in a path with a speed limit of 50 km/h and with travel signals placed every 0.2 km. Scenarios regarding the implementation of the green wave and desynchronization cases were compared. The results showed a reduction of emissions in the range of 10-40% for the synchronization scenario. In Lv and Zhang [54], VISSIM was combined with MOVES to evaluate traffic lights synchronization. They compare different scenarios adjusting the cycle phase and the offsets and investigate, through a statistical analysis, the parameters of traffic signals synchronization that
can affect more emissions. The synchronization quality is determined by the platoon ratio (defined as the ratio of the traffic flow rate during green to the average flow rate in the entire cycle [54]).

The traffic micro-simulation model PARAMICS has been combined with Versit+ to estimate the potential impact of speed limit reduction and traffic signal coordination in an area of Antwerp, in Belgium [55]. The effect of different strategies regarding signal timing has been evaluated by [56] where the outputs of VISSIM has been used for calculation of the VSP (Vehicle Specific Power) which is an indicator of the power demand by the engine. Concerning emission calculations, VSP has been translated to the relevant emission rates. The performance of speed control traffic signals has been evaluated by [57] with the use of a modal emission approach developed by [58] and corrected with EMEP/CORINAIR methodology so as EFs of the modes to be applicable for the Portuguese fleet.

Concerning the assessment of more vehicle-specific systems, Panis et al. [12], has developed an instantaneous speed-based emission model and combined it with the DRACULA traffic micro-simulation model in order to assess the impact of the ISA system. The emission model that has been developed calculates emissions as a function of instantaneous speed and acceleration and has been constructed using a sample of instantaneous emission measurements. EFs / functions are estimated with the use of regression over the sample of measurements. Despite the fact that the dataset of emissions that have been used was poor and representative only for specific vehicle classes, the ITS modeling and impact assessment approach is remarkable because of the ISA traffic modeling and because of the environmental assessment with the use of analytic vehicle speed profiles to emissions calculation compared to the average speed approach, which is used widely in transport-related evaluation studies.

As it has been mentioned above, also important is the contribution of emission model in the development of intelligent systems that are oriented to reduce fuel consumption and emissions. Emission models are used for the development and the optimization of ITS and especially for the systems that are related with the provision of routing information and the indication of eco-driving advices. These systems have been developed by [59] and [60].
3  Case study

3.1  Traffic signals and their effect on energy consumption and emissions of road transport

Traffic signals consist an important factor of energy consumption and emissions increase. Traffic signals cause delays at an intersection and at a link level and affect the performance of traffic flow. The operation of traffic lights at a signalized intersection can be described by the following parameters [53]:

- The cycle time is defined as the sum of the durations of all distinct phases of a signalized intersection
- The Phase is a particular state of traffic signals
- The green split for the i approach of an intersection is defined as the ratio of green time and the cycle time

At intersections level, traffic lights increase delays resulting at an increase in fuel consumption and emissions. Delays may reflect the effect of stop and go traffic, depict a parameter that can be quite easily quantified and therefore can consist an important indicator of fuel consumption and emissions increase. The minimization of delays is an indicator of successful traffic lights operation and therefore of fuel consumption and emissions reduction. In traffic engineering, delay is described by delay events [61].

“A control-delay is the difference in time taken by a vehicle to reach cruising speed at a distance downstream of an intersection (after slowing down and stopping at the intersection) and time taken had the vehicle maintained its cruising speed through the intersection. The time-in-delay is the time from when a vehicle starts to slow down until it reaches cruise speed again (is always greater than control-delay) and the stopped-delay is the time spent by vehicles in idling mode. The control-delay is the average of a time-in-delay and a stopped-delay [61]”.

-39-
The analysis made before shows that the delay as an indicator is able to capture the effect on fuel consumption and emissions since it incorporates all the different modes that are met at a signalized intersection and are responsible for fuel consumption and emissions increase, such as decelerations, idling and acceleration. Moreover it provides a rate of comparison with cruising events where intersections do not caused delays and cruising speeds can be observed. This linear relationship between total delay and fuel consumption and emissions has been proved by Guo and Zhang [62] and the formation of relationships between emissions and delays is an important task of traffic signals optimization in terms of emissions reduction. A constraint is observed in cases where the minimization of delay is implemented at an arterial level and delays could occur for reverse flow or for pedestrians [53].

When the interest is focused on a sequence of intersections and on the coordination of traffic lights, then the main parameters that affect the synchronization are the cycle time, the stage split and the offset. The offset is defined as the difference in time between the start of a cycle at an intersection and the start of a cycle at a reference intersection [53].

This time shift is capable to achieve the synchronization of traffic lights and the generation of green waves. Green waves can improve traffic flow, through its homogenization [15]. Therefore the synchronization affects traffic variables, such as the accelerations and the idling time, which are decisive parameters of fuel consumption and emissions increase. Traffic flow becomes smoother, with lower driving dynamics and more constant speeds. The green waves’ effect is depicted on the macroscale character-
istics of traffic flow (average speed increase, delays reduction, increase of capacity), while it is clearly revealed on the affected individual driving patterns. The latter underlines the importance of the microscale models use (traffic and emission) for the evaluation of these cases. The appropriate combination of them consist an accurate way of optimization and evaluation.

The operation and synchronization of traffic lights can be fixed or adaptive. There are systems of fixed time (Fixed time control), in which the time of each phase has been determined in advanced, based on the default settings and does not depend on the current traffic situation. Also there are systems that their operation is adaptive (Adaptive control). Through roadside units and detectors (e.g. CCTV cameras), the signalized plan is altered dynamically according to real time traffic condition. Therefore the detection of queues is a factor of the signalized plan adjustment. The plan can be adjusted at short time intervals. The establishment of green waves, either with the coordination of fixed plan signals, or with the installation of advanced Urban Traffic Control (UTC) systems, act on the whole traffic flow and contribute to its homogenization.

The effect of fuel consumption and emissions depends on the quality of the coordination, the parameters of traffic lights operation and coordination (cycle length, phases, offset) and the specific characteristics of the road network. The effective coordination is able to increase the capacity of the road network [53]. An increase in cycle length can increase delays and thus emissions such as CO, HC and NOx [54] due to the increase in waiting time. Also an important factor and indicator of the coordination quality is the platoon ratio, which is defined as the ratio of the flow rate during the green time and the flow rate during a cycle (Highway Capacity Manual). The late platoon arrival at the next intersection will decrease emissions while the early platoon will increase them. This depends on the acceleration and deceleration (followed by acceleration) events, where the early platoon can increase them even if the number of stops remains the same [54]. According to Coensel et al. [53] the greater positive effect of green wave on emissions is achieved for traffic flows close to capacity. Rakha et al. [51] has proved that the dynamic adaptation of offset can bring about a reduction up to 50% in fuel consumption.

The evolution in Information and Communication Technologies (ICT) allowed the stronger connection of vehicle’s with traffic signals and the development of systems that are more vehicle-oriented. This evolution enables the transmission of real time
SPaT information to vehicles. The information can vary from time to green or time to red information, to detailed speed profile indications. The information affects the individual driving pattern, while is able to influence the whole traffic flow. The rate of influence is related to the kind of information provided, to the system’s penetration, to the specific characteristics of the road network and to the driver’s behavior. The case study examined and the system which is evaluated in the present study aims at identifying the influence of a C-ITS able to provide a detailed speed profile optimized in terms of fuel consumption and emissions.

3.2 Energy Efficient Intersection - Overview

Energy Efficient Intersection (EEI) is a Cooperative ITS system, which is able to reduce energy consumption and emissions of a vehicle at a signalized intersection through the provision of speed advices to the drivers, in order to reduce stop and go traffic. The system detects a vehicle that approaches a signalized intersection and taking into account the current phase and the duration of the signal, as well as the current position and speed of the vehicle, provides speed information to the driver, which is optimized in terms of reducing energy consumption and emissions. The system is able to provide Signal Phase and Timing (SPaT) information to drivers, linking with this way the vehicle with the infrastructure (V2I). The driver, following the speed advice provided, is able to pass the intersection without stopping. The efficiency of the system for a discrete vehicle is related to the reduction of stopped time (idling mode) and to the reduction of accelerations (less inertia force). The difference of the system compared to the establishment of green waves and the dynamic adjustment of traffic lights is that the first acts on the traffic flow as a whole, while the latter affects vehicles that accept a speed advice. An important task beyond the scope of the present thesis, is to investigate the potential differences and synergies among these two cases and a further step is the examination of the C-ITS potential to establish green waves. The system that is evaluated in the context of the present thesis is an application developed by CERTH/HIT within the European project Compass4D.

In literature, a limited number of cases is observed regarding the state of art in the development of such systems while even fewer are the cases where an integrated network performance evaluation is performed. Moreover a lack of real demonstration of
the system is observed revealing the immaturity of the system. Therefore an integrated analysis of the systems should be extended to the followings tasks:

- The identification of the most efficient speed profile for all the cases (traffic signal phases) that a vehicle encounters at an intersection
- The comparison of scenarios with speed advice provision and with base cases where the service is not provided
- The identification of the network performance through the examination of different scenarios concerning the network characteristics, the distance that speed advice is provided, the penetration rate of the system and the sensitivity of the system to traffic lights settings

The first part of the following analysis presents the main logics that are met in the literature and the findings regarding some of the tasks described above and mainly focuses on the description of the logic that is examined and adopted in the framework of the present study, while the second tries to answer to some of the tasks presented above.

### 3.2.1 Literature review of Energy Efficient intersection

Rakha et al. [46] proposes a methodology regarding the provision of speed advice, when SPaT information is available. Examining a vehicle approaching an intersection the study distinguishes five cases. The first three are related to the case where the traffic light is green. For the first case, where adequate time to red is observed, vehicle is able to pass with its current speed without any adjustment. In the second case where the time to red is limited vehicle has to accelerate within the legal speed limits in order to pass. In the third, there is not enough time and therefore vehicle cannot pass. The fourth and the fifth cases occur when the traffic light is red. Then, if time to green is small, then vehicle with its current speed could pass through the intersection without stopping. If time to green is enough, then it should slow down to specific speed. The latter case is examined extensively by Rakha, since it accumulates the primary interest but also the greatest difficulty. Therefore it proposes a deceleration speed profile that covers two extreme circumstances. The first is related to the provision of a constant deceleration rate until the intersection and the second is related to the provision of a constant but sharper acceleration profile that is followed by constant speed. Between these two profiles infinity of cases can occur depending on the time percentage of each mode (con-
stant speed mode and deceleration mode). The study concludes that the most efficient deceleration case occurs when an intense deceleration is followed by a long period of cruising. This conclusion is derived through an analysis of seven speed profiles that cover a range between the two extreme cases described before. Upstream the intersection the speed profile with the lowest deceleration rate is the most efficient in terms of energy consumption while taking account downstream conditions (the need for acceleration to a high velocity); fuel consumption is minimized for the profile with the more intense deceleration rate. The acceleration profile that is proposed downstream is produced through an analysis of longitudinal forces of typical vehicles. The analysis of Rakha focuses on a single vehicle, at a single intersection and consists an analysis concerning the identification of the optimum speed profile.

Schuricht et al. [63], examines all the possible cases that a vehicle may encounter approaching the intersection and proposes speed profiles for each case. Regarding the case that vehicle reaches an intersection at red phase and has to pass without stopping, they conclude to speed profiles similar to those proposed by Rakha et al. (deceleration and constant speed). Moreover they propose speed profiles for the cases where a vehicle cannot pass through the intersection, enhancing the possibilities for engine or mechanical braking and coasting in the deceleration profiles. The maximum effect, compared to an non-assisted scenario, is observed when the driver is assisted to decelerate and keep a constant speed in order to pass through the intersection a fact which is also has ben underlined by Rakha et al. This effect has been calculated to be a reduction up to 36,3% on fuel consumption. The assistance in case of the provision of a deceleration advice when it is not feasible to pass through the intersection has been calculated in the range to be approximately (4,6%) while the overall average effect has been calculated to be 8,7%. Schuricht et al. recognizing that a realistic representation should take also into consideration the length of queues in order to ensure the uninterrupted intersection crossing. Therefore they impose a time delay to speed calculations. Their analysis is performed at an individual vehicle level.

The logic that is met in Mandava et al. [64] is similar to those previously presented; while it takes account the parameter of the ability of the vehicle to follow an intended acceleration. This is ensured creating an optimization problem where the objective function aims at the acceleration minimization and one of the constraints entered is that the tractive power should not to exceed the maximum value allowed by the engine power.
Stochastic simulations over a hypothetical network of 10 signalized intersections showed a potential reduction of energy consumption and emissions in the range of 12-14%.

Vreeswijk et al. [65] examined only the case where vehicles during the red phase accept a constant deceleration speed advice of 0.45 m/s² in order to reduce idling time. They evaluated the system through the combination of VISSIM with Enviver and they found that CO₂ emissions can be reduced by 4-5%.

The logic of the Energy Efficient Intersection system, which has been used by CERTH/HIT as a basis for the development and the simulation of the EEI is based on the work of Barth et al. [66] and Xia et al. [67]. More specifically, the logic that Barth et al. and Xia et al. presented, considers that the minimum energy consumption for a vehicle approaching an intersection is achieved when it cruises with a speed closely to the speed limit and when it crosses the intersection without stopping. So taking into consideration the phase of the signal and the respective times to red or to green and with given the distance to the intersection, the range of targeted cruising speeds is calculated. Within the range of speeds, the higher possible is considered as target speed. Keeping this speed steady, vehicle is able to pass through the intersection without stopping at the traffic light. When the vehicle has lower speed than the target value, it has to accelerate and reach this target speed. Barth et al. propose a realistic acceleration profile that is able to be followed by conventional vehicles. Therefore the predetermined trigonometric speed profile used is described by the set of equations below:

\[
v(t) = \begin{cases} 
  v_h - v_d \cos(st) & \text{for } t = 0 \text{ to } \pi/2s \\
  v_h - v_d \* \frac{s}{a} \cos(t - \frac{\pi}{2s} + \frac{\pi}{2a}) & \text{for } t = \pi/2s \text{ to } (\pi/2a + \pi/2s) \\
  v_h + v_d \* \frac{s}{a} & \text{for } t = (\pi/2a + \pi/2s) \text{ to } d/v_h 
\end{cases}
\]

(4)

Where \(v_h\) is the higher limit of the targeted speed and \(v_d\) is the difference between the current velocity of the vehicle and the higher limit of the velocity range. The profile contains \(s\) and \(a\), which are parameters that adjust the speed profile. The \(s\) parameter determines the intense of acceleration while a parameter ensures that the vehicle following the profile is able to reach at the intersection the desired time-stamp. The identification of the \(s\) parameter aims at the minimization of the total power demand of the engine. Therefore \(s\) can take several values in the range \([\pi/T, 2.5\pi/T]\), which form the speed profile from smooth to more aggressive.
The logic adopts constraints which are described through a driving pleasure function and through the need the vehicle to reach the target point at a specific time. The latter is described by Figure 15 where the area (means traveled distance in a velocity–time diagram) A should be equal to the sum of B1 and B2 areas in order to reach the next intersection in the same shortest time.

![Figure 15: Acceleration profile for reaching a specific location at a specific time](image)

As higher the s parameter, the sharper the acceleration and the region A is decreased. Moreover the higher the value of s, the total energy demand of the trajectory, derived from the tractive power equation seems to be minimized. A similar deceleration pattern is followed and in the cases where the current vehicle speed is higher than the target speed and there need to slow down to the target speed arises. The trigonometric speed profile which is adopted is indicated by the equations below:

\[
v = \begin{cases} 
v_h - v_d \cos(st) & \text{t = 0 to } \pi/2s \\
v_h + v_d + \frac{s}{a} \cos(t - \frac{\pi}{2s} + \frac{\pi}{2a}) & \text{t = } \pi/2s \text{ to } (\pi/2a + \pi/2s) \\
v_h - v_d - \frac{s}{a} & \text{t = } (\pi/2a + \pi/2s) \text{ to } d/vh 
\end{cases}
\]  

(5)

The identification of the s parameter is essential for the effectiveness of the system since it determines the deceleration profile and therefore the target velocity that should be adopted. If the s parameter is high, then the deceleration is harder and the vehicle will have a higher steady speed approaching the intersection. This is translated to the need for a lower acceleration downstream of the intersection. In contrast, a lower value of s will result to a smoother deceleration and the need for a higher acceleration downstream the intersection occurs. These two scenarios consist the two extreme cases.
Within these two, an infinity number of other cases can exist depending on the value of \( s \). The deceleration profile adopted is presented on Figure 16.

![Figure 16: Deceleration profile for reaching a specific location at a specific time [67]](image)

The adoption of a specific speed profile, in case of deceleration, seems to be more complex compared to the acceleration case, because the effectiveness of the choice depends both on the traffic conditions upstream and downstream the intersection. This is strongly related to the fact that modern vehicles use the fuel cut-off system, when they are at deceleration mode. The low deceleration scenario, in some cases, could be more efficient in terms of fuel consumption gains, since vehicles don’t consume fuel during this mode (provided that the engine speed is high enough and fuel is not injected in order to keep the engine in operation). On the other hand, the scenario with the hard deceleration and the constant speed could have higher total fuel consumption, if the need for acceleration after the intersection is not high enough to compensate the need for maintaining constant speed. In each case, the total energy demand, taking account the downstream effect, determines, which is the optimum speed profile in terms of energy consumption minimization. Barth et al. [66] have adopted the “hard deceleration” scenario in their algorithm through a parameterized analysis indicating that this scenario is more effective in cases where vehicles have to accelerate downstream up to the speed limit (e.g. 50 km/h). The same effect was indicated by Rakha & Kamalanathsarma [46], indicating that the fuel consumed downstream for the smooth deceleration scenario is sufficient enough to compensate the upstream gain. Therefore the selection of \( s \) in the predefined speed profile is essential for the system's effectiveness. The deceleration
profile is given by the set of equations below where the variables and the parameters are the same with those described in the acceleration case.

The test of these logics at a traffic level and the identification of their environmental impact is limited. Barth et al. [66] have developed the algorithm described before and evaluated at an individual vehicle level with the use of CMEM emission model. Simulations showed that for the vehicles that get the speed advice, fuel consumption and CO2 emissions can be decreased by 12%. Moreover, the algorithm was evaluated in an extended road network by Xia et al. [67], combining PARAMICS traffic microsimulator with CMEM emission model. Through the integrated simulation the influence of the system on the whole traffic was tried to be identified. Different demand level and penetration rate scenarios were examined. For the one-lane network, higher total traffic savings were observed for low demand levels and for higher penetration rates. The highest decrease in fuel consumption was approximately 13% and was observed for a traffic demand of 100 vehicles/hour/link and a 100% penetration rate. For the modeled multiple-lane network, results in the range of 1-10% reduction were observed. Moreover through the multiple-lane network simulation, it was examined the sensitivity of the system’s impact, due to traffic signals’ settings, such as the cycle length and the duration of the green phase. The increase of cycle length is observed to limit the positive effects.

R.T v. Katwijk [68] has developed and evaluated a speed adaptive system similar to the one presented below, but with the extension of the dynamic adaptation of traffic signals according to the information they receive by vehicles. The system calculates three alternatives. The first is the conservation of constant speed which is followed by a deceleration closely to the intersection, the second is a smooth deceleration far from the intersection and the main constant speed towards the intersection and the third a sharp deceleration which is followed by constant speed. For each alternative CO2 emissions are calculated and therefore the optimum is chosen. The system has developed and evaluated with the use of VISSIM and EnviVer. The paper is the first that examines the combination of the system with the dynamic adjustment of traffic lights. The overall effect of the system was calculated to be a reduction of 19% on CO2 emissions.

Table 5 summarizes the findings of the previous review regarding the logic and the analysis that is met in literature.
Table 5: Summary of literature review regarding EEI

<table>
<thead>
<tr>
<th>Paper</th>
<th>Description</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rakha et al. [46].</td>
<td>Identification of the optimum deceleration speed profile</td>
<td>Single vehicle/ Single intersection</td>
</tr>
<tr>
<td>Schuricht et al [63].</td>
<td>Identification of the optimum speed profile for several cases/ Consideration of queues' length</td>
<td>Single vehicle/ Single intersection/</td>
</tr>
<tr>
<td>Mandava et al. [64]</td>
<td>Speed profile formation/ Vehicle dynamics consideration</td>
<td>Single vehicle/ Sequence of intersections</td>
</tr>
<tr>
<td>Barth et al. [66]</td>
<td>Identification of the optimum/ acceleration-deceleration speed profile</td>
<td>Single vehicle/ Single intersection/ Sequence of intersections</td>
</tr>
<tr>
<td>Xia et al. [67]</td>
<td>Implementation of the profile proposed by [47]</td>
<td>Network performance evaluation</td>
</tr>
<tr>
<td>Vreeswijk et al [65]</td>
<td>Deceleration rate provision</td>
<td>Network performance evaluation</td>
</tr>
</tbody>
</table>

The findings of the review presented above can be summarized on the followings:

- Most studies conclude that the phase where the traffic lights is red concentrates the highest interest compared to the others
- The speed profile for this case proposed by the majority of the studies is that of sharp deceleration and the conservation of constant, as higher as possible, speed towards the intersection
- The acceleration mode downstream the intersection is the most deterministic factor regarding energy consumption and CO$_2$ emissions
- The provision of deceleration advices in cases where it is not feasible to pass through the intersection is an important task and should be compared with cases where advice is provided at the end of the green phase and when vehicles have to pass at the next green phase
- The indication for conservation of constant speed is able to prevent unnecessary acceleration events
- Most cases use predefined speed profiles and an important issue that should be identified is the engine braking deceleration rate, brakes deceleration rate and coasting rate.
• The gear shift pattern is examined only by [63] but it is not analyzed
• Regarding the impose of acceleration advices, these should be examined if they can be followed by vehicles and this to be included in the calculation process as it is examined by [46] and [64]
• The analysis in the majority of cases is performed at a single intersection and the network performance evaluation is limited
• The length of queues has been taken account by [46] and by [63]
• In the majority of cases the evaluation is performed with instantaneous speed-based emission models, while only [66] and [67] use an instantaneous power-based model which can better reveal the effectiveness of each strategy.

3.2.2 Case study – Contribution

The logic of the algorithm as described above has adopted, extended and modeled by CERTH/HIT. The first task that is examined in the framework of the present thesis is the logic of the system as it has been adopted in order to identify which is the optimum combination of parameters that can be applied and how the algorithm can be used according to the needs of each case. When a vehicle approaches at a signalized intersection then a number of cases can occur:

• The signal is green and vehicle with its current speed is able to pass through the intersection without any speed adjustment
• The signal is green but with the current speed it has to accelerate in order to pass without stopping
• The signal is green but the vehicle because it is not feasible to pass, has to decelerate and keep a constant speed in order to pass without stopping at the next green phase or to smoothly decelerate in order to avoid unnecessary accelerations and steady speeds, while in parallel to reduce idling time
• The signal is red but the vehicle with its current speed is able to pass through the intersection
• The signal is red but the vehicle has to decelerate and keep a steady speed in order to pass through the intersection without stopping
Therefore, the SPaT and the vehicle’s current speed are the deterministic parameters for the selection of the optimum strategy. Since the scope of the system is to reduce energy consumption at a signalized intersection, then the logic that is adopted, should have as a primary scope the minimization of the total energy consumed upstream and downstream of an intersection. Literature concludes that the most convenient profile for the deceleration case, which is the most interest as described before, is that of deceleration that is followed by constant speed. The next example tries to identify that and compare it with a more constant deceleration profile.

Assuming the hypothetical example of an intersection in which a vehicle is approaching at a velocity of 50 km/h and the distance to the intersection is 200 m. The traffic light is red and the remaining time to green is 20 seconds. Implementing the speed profile proposed by Barth et al. [66], this can be formed applying different values to the s parameter. Therefore taking different values in the range of $[\pi/T, 2.5\pi/T]$, with a step of $0.5\pi/T$, where $T$ is the remaining time to green, four different speed profiles are formed and four cases are distinguished. The possible range of speed profiles implementing the algorithm for different $s$ values is presented in Figure 17.

![Figure 17: Possible upstream speed profiles for different values of the $s$ parameter (four cases)](image)

As it is depicted in Figure 17, as higher is the $s$ parameter, the harder the deceleration of the vehicle and the greater the period during in which it contains steady speed. Decreasing the parameter of $s$, the time the vehicle accelerates more smoothly is increased. Moreover the graph shows that in the case where a greater $s$ is applied, then the
velocity of the vehicle when it reaches at the intersection is greater compared to other cases. Applying the instantaneous speed-based emission model Enviver [69] on the speed profiles described before, CO$_2$ emissions upstream the intersection for the four cases described before are provided in Figure 18.

![Figure 18: CO$_2$ Emissions in grams regarding the four cases](image)

The figure shows that upstream the intersection, applying a lower $s$ value (4th case) as it is expected leads to lower total CO$_2$ emissions, due to the fact that during deceleration fuel cut off system in modern vehicles is activated. On the other hand taking account the need for acceleration downstream the intersection applying a typical acceleration profile till the speed of approximately 50 km/h the formulated speed profiles are presented in
Figure 19: Possible downstream speed profiles for different values of the $s$ parameter (four cases).

As it is shown in Figure 20, applying the emissions calculation for the total speed profile (upstream and downstream), the one with the lowest $s$ value (4th case) presents finally a dramatic increase in CO$_2$ emissions compared to the others. On the other hand the speed profile with a sharper deceleration rate (1st case) seems to be eventually the most effective. Therefore the effectiveness of this profile is related to the fact that vehicles have to accelerate from a higher speed compared to the other cases and this underlines the importance of the downstream traffic conditions.
Figure 20: Upstream CO\textsubscript{2} emissions and total CO\textsubscript{2} emissions for the four cases examined

The simulation at a traffic network level increases the complexity of the system due to the influence of parameters such as the network’s characteristics, the settings of traffic signals and the interaction with the other vehicles of the network. The example before indicated that the logic should be adjustable according to the traffic conditions and the needs that occur. If the need for downstream acceleration is not intense, then a more smooth deceleration profile could be adopted. It has to be mentioned that with these considerations important vehicle parameters such as the gear ratio are partially taken account, since the speed profile is predefined and it is assumed that a typical vehicle is able to follow it.

3.3 Traffic modeling of Energy Efficient Intersection

For the traffic modeling part, AIMSUN micro-simulator is used. These types of traffic models are able to simulate the movement of vehicles within a network that has been pre-identified. The logic of the simulation is based on three sub models, which are the car following model (modified Gipps model), the lane changing model and the gap acceptance model.
The model updates vehicles’ position for every temporal step, dictating the longitudinal and the lateral drivers’ behavior. Microscopic models are able to simulate vehicle dynamics in a detailed level [10] and provide, as an output, the instantaneous speed, acceleration and position of all vehicles within the simulation timestamp. The derived traffic flow data can have a resolution up to 10 Hz.

The logic of EEI, as described in the previous section, is integrated to the AIMSUN traffic micro-simulation model as an external C-ITS test bed. With the C-ITS test bed, in which there are included the simulation algorithm and the constraints described in the previous section, the traffic model is able to simulate the effect of the system on the movement of individual vehicles. The external C-ITS test bed, communicates with the traffic micro-simulation model. It obtains information regarding the simulated traffic (signal state) and is able to intervene on the traffic model’s mathematical background and “enforce” its logic to the vehicles’ movement (speed advice provision). As a result, the vehicle’s speed profile is modified according to the one indicated by the external test bed algorithm. This effect is depicted on the simulated vehicles’ speed profiles.

The traffic simulation is performed by CERTH/HIT. Therefore the present study uses data derived by CERTH/HIT’s simulation and evaluates and analyzes the effect of the system on fuel consumption and CO₂ emissions. Figure 21 depicts in a flowchart the logic of EEI, as it has been adopted by CERTH/HIT. According to the flowchart, when vehicles are in a car following mode, then speed advice is not provided. Moreover a minimum speed threshold of 20km/h has been set, since it is not realistic to develop a system that provides cruising indications at very low speeds. In addition a time delay is applied to the desired speed calculation so as to prevent drivers to reach the intersection just in the time where the red phase changes to green, since in reality drivers could be cautious facing a red light till the last moment.
3.4 Emission modeling

The environmental impact of the system is identified with the use of EnViVer emission model. EnViVer is an emission model based on Versit+micro, which is a statistical emission model developed by TNO. Versit+micro is a special edition of Versit+ that has been developed in order to be feasible the communication with traffic microsimulation models. In the previous version of Versit+ [42] the lack of second by second measurements created limitations regarding the development of a model that can take account in their calculations driving dynamics in accuracy. So, for that purpose a statistical methodology was developed. More specifically the development of EFs was based on a database of many chassis dynamometer vehicle bag measurements performed over several driving cycles. In each of these measurements, the total mass of exhaust emissions is gathered and analysed. Therefore a total emission rate (bag measurements) for
each pollutant occurs, characterizing the whole driving cycle and the tested vehicle. These driving cycles are analysed in their kinematic parameters (average speed, standard deviation of speed, relative positive accelerations, number and duration of stops etc standard, etc.). Emission data are clustered according to the pollutant and the vehicle category and average values occur. Emission functions are developed with the use of linear regression. The linear regression models needs the specification of input parameters, which will be used as independent variables in the emission function. This is achieved by applying a statistical selection in order to determine which kinematic parameters could be the best predictors. Then these linear regression models are fitted to these average emission rates and with the use of maximum likelihood methods, the coefficients of regression are determined.

Regarding the use of the model and the required input data, these are summarized in Figure 22. When a speed profile (driving pattern/driving cycle) is entered, it is analyzed also in the parameters mentioned before. These parameters are used as input variables to the emission functions of the model that estimate hot running emission factors.

![Figure 22: The Versit+ structure [42]](image)

The increase in the availability of instantaneous emission measurements (PEMs or modal measurements) and the improvement of their quality led to a change in model’s philosophy and the evolvement to an instantaneous speed-based model where emissions
are estimated second by second as a function of speed and acceleration [69]. A challenge of the evolution was the transformation of the bag-measurements large database to second-by-second EFs. This physically was not possible because for each driving cycle only one aggregated bag emission value occurs. Therefore a statistical analysis was adopted. According to this analysis a dynamic variable \( w \) was introduced. This variable is given by the formula below:

\[
w = a + 0.014v
\]  

(6)

where \( a \) is the instantaneous acceleration (m/s\(^2\)) and \( v \) is the instantaneous speed (km/h). With the introduction of this variable it considered that emissions vary slowly over this line. Therefore each combination of instantaneous speed and acceleration provides a value for \( w \). The \( w \) parameter is used in combination of specific kinematic parameters so as to define the emission functions by which instantaneous emissions will occur. Therefore specific velocity ranges have been identified (\( v<5 \) km/h, \( 5<v<50 \) km/h, \( 50 \) km/h\(<v<80 \) km/h, \( 80<v \) km/h) and the relations that calculate emissions, where \( EM \) is the emission in g/s, are:

\[
\begin{align*}
v < 5, a < 0.5 : EM &= u_0 \\
v < 50 : EM &= u_1 + u_2w + u_3(w - 1) \\
50 < v < 80 : EM &= u_4 + u_5w + u_6(w - 1) \\
80 < v : EM &= u_7 + u_8(w - 0.5) + u_9(w - 1.5) 
\end{align*}
\]  

(7)

The \( u \) parameters of the above list of equations are coefficients derived by a statistical process of the emission measurements and are related to 10 kinematic parameters and there are defined by a statistical analysis similar to that described before regarding the previous version of the model. This transformation of the model allows it to use either bag or instantaneous measurements.

### 3.5 Integrated modeling process
The identification of the system’s effect on traffic energy consumption and emissions is performed through the combination of the appropriate models. This selection, regarding the evaluation of ITS, is related to the parameters influenced by the system [70] either at a traffic level or at emissions level. These parameters according to the Amitran methodology [18] are the followings:

- The influence of the system on traffic demand. If the system influences traffic demand then the traffic demand model should be modified.
- The influence of the system on route choice and mode choice. If the system affects these parameters then the traffic assignment model should be modified.
- The influence of the system on driving behaviour and driving pattern. If the system affects these parameters then a traffic micromodel should be used and modified.
- The effect of the system on fuel consumption and emissions. If the system affects the driving pattern, then emission models with sensitivity on instantaneous speed and acceleration should be used.

In the case of EEI, the modelling process that has been adopted is in line with the evaluation framework for ITS and C-ITS described above and through the emission modeling analysis that has been presented in a previous section. Concerning the parameters set by Amitran, EEI is a system that influences driving behaviour and driving pattern, while no short-term changes are expected on traffic demand and on route and mode choice.

A traffic micromodel is used in order to provide detailed second by second data for the movement of vehicles of the whole network. The logic of EEI is imposed by an external C-ITS Test bed, since traffic simulators do not have such a detailed intervention function. These two elements consist the traffic simulation part of the integrated process. In the traffic simulator, road network and road infrastructure (eg. traffic lights) are represented. The traffic model is calibrated with the use of real traffic data in order to be able to represent accurately real traffic conditions. The simulation of the system is performed through the external C-ITS test bed. The C-ITS test bed examines the parameters of the traffic simulation (vehicles’s position and speed, traffic signals phase and timing), calculates the routines and the subroutines that have been predefined and imposes the logic of EEI in the traffic simulator. Therefore trajectories and speed profiles for each vehicle within the simulation network are derived. These data are fed in the
emission model in the form of an .fzp file. The emission model is able to form the speed profile of each vehicle and calculate CO₂ and NOx emissions and PM₁₀, based on the statistical methodology described in the relevant section.

The integrated modelling process that was adopted is able to capture the system’s effect since the emission model takes account driving dynamics through the statistical second by second analysis of the driving pattern. Moreover the ability to estimate emissions for all vehicles within the simulation timestamp allows to evaluate the network’s performance.

Since Enviver is a traffic emission model and not a detailed vehicle simulator, this creates constraints regarding the analytical data post-processing, at the individual vehicle level. On the other hand, the fact that the model is able to provide emission estimation for the whole traffic based on second by second data is of great importance and it will be revealed at the examination and evaluation of the case study. After the estimation of the environmental effect, according to the results, modifications are made in the logic of the system, incorporated in the external C-ITS test bed. Moreover the integrated process reveals the weaknesses of the system and indicates the possible changes and optimizations. The integrated modelling process of the EEI system is depicted in a schematic in Figure 23.

![Figure 23: The integrated traffic and emission modeling process of EEI](image)

-60-
A possible future extension is related with the aggregation of the results at a network level through the combination of macro models. Moreover a dispersion model could be added in the integrated process. The latter demands the full representation of fleet composition and the induction of parameters related to the weather and atmospheric conditions. These two additions are beyond of the scope of the present study.

As part of the traffic modeling process, vehicles of the network have been partitioned into four types: Car, Taxi, Bus, and Truck. These vehicle types must be linked to the emission classes that are contained in EnViVer model which are Light-duty, Bus and Heavy-duty. For each class it should be determined the fuel type allocation (Petrol, Diesel, LPG, CNG, Electric) and the vehicle age distribution (% of vehicles newer than 1 year, average vehicle age, average exit age). The latter information is used by the model to automatically classify the vehicles according to the European emission legislation (Euro limits). Currently, the model does not allow the adjustment of the default typical vehicle classes. Therefore the emission classes that are contained in the model represent a typical vehicle fleet (the dutch fleet). Therefore it is not secure to extract conclusions regarding pollutants that are calculated by the model such as NO\textsubscript{X} and PM. Moreover despite the fact that the model calculates emissions based on second by second data, it provides a single aggregated emission value for every vehicle, and therefore this does not allow the detailed assignment of instantaneous emissions with the instantaneous speed. Since the mechanisms of NO\textsubscript{X} and PM\textsubscript{10} production is complex and depends mainly on the fuel type used, on the engine operation and on the after treatment performance, the extraction of safe conclusions regarding these pollutants is not safe. On the other hand, since CO\textsubscript{2} is strongly depends on the fuel consumed and is related to the power demand by the engine, the results could be considered as unbiased. It has to be mentioned that the reduction of CO\textsubscript{2} is examined and not the total amount of CO\textsubscript{2} emitted as an absolute value. The latter minimizes the constraints that arise due to the default vehicle classes.

In order to estimate to assess the validity of the emission model three driving cycles where used in order to test the emission values that the model estimates. Therefore the NEDC, the FTP-75 and the Artemis urban driving cycles were used. The derived emission factors, for a Light Duty vehicle of the model, are presented on the table below. The Light Duty vehicle class contains passenger cars (M1) and commercial vehicles with a mass of up to 3500 kg (N1 class 1 to 3) [Enviver manual].
Figure 24: EnviVer’s EFs over different driving cycles

<table>
<thead>
<tr>
<th>Emission factors</th>
<th>Driving cycle</th>
<th>EF</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>NEDC</td>
<td>195 g/km</td>
</tr>
<tr>
<td>NOx</td>
<td>NEDC</td>
<td>0.33 g/km</td>
</tr>
<tr>
<td>PM₁₀</td>
<td>NEDC</td>
<td>0.042 g/km</td>
</tr>
<tr>
<td>CO₂</td>
<td>FTP75</td>
<td>221.63 g/km</td>
</tr>
<tr>
<td>NOx</td>
<td>FTP75</td>
<td>0.36 g/km</td>
</tr>
<tr>
<td>PM₁₀</td>
<td>FTP75</td>
<td>0.043 g/km</td>
</tr>
<tr>
<td>CO₂</td>
<td>Artemis Urban</td>
<td>341.68 g/km</td>
</tr>
<tr>
<td>NOx</td>
<td>Artemis Urban</td>
<td>0.572 g/km</td>
</tr>
<tr>
<td>PM₁₀</td>
<td>Artemis Urban</td>
<td>0.058 g/km</td>
</tr>
</tbody>
</table>

Concerning the fact that the Light Duty vehicle of the model represents an average vehicle of the entire fleet, in which petrol and diesel vehicles of various technologies and engine capacities are weighted, EFs derived over the previously mentioned driving cycles are considered to slightly overestimate real conditions. This is enhanced by EFs derived by chassis dynamometer measurements, as those presented by Fontaras et al. [71], where for Euro 5 vehicles an average value of 160 g/km for petrol and 133 g/km for Diesel vehicles is reported. Moreover the reported values of new coming vehicles in Greece from 2000-2008 are lower compared to the values provided by the model. Anyway for the purposes of the present thesis and since they aim to represent an entire fleet, these values are judged satisfactory, a fact that is enhanced taking account that in the LD vehicle of the model there are contained vehicles belonging to M1 and N1. The increase in EFs over the more power demanding driving cycles (FTP and Artemis urban) confirms the model’s ability to capture driving cycles’ dynamics.
3.6 Case study evaluation - Effect on CO\textsubscript{2} emissions

As a first step of the application and evaluation at a traffic level, in order to understand the effectiveness of the algorithm, the simulation and the evaluation of the system is concentrated on the individual vehicle level. The aim of this part is to reveal the potential benefits that individual vehicles could have by the implementation of the system. Therefore for the road network of Tsimiski, which is a main arterial road with consecutive intersections, individual vehicles equipped with the system are simulated. Their movement is not obstructed by other vehicles and the only interruption is imposed by traffic signals. The results show that within a path of approximately 3 km, a reduction in CO\textsubscript{2} emissions in the range of -1.8\% to -9\% can be achieved. All the 13 vehicles face different phases of the signal timing, so the range of the reduction could be considered as representative for a typical urban network. Table 6 summarizes the results obtained by the emission model. The calculation scenario contained 13 vehicles and it is observed that all of them present a reduction in CO\textsubscript{2} emissions.

<table>
<thead>
<tr>
<th>Emissions</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO\textsubscript{2} emissions</td>
<td>-1.8% to -9%</td>
</tr>
<tr>
<td>NOx emissions</td>
<td>-3.73% to -11%</td>
</tr>
<tr>
<td>PM\textsubscript{10} emissions</td>
<td>-1.20% to +7%</td>
</tr>
</tbody>
</table>

Figure 25 shows a typical speed profile that can be observed for a vehicle crossing the Tsimiski street, while Figure 26 presents how the speed profile is adjusted with the implementation of EEI and the speed advise provision.
Figure 25: Typical speed profile at Tsimiski str. without the implementation of the system and instantaneous CO2 emissions

Figure 26: Adjusted speed profile due to the EEI implementation and instantaneous CO\textsubscript{2} emissions

From the speed profile provided for the base case, it is observed that the vehicle without speed advice provision has to stop at intersections, while the second speed profile represents how the speed advice is implemented and the vehicle is able to pass through the intersections without stopping. So the first conclusion that individual vehicles could have significant effects positive effects in the reduction of their CO\textsubscript{2} emissions and therefore in their fuel consumption. The more clear identification of the system’s effect demands the analytic, second by second mapping of CO\textsubscript{2} emissions over the speed profile. As it has been mentioned above, even though Enviver estimates emissions on a
second by second basis, it provides a total emission value (expressed in g or g/km) for each speed profile. Therefore the second by second analysis demands the use of another model. For this purpose the instantaneous model of Panis et al. [12] has been used. The analytic comparison of the speed profile with the instantaneous CO\(_2\) emissions are provided in Figure 25 and Figure 26 where it is clearly shown the extent to which accelerations are responsible for CO\(_2\) emissions increase.

Moreover a comparison of the two speed profiles in a common graph is depicted on Figure 27. There the comparison of the base case speed profile and the speed profile with the system plotted over the cumulative CO\(_2\) emissions for each case, clearly reveals the reasons that can consist the system effective and also the constraints that arise and are able to turn the system ineffective.

![Figure 27: Comparison of speed profiles and presentation of their cumulative CO\(_2\) emissions](image)

During the deceleration mode the base case scenario seems to be less energy demanding and therefore less CO\(_2\) is emitted, since within the scenario with the system, a steady speed is imposed and therefore energy is consumed. On the other hand taking account the acceleration mode downstream, then the effectiveness of the system is observed. Here it has to be mentioned that when the scope is to pass through the intersection, then according to the logic adopted, vehicles have to travel at very low speeds. This may be feasible only for urban environments and under conditions, while for other traffic environments this is prohibitive.
The speed profiles chosen to be analyzed also reveal another important fact. The speed provision on a sequence of intersections and especially when the distance between them is short (common characteristic in urban environments), then vehicles accelerate downstream the intersection to a lower speed compared to the base case, as well immediately have to decelerate to a constant speed that will allow them to pass through the next intersection without stopping. This presents gains compared to the base case where vehicles accelerate to a higher speed and afterwards decelerate and stop at the intersection, but it arises another task that should be examined. This is related to the consideration in the calculations of the phase of the next signal or the provision of the advice for the next intersection just the time the vehicle passes through the previous one. This extension would lead us to a constant speed profile for the EEI scenario and the unnecessary acceleration could be avoided, leading to greater gains.

Another important issue that arises is related to the cases where speed advice should not be provided or the advice that should be provided is only related to a smooth deceleration rate. This can be implemented only for cases where it is impossible for vehicles to pass through the intersection (approaching the intersection the time the signal turns to red). This case was able to be identified because of the use of the traffic simulator. Therefore a typical speed profile of the AIMSUN traffic model was used. This profile represents the base case where vehicles facing the red light decelerate sharply and stop. In addition a second profile representing the case where a deceleration advice is provided is compared with the base case. The latter deceleration profile has been derived by Barth et al. [66]. Figures below show these two profiles in a distance-time graph for an intersection. The case examined has a long idling period.

![Figure 28: Two upstream cases in a space-time graph](image)
So comparing these profiles, by calculating CO₂ emissions, the results show that applying a deceleration speed profile CO₂ emissions can be reduced by 15% compared to the base case.

![Figure 29: CO₂ emissions for both cases](image)

Here it has to be mentioned that this example does not distinguishes the coasting scenario where the engine is discoupled from the transmission and fuel is injected so as to keep engine in operation and the braking scenarios (engine braking or friction brakes) where fuel cut-off system is activated. This happens because the speed profile is predefined. But it is a fact that for the coasting scenario for a typical vehicle has as a result a lower deceleration rate compared to the one implied by the deceleration profile. Therefore in order to identify the rate to which the deceleration profile used in the algorithm is related to braking, the coasting scenario for a typical vehicle was calculated. The mass of a typical vehicle has been assumed to be in the range of 1300 kg - 1500 kg including the mass of the rotating parts, the rolling friction coefficient 0.015, and the product of the frontal area with the aerodynamic drag coefficient to be equal to 0.7 m². The coasting deceleration rate was formed through arithmetic solution of the differential equation of longitudinal dynamics. The analysis showed that the predefined deceleration speed profile implies a deceleration rate higher that the coasting verifying that it is possible to be followed by vehicles. Moreover in a future extension the coasting decelera-
tion rate could be used as a constraint regarding the deceleration rate imposed. Nevertheless the example shows that in cases where the vehicles cannot pass through the intersection, then deceleration advices could be provided increasing the potential benefits.

At this point, it has to be underlined that the distance a vehicle covers being in a coasting mode is greater than the distance covered by the braking mode, because the only forces that act on the vehicle are those of friction and of aerodynamic drag. Vehicles decelerate with a lower rate when they are at a coasting mode, while a higher deceleration rate is met during the engine braking (depending on the gear ration) and the friction braking. Thus the identification of the most efficient scenario compared to these three does not only related to the fuel consumed during this mode but also to the conditions before the deceleration. For example if an advice for engine braking is given then it should be taken account that the vehicle will cover the longest distance, the engine braking a shorter distance and the friction braking the shortest. Given the traffic signals’ timing, and the vehicle’s speed and distance, then a combination of scenarios enabling these modes could be applied. This case also underlines the need for the development of a system that is adaptable and capable to handle each situation in a different and energy optimized way.

The next section evaluates the performance of the system when it is applied at traffic level. Therefore interventions with other vehicle as taken account and the effect of the system on the performance of traffic flow is captured, analyzed and assessed.

3.7 Traffic analysis

Primary, in order to capture the precise operation of the system, the traffic simulation has been performed for a small road network, with one signalized intersection. The main arterial road is composed by two lanes, and vehicles have the ability to continue at the main arterial or to turn left or right to the cross flow arteria. Traffic demands’ generation is performed only for the main arterial and several demand scenarios are examined. Moreover the speed advice is given in advanced for various distances before the intersection. In addition, several penetration scenarios are considered. A parametric analysis is performed adjusting the traffic demand, the traffic lights settings and the speed advice provision distances. The cycle is consisted by two signalized phases. Ta-
Table 7: Scenarios that have been examined presents the different scenarios that have been adopted.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic Demand</td>
<td>900, 1200 Veh/h</td>
</tr>
<tr>
<td>Penetration Rate</td>
<td>100%, 80%, 60%, 40%, 20%</td>
</tr>
<tr>
<td>Distance of speed advice provision</td>
<td>800 m, 600 m, 400 m, 200 m</td>
</tr>
</tbody>
</table>

For fixed traffic signal phases the scenarios that occur are 2X5X4. Then adjustments in the operation of traffic lights are added. Therefore the table 5 is modified and this is depicted in Table 8.

Table 8: Scenarios with the adjusted green split

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand</td>
<td>900, 1200, 1500 Veh/h</td>
</tr>
<tr>
<td>Penetration Rate</td>
<td>100%, 80%, 60%, 40%, 20%</td>
</tr>
<tr>
<td>Distance of speed advice provision</td>
<td>600 m</td>
</tr>
<tr>
<td>Traffic signals</td>
<td>46%, 54%, 62.5%, 72% Green split</td>
</tr>
</tbody>
</table>

Moreover in order to identify in which traffic environments the system could be applied, several speed limits are examined. shows which scenarios are examined to fulfill that purpose.

Table 9: Scenarios with increased speed limit
The traffic simulation was performed within a timestamp of 1 hour. Vehicles trajectories and speed profiles with an resolution of 1 Hz, since this is the optimum input for the emission model, are fed into the emission model. Scenarios which enable the system and scenarios in which the system is deactivated are compared. The scenarios are identified according to the demand of the network, the penetration of the system and the distance in which the speed advice is provided. At the next section it will be provided the results of specific of the simulations described on the previous tables.

### 3.8 Results

For each scenario a base case exists depicting the normal traffic flow and this base case is compared with an identical case where the system is implemented. So the effect on CO₂ emissions presented in the figures below is expressed as the difference from the base case. A negative value on the y-axis shows a reduction on traffic CO₂ emissions when the system is implemented and a positive values show the opposite.

Figure 30 presents the results of the scenario with traffic demand of 900 vehicles per hour, for different speed advice provision distances and for several penetration rates. The green split of the main traffic flow’s phase is 46% and the cycle duration is 120 seconds. As it is presented in the figure below, CO₂ emissions show in general an increase for the scenarios where the system is activated except from the cases where the
speed advice is provided 800 m before the intersection and for the penetration rates of 100%, 80% and 40%.

![CO2 difference with the implementation of the system, compared to the base case](image)

Figure 30: CO2 difference with the implementation of the system, compared to the base case

This increase in total traffic emissions shows that the system with the logic that has been adopted could have a negative impact, regarding specific parameters and road characteristics. This logic provides speed advice in any case except of the case where the vehicle is on a car-following mode and has other vehicles in front of it.

Here it has to be mentioned that the simulation is performed for one intersection and therefore the results are related only to this road part. Moreover despite the total increase or decrease in traffic emission, there are individual vehicles that present significant gains or significant losses. The case study is used as an example of the possibilities that arise regarding the evaluation of a system either at a vehicle level, or at a traffic level.

As it has been mentioned in a previous chapter the system enforces the speed profile even in the cases where the adequate speed to pass the intersection is under the threshold limit of 20 km/h. Therefore vehicles decelerate to 20 km/h, keep this constant speed, but finally do not pass through the intersection. This weakness is revealed when the examination is performed at a network level and an adjustment should performed so as vehicles not to take speed advices in cases where the desired speed that is needed in or-
order to pass through the intersection is lower than the threshold speed limit that is applied. This effect is presented since red phase is longer than the green and therefore vehicles frequently are obliged to stop at the intersection. The conclusion is also enhanced by the scenario of the advice provision at 800 m where enough time and space for the implementation of the profile exists and therefore a positive effect is observed. Negative effects are also observed for higher demands. These negative effects can be attributed to the formation of queues and especially for the scenarios where the penetration level is low. Moreover non-equipped vehicles tend to overtake equipped and there are driven to unnecessary accelerations.

Since the system shows sensitivity on traffic signal settings then different scenarios were examined adjusting specific settings. Thus the duration of the green phase was extended and scenarios with 54% and 62,5% and 72% green split were examined, while the duration of the overall cycle remained the same (120 seconds). It was selected to test the variance in green split at the 600 m distance of speed advice provision. The logic shows to be effective as increasing the green split for the demand of 900 veh/h. Figure 31 shows that trend.

![Figure 31: CO2 difference compared to the base case, for different green splits](image)

It is observed that an increase in green split has an influence leading to a reduction of CO₂ emissions for specific cases. This can be justified considering that an increase in the green phase provide vehicles with enough time so as to be able to fully implement the indicated speed profile. So in the scenario with the 72% green split and 100% pene-
tration, the maximum reduction is observed. The maximum effect at 100% penetration also shows the effectiveness of the formation of platoons (potential establishment of green wave). At low penetration rates the increase of emissions is justified by the formation of queues.

In addition an increase in the speed limit was implemented. This increase was examined for the scenario of the 600 m speed advice, the 54% green split and the 900 veh/h. The scenario of the speed limit increase shows to be in general more effective compared to the scenario with the speed limit of 50 km/h and this can be explained by the fact that vehicles are able to travel at higher steady speeds. Figure 32 shows that trend. This observation verifies that the system could be effective in rural and peri-urban roads.

![Figure 32: CO₂ difference compared to base case for different speed limits](image)

Therefore for the scenarios that the system shows effectiveness there have been examined cases for higher traffic demands.
Figure 33 shows that the system could be effective also for higher demand levels, but only for specific penetration rates. This can be explained due to the formation of queues at traffic lights. Also it is shown that for the 1200 veh/h demand scenario the increase in emissions is lower compared to the increase in the 900 veh/h scenario, at the penetration level of 20%. This can be explained by the fact that the logic sets vehicles at a car-following mode when they meet vehicles in front of them and as it is natural, at high demand levels the probability to meet vehicles in front of them is higher. The indications concerning the demand and the green split shows that the system in an urban environment may not be effective but this also demands further investigation and a simulation at a network level with a sequence of intersections. For all the other scenarios presented on the tables at the beginning of the chapter, the trend shows an increase in CO2 emissions and this can be explained due to the increased traffic demand.

3.9 Analysis

The further analysis of the results is performed for the scenario where one of the maximum effects was observed (600 m speed advice, 900 veh/h and for an increased green split of 62.5%). Figure 34 and Figure 35 show the trajectories of 250 vehicles for the
base case where the system is deactivated and for the 100% penetration scenario. The intersection is placed at the distance of 800 m (y-axis).

Figure 34: Trajectories in a time-space graph for the base case scenario

Figure 35: Trajectories in a time-space graph for the 100% penetration scenario
As it is shown from the time space graph, for the base case scenario vehicles periodically stop at the intersection, while when the system is implemented to all vehicles, then almost no one stops and the total delay is reduced. For the base case scenario the number of stops is 389, while for the scenario with the 100% penetration the stops are only 8. The decrease in vehicle’s speed that is implied, so as vehicles to pass through the intersection is depicted in Figure 35, by the slope of the time-space graph.

One important advantage of the combination of microscale models is the ability to handle and examine all the simulated vehicles individually. Figure 36 shows a comparison of the base case of the normal traffic flow, with the 100% penetration scenario. Each dot represents CO2 values in g/km before the implementation of the system (base case) and after the implementation of the system (EEI scenario). When there is no change in emissions between these two scenarios, then dots should be on the line of 45°. When an increase is observed with the implementation of the system, then dots are being offset over the line of 45 degrees and when a decrease is observed dots are under the line.

![Figure 36: Simulated vehicles before and after the implementation of the system (100% penetration)](image)

For the 100% penetration, as presented in the graph below, the majority of vehicles present a decrease in their emissions, while there are some, for which an increase is observed. At a penetration rate of 20%, the picture is adverse and a decrease in the positively affected vehicles is observed. There are more vehicles, compared to the 100% penetration scenario, for which an increase is observed. This is depicted on the graph
below. For the other penetration rates (80%-20%), the overall picture can be described as an intermediate state of these two.

Figure 37: Simulated vehicles before and after the implementation of the system

The analysis concerning the equipped and the non-equipped vehicles indicates that for the high penetration scenarios, the equipped vehicles contribute more to the emissions reduction, while at low penetration scenarios equipped vehicles are the reason for the emissions increase, as depicted on the figure below, where the average CO\textsubscript{2} emissions in g/km for equipped, non-equipped and the whole traffic flow are presented. The explanation for this increase is mainly related to the formation of queues at the intersection and the interaction with un-equipped vehicles. Equipped vehicles cannot implement the speed profile and either stop before the intersection or they present fluctuations in their speed profile before the end of the queue. A possible extension in the logic of the system, as has previously presented, is related with the inclusion of queues in the calculation of the optimum speed profile for each vehicle.
Figure 38: Average CO2 (g/km) for equipped vs. non-equipped for the scenario examined (600 m speed advice, 900 veh/h 62.5% green split)

A further analysis, for the same scenario, regarding the more microscopic characteristics that determine the effectiveness of the system, it has been performed through the analysis of the instantaneous speed and acceleration distribution. For the base case it is revealed that accelerations and decelerations (inevitable followed by accelerations), at low speeds are observed. High frequency of intense accelerations and decelerations at mid-range speeds and a high accumulation of steady speeds between 45-60 km/h are presented.
With the application of the system, on the scenario with the 100% penetration, the justification made in the space-time graph (Figure 40) is verified. Accelerations and decelerations at low speeds disappear, high accelerations and decelerations at mid-range speeds are reduced, while there is an increase in the frequency of steady speeds from 25-45 km/h. This exactly reveals that the logic implemented by the algorithm is effectively applied for this scenario.
Moreover in order to explain the findings regarding the equipped and the non-equipped vehicles, the speed acceleration distribution was examined. As it can be seen by Figure 41 the implementation at this penetration rate increases the accelerations and therefore an increase in emission is observed.

Figure 40: Speed acceleration distribution for the 100% penetration

Figure 41: Speed acceleration distribution for the 20% penetration
The average speed of each simulated vehicle was calculated as the total distance covered over the respective time. The emission values calculated for each vehicle are plotted over their respective average speed. Generally an increase in average speed leads to a reduction in CO$_2$ emissions. Figure below presents this trend for the base case scenario and for the scenario with 100% penetration. The comparison between these two cases shows that the implementation of the systems leads to lower emissions in the average speed range of 35-45 km/h. This can be explained by the logic of the system and has been previously shown in the speed-acceleration distribution graph, where with the implementation of the system an increased frequency in mid-range speeds is observed.

![Figure 42: Relationship between CO$_2$ and average speed for the 100% penetration and the base case](image1)

![Figure 43: Average speed vs CO$_2$ emissions for the 100% penetration and the base case](image2)
When the penetration rate is reduced, then this picture also changes with the scenario of the system’s implementation approaching the base case. This is presented in the figure below where the base case and the 20% penetration scenario are compared.

![Figure 44: Relationship between CO2 and average speed for the 100% penetration and the base case](image)

As we can see by the figures presented above, for the same average speed a wide range of emissions can occur. This indicates the weakness of the average speed approach to capture the effectiveness of systems that affect the dynamics of the driving pattern.

A further analysis of the results concerning the identification of indicators that are able to predict the effect of the system was performed. As mentioned before, the system is able to reduce the number of stops. For specific cases the number of stops is a good indicator of the system’s effectiveness. Indicatively it can be mentioned that the implementation of the system for the scenario examined and for the 100% penetration rate, shows a dramatically decrease in the number of stops. But fuel consumption and emissions do not depend only on the number of stops. Accelerations play the most important role. Of course a stop is followed by acceleration but the intense of the acceleration before and after the stop is a parameter that should be further examined. RPA is used as an indicator of accelerations intensity. The definition of RPA was given in the chapter of driving cycles and the indicator had been introduced for the analysis of real driving patterns [9] and driving cycles [24], [39]. Therefore for the total number of vehicles and for the scenarios examined the increase that is observed for the 100% penetration can be
justified through the examination of this indicator. Table below shows the average values of RPA for the entire fleet and for each case.

Table 10: Relative positive acceleration for the base case, the 100% penetration and the 20% penetration

<table>
<thead>
<tr>
<th>Case</th>
<th>Vehicle Category</th>
<th>RPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Penetration</td>
<td>Equiped</td>
<td>0.070 m/s²</td>
</tr>
<tr>
<td>Base case</td>
<td>All</td>
<td>0.073 m/s²</td>
</tr>
<tr>
<td>20% Penetration</td>
<td>Equipped</td>
<td>0.081 m/s²</td>
</tr>
<tr>
<td>20% Penetration</td>
<td>Non-equipped</td>
<td>0.075 m/s²</td>
</tr>
<tr>
<td>20% Penetration</td>
<td>All</td>
<td>0.076 m/s²</td>
</tr>
<tr>
<td>Base case</td>
<td>All</td>
<td>0.073 m/s²</td>
</tr>
</tbody>
</table>

As it is shown form the table below, RPA follows the trend regarding the increase of CO2 emissions for all the cases (100% penetration-20% penetration-Base case) and all the vehicle types (equipped, non-equipped).

The analysis regarding the microscopic characteristics for one of the simulated scenarios indicated the importance of speed-acceleration distribution, because it is an easy way to represent the simulated diving patterns and it is able to depict the impact that a measure has on specific modes (accelerations, decelerations, steady speeds). Average speed is a good indicator regarding macroscopic analysis but when the analysis is concentrated on individual driving patterns, then a large variance on average speed and emissions occur. The system examined in the present study is able to reduce the number of stops and therefore reduce fuel consumption. For specific cases (for example 20% penetration), the decrease in the number of stops cannot predict the increase in total emissions. Therefore kinematic parameters that take account the intense of accelerations have been used. RPA seems to be a good indicator that is able to explain the variance in emissions.
4 Conclusions

Intelligent transport systems (ITS) are able to play an important role in the effort for the reduction of fuel consumption and emissions of the transportation sector. ITS oriented in traffic management and travel information provision have greatly been developed and have been implemented in many European cities bringing particularly positive results, while vehicles recently have started to be equipped with in-vehicle systems. The new challenge for the scientific society is the development of systems, referred to as Cooperative ITS (C-ITS), that connect vehicles with the road infrastructure. This connection seems to be of great importance since it is able to increase the quality and the availability of traffic data, a key factor for the optimization of transport systems and for the success of transport strategies. The bilateral data exchange is essential for the development and the implementation of systems contributing to the reduction of fuel consumption and emissions. Operators obtain the possibility of continuous traffic monitoring and the access to discrete driving patterns in a high level of detail.

Despite the fact that the effectiveness of all these systems in improving the operation of the transport system has been already well examined and continues to be examined as the systems are being evolved, the recording of the impact on energy consumption and emissions is at an early stage or is examined fragmented. The evaluation of the existing systems and the further development of them demand an accurate assessment methodology, which is able to capture in a high level of detail the real impact of these systems on energy consumption and emissions. The lack of a systematic methodology for assessing the environmental impact of ITS and C-ITS has been recognized and therefore a methodology is currently formed.

An ITS important evaluation method is the modeling process, where a traffic simulation model is combined with an emission model. In the modeling process, after the description of the network and the simulation of the system and the identifications of the scenarios in the traffic model, exported trajectories describing discrete vehicle’s speed profiles and other more aggregated or analytic traffic variables, are fed into emission models. The appropriate combination demands the full understanding of the variables that are affected by the system. Several traffic emission models exist, which estimate emissions using different approaches and can be used in a variety of applications such as the development of national emission inventories, the monitoring of traffic pol-
olution, and the projections regarding the impact of new vehicle technologies, fuel uses and transport demand. Regarding the assessment of ITS, the suitability of a traffic emission model to be used for specific applications is strongly related to the way it estimates the appropriate Emission Factors (EF) and to the way the EFs, it contains, have been developed. For systems that influence macroscopic characteristics of traffic flow, more aggregated emission models could be used, but their weakness to capture precisely traffic and driving dynamics creates barriers regarding the appropriate environmental evaluation of ITS. These models can be mainly used for the aggregation of the results derived by more microscopic approaches. Since the majority of the ITS affect the individual vehicle, fuel consumption and emissions are strongly related with traffic variables such as speed, positive acceleration and idling time. Thus, the environmental assessment of a system that affects the speed profile of a vehicle within the traffic framework should be based on approaches that are able to produce EFs for every second (g/s) and correlate them with the instantaneous operation of a vehicle.

This is done directly or indirectly by the three types of models ensuring lesser or greater level of accuracy. Linear regression models correlate bag-driving cycle’s measurements to the instantaneous speed and acceleration pattern of vehicles, through an analytical kinematic parameters analysis and a complex statistical process. Instantaneous speed-based models correlate instantaneous modal emission measurements with the combination of speed and acceleration that caused them and Instantaneous power-based models that calculate fuel consumption and emissions of a vehicle with the most accurate way (for traffic-related purposes), by translating vehicle’s speed profile in longitudinal dynamics and calculating the instantaneous power demand of the engine, using engine emission maps or modal measurements. Instantaneous power model can be used in the evaluation of every type of system (vehicle-based or traffic oriented) while instantaneous speed-based models can be combined effectively with traffic micro-models.

In the framework of the thesis a C-ITS, the Energy Efficient Intersection (EEI) system has been evaluated regarding its effect on CO\textsubscript{2} emissions of road transport. Energy Efficient Intersection is a system that can reduce energy consumption and emissions of a vehicle at a signalized intersection through the provision of speed advices to the drivers, in order to reduce stop and go traffic. The system detects a vehicle that approaches a signalized intersection and taking into account the phase and the duration of the signal, as well as the current position and speed of the vehicle, provides speed information
to the driver which is optimized in terms of reducing energy consumption and emissions. The development of these systems demands the systematic and analytic description and examination of all the conditions that a vehicle will face approaching at an intersection. The optimal logic of a system that aims at the minimization of fuel consumption and CO$_2$ emissions is related with the provision of speed advices which ensure that the vehicle will pass through the intersection with the maximum allowable constant speed. Considering the conditions upstream and downstream the intersection, the deterministic factor of the effectiveness of such a system is the avoidance of acceleration from standstill, which is a very energy consuming mode and is inevitable if a vehicle stops at an intersection. Acceleration from a higher speed is able to provide benefits up to 10% in terms of CO$_2$ emissions reduction.

Regarding the identification of the effect of the system on the individual vehicle and on the whole traffic, considering a representative traffic environment, an integrated modeling process has been followed and data from a traffic micro simulator has been used. For the estimation of CO$_2$ an instantaneous speed-based emission model has been used which was judged adequate to capture the system’s effect, while the whole process indicated that the simulation of ITS and C-ITS demands the combined use of the appropriate traffic and emission models. The integrated modeling process is able to quantify the possible environmental effect of ITS and reveal the areas that should be improved.

The examination at the individual vehicle level showed important benefits, but the analysis indicated that the system should be adjustable according to the existing traffic conditions. Therefore adaptations such as the consideration of the length of queues can be included in the logic and the status of the next signal, while there should be distinguished cases where the advice should not be provided or only advices for smooth deceleration could be provided when it is not feasible to pass through the intersection.

The analysis at a traffic level showed that the system can be effective at peri-urban traffic environments where low traffic demand is observed and there is enough space for vehicles to implement the indicated speed profile. An increase in the traffic demand shows adverse effects and this enhances the need for a more adaptive system. The system shows sensitivity regarding the distance of speed advice provision and the traffic lights settings.
Bibliography


[50] G. Scora and M. Barth, "COMPREHENSIVE MODAL EMISSIONS MODEL (CMEM), version 3.01 " University of California, Riverside Center for Environmental Research and Technology 2006.


