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Study of the impact of CO_2 emission reduction measures in real driving conditions

– PhD THESIS SUMMARY –

Scientific supervisor

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PREFACE

Climate change is one of the greatest challenges of the 21st century, and carbon dioxide (CO_2) emissions from the transport sector are a significant contributor to this global problem. Vehicles are responsible for a significant proportion of total human-caused greenhouse gas emissions, making their reduction a key priority in the fight against global warming and a major step towards a sustainable future.

To develop viable solutions in this direction, it is crucial that the analysis of CO_2 emissions is carried out on the basis of data that is as close as possible to the real conditions of use of vehicles. Traditional studies based on standardized test cycles do not always faithfully reflect the real behaviour of drivers and the specific characteristics of each vehicle in varying traffic and environmental conditions. Thus, the use of real vehicle recordings during their movement on the usual routes of users provides a much more accurate perspective on fuel consumption and emissions generated. This approach allows the identification of emission reduction strategies adapted to each type of user and specific operating conditions. In addition, the analysis based on real driving profiles can support authorities and the automotive industry in the development of more effective policies and innovative technologies capable of reducing the negative impact on the environment.

This paper aims to explore the impact of measures to reduce CO_2 emissions from motor vehicles, using both homologation cycles and real driving cycles obtained through recordings on motor vehicles in circulation. Through this approach, we aim not only to highlight the importance of a more accurate analysis of CO_2 emission reduction methods, but also to underline the enormous potential that such studies have in defining efficient and sustainable solutions for the future of mobility.

Also, within the framework of the work, a program was developed to facilitate working with cycles and records on customer vehicles. It allows creating a database of records, viewing signals, converting and saving them in different formats. Additionally, various cycle characterization parameters can be calculated, comparative graphs can be made with them and a personalized record base can be created by filtering them. The program can be expanded by introducing other types of calculations, such as calculating a Stop & Start signal.

To calculate the CO_2 emissions, it was decided to develop and use LMS Imagine.Lab AMESim models, a modelling and simulation environment for engineering. These are based on the IFP Drive library, but also contain components (sub models) from the Mechanical and Signal and Control libraries and allow the tracking of an imposed speed cycle taking into account the thermal regime of the engine and gearbox and offer the possibility of implementing different strategies such as Stop & Start. Subsequently, starting from the calculated CO_2 emissions, a method is presented to transform the results obtained on real driving cycles into those with a reliability objective. The method presented can be extrapolated to a car fleet in order to be able to accurately quantify the efficiency of different technologies for reducing those emissions and to calculate the amount of CO_2 emitted over the life of a vehicle.

The paper is structured in five chapters as follows:

Chapter I analyses the current state of research in the field of CO_2 emissions and their impact on the climate as well as the need to use real driving cycles and how they are used today in the automotive field.

Chapter II presents the process of recording on vehicles and how to manage them as well as the recording management program developed within the paper.

Chapter III includes various studies of measures to reduce CO_2 emissions. It began with an analysis on homologation cycles to evaluate the efficiency of the different technologies used for this purpose but also of the platoon driving strategy that can be easily implemented on modern vehicles. It continues with the calculation of CO_2 emissions for a C class SUV car, whose route was recorded and processed according to the RDE procedure. These analyses are also performed for electric vehicles to assess the impact on their electricity consumption and a method for equating it to CO_2 emissions is presented.

Chapter IV presents a method for using records from a database of customer vehicle records of a major automobile manufacturer. They will be used to analyse the impact of the Stop & Start system on CO_2 emissions in real driving conditions. The impact of each Stop & Start strategy will be calculated and analysed as well as the opportunity to use this system depending on the driving mode of the studied vehicles. Finally, a method will be presented to evaluate the impact of CO_2 emission reduction measures on a vehicle fleet at a given reliability objective.

Chapter V includes the conclusions of the various studies carried out within the work; a synthesis of the original contributions made in this field as well as the prospects for further development.

* * * * *

This work represents an essential stage in my academic career, completing my years of higher education at the Faculty of Transport of the National University of Science and Technology Politehnica Bucharest and also incorporating the experience accumulated in over 10 years of work in the automotive field.

On this occasion, I would like to express my sincere thanks to my doctoral supervisor, Professor Gheorghe Frățilă, for his professionalism, scientific and moral support and academic rigor demonstrated throughout the entire research.

I also wish to express my gratitude to Mr. Marius Bățăuș, for his valuable advice, pertinent observations and support that contributed to the development of this work.

Last but not least, I would like to thank my parents, wife and daughter, who supported me in times when my attention and time could not be directed to them and who believed in my success.

I. The need to reduce carbon dioxide emissions

Global warming can be felt by each of us today, with 2023 being the warmest year on record, with an average global temperature of 14.98°C (figure 1.1). The industrialization of an increasing number of countries has led to an increase in greenhouse gas emissions (figure 1.1), necessitating efforts to reduce emissions and eventually achieve net neutrality.

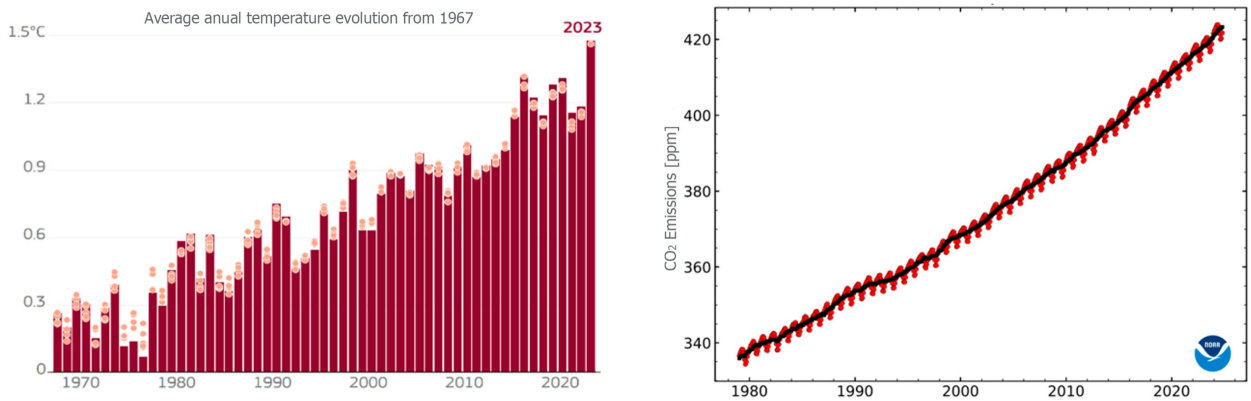


Figure 1.1 – Evolution of average annual temperature and CO_2 emissions

The European Union has managed to reduce carbon dioxide emissions by 31% compared to 1990, aiming to achieve climate neutrality by 2050 (figure 1.2).

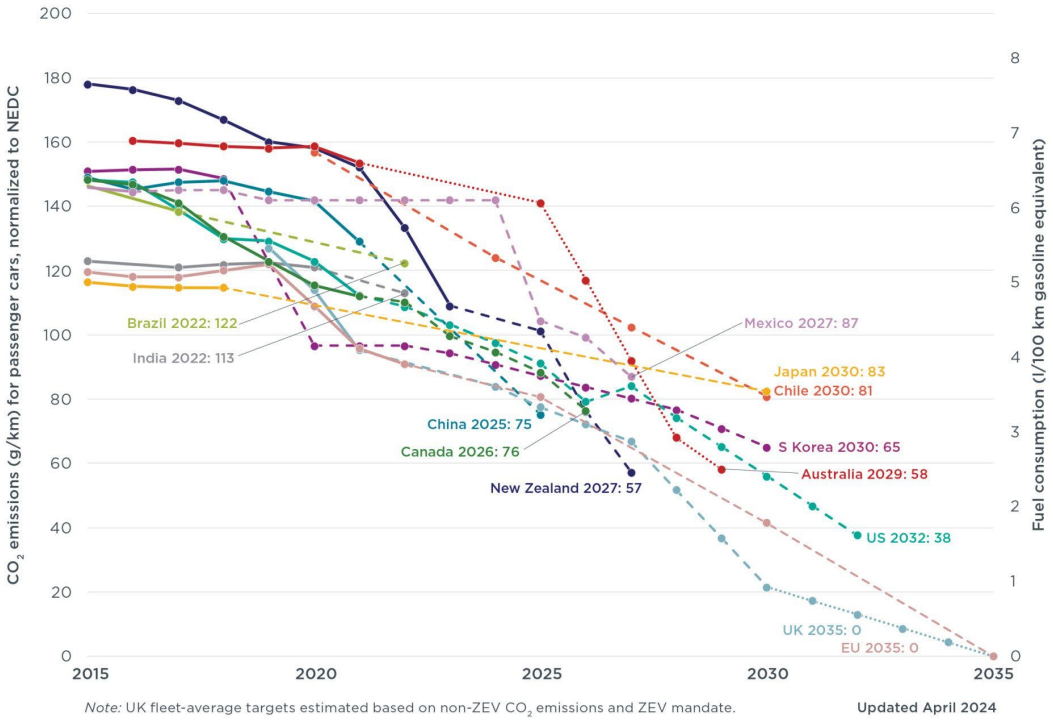


Figure 1.2 – CO_2 emission targets normalized to the WLTP cycle

According to the European Environment Commission, the road transport sector is responsible for around 23% of total CO_2 emissions, i.e. 803 million tones in 2022, and is expected

to reach 639Mt CO_2 in 2030. Today, there are 12 countries, plus the 27 in the European Union, that have set fuel consumption and greenhouse gas emission standards for both passenger cars and commercial vehicles. Together, they cover more than 85% of global car sales, thus forcing manufacturers to develop cleaner technologies.

The most ambitious targets have been set by the European Union and the United Kingdom, with 0 g/km CO_2 emissions by 2035. Achieving them requires increasing sales of fully electric vehicles, and the obstacles they face (short range, high price, poor infrastructure) currently call their feasibility into question.

II Software development for analyzing travel cycles

To facilitate the work with standardized cycles and those recorded in the following chapters, a program was created that allows their management, conversion, visualization and analysis. The program, entitled "CycleBox", was built in the MATLAB programming environment developed by MathWorks. In order to obtain a friendly interaction environment, a MATLAB module entitled "App Designer" was used that allows the creation of a graphical interface and the programming of its buttons.

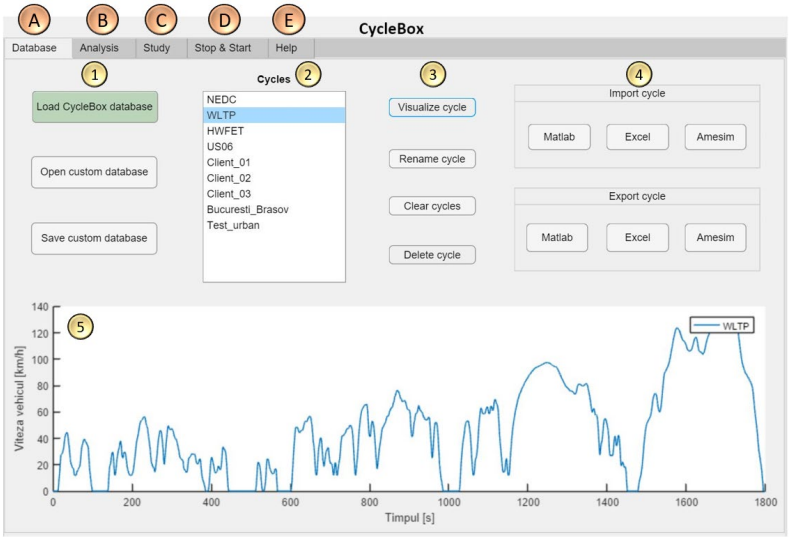


Figure 2.1 Main software interface

The analysis module (B) is shown in figure 2.2. Its main role is to easily perform certain cycle characterization calculations and integrate them into the database.

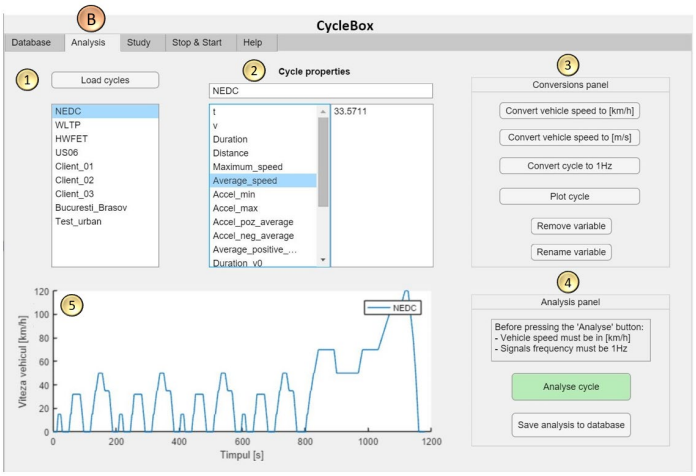


Figure 2.2 Analysis module interface

The study module (C – figure 2.3) is designed to create comparative graphs between cycles in the database based on the properties calculated in the analysis module. It is also possible to create customized databases by placing conditions on previously calculated parameters.



Figure 2.3 Cycle study mode interface

In the Stop & Start module (D – figure 2.4), a signal for a simplified version of this system can be generated based on conditions imposed on the vehicle's speed or other recorded signals.

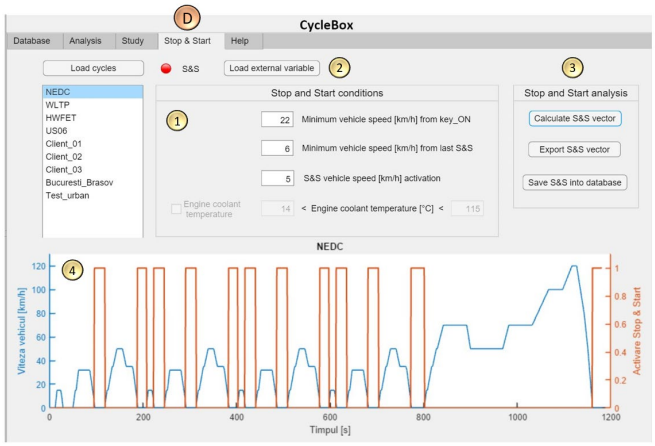


Figure 2.4 Stop & Start module interface

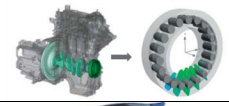
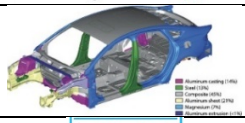
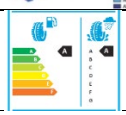
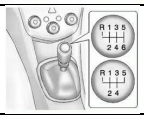
The developed program represents an interactive and visual proposal for working with cycles from different sources and different formats that can be accessible to anyone without requiring programming knowledge. Depending on the project requirements, extensive databases/records can be created and the option to analyze them and filter by calculated parameters provides a powerful tool in selecting the most representative records. The program can be customized depending on the records that will feed it and depending on the availability of recorded parameters, additional calculations similar to Stop & Start can be implemented.

III. Efficiency of measures to reduce CO_2 emissions

3.1 Efficiency of measures to reduce CO_2 emissions in standardized cycles

To reduce CO_2 emissions, the impact of implementing available efficiency packages with existing technologies presented in Table 3.1 will be studied. These will be implemented on a C-class sedan and an SUV, both in the economy class.

Table 3.1 Measures to reduce CO_2 emissions

Improved alternator	
Stop & Start system	
Engine roller bearing	
Reduced vehicle mass	
Low resistance tyres	
Aerodynamic improvement	
6 gears MT	

The study is carried out using a model developed in LMS Imagine.Lab AMESim, an engineering modeling and simulation environment. It is presented in detail in Figure 3.1 and allows the determination of the CO_2 emissions of the two vehicles along their journey and the implementation of the respective efficiency packages. The simulations were performed on the WLTC and CADC cycles.

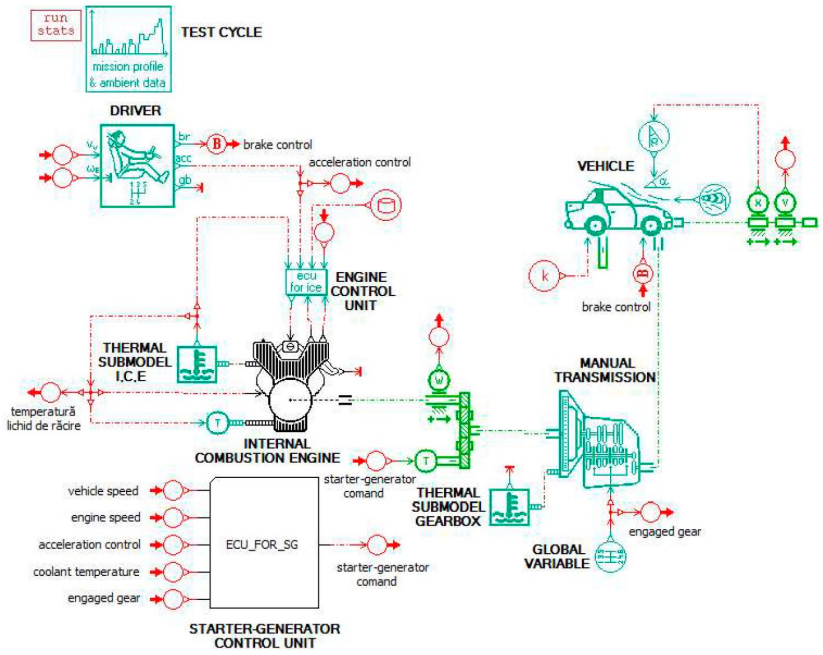


Figure 3.1 The vehicle and powertrain model for CO_2 emissions computation.

In the WLTP cycle (Figure 3.2), a 13.7% reduction in CO_2 emissions was achieved for the SUV and 16.3% for the C-class vehicle. The greatest impact was the use of low rolling resistance tires (4.6%), while the efficiency of the alternator and the reduction of engine friction had the smallest contribution (under 1%).

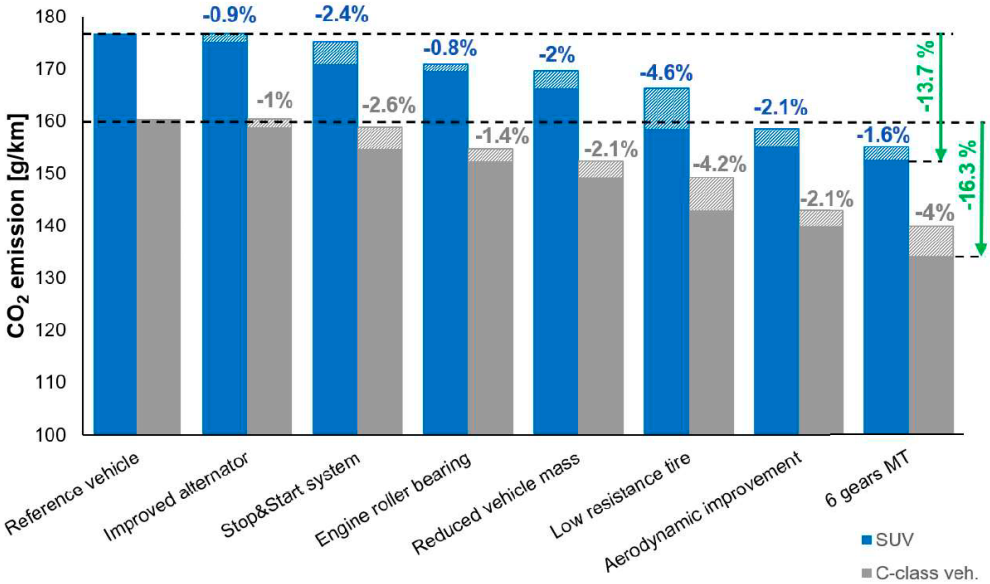


Figure 3.2 CO_2 emissions reduction in WLTC.

For the CADC cycle (Figure 3.2), a 14.5% reduction in CO_2 emissions was achieved for the SUV type vehicle and 16.7% for the C-class vehicle. The greatest impact was the use of low rolling resistance tires (4.1%), closely followed by the use of the Stop & Start system (3.8%), while improving the efficiency of the alternator and reducing engine friction had the smallest contribution (below 0.7%).

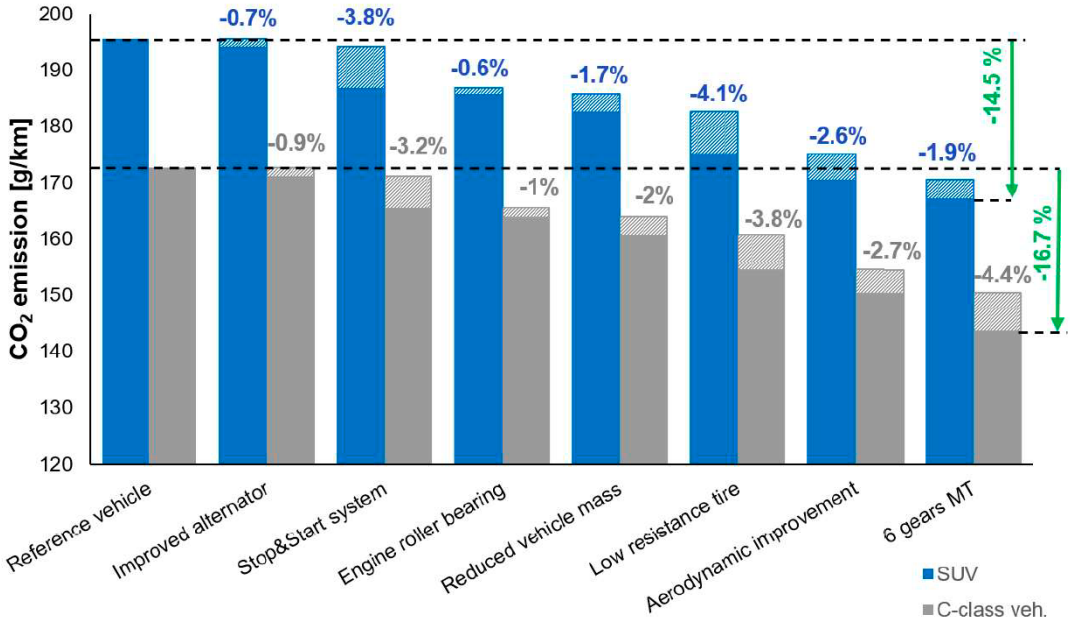


Figure 3.3 CO_2 emissions reduction in CADC.

In order to properly assess the impact of the measures, a simulation of the vehicle's dynamic performance was also carried out. For the SUV, a 3.5% increase in maximum speed and an 8.9% decrease in acceleration time from 0 to 100 km/h were determined. For the C-class vehicle, a small 0.2% increase in maximum speed and a 6.1% decrease in acceleration time from 0 to 100 km/h were determined.

3.2 Study of CO_2 emissions when driving in convoy

The introduction of autonomous driving is now possible due to improvements in advanced driver assistance systems (ADAS) and vehicle-to-vehicle (V2V) communication. These technologies now allow for coordinated platooning as a means of reducing fuel consumption.

The evolution of the vehicle speed profile in a platoon can be observed using a leader-following model whose diagram is shown in Figure 3.4.

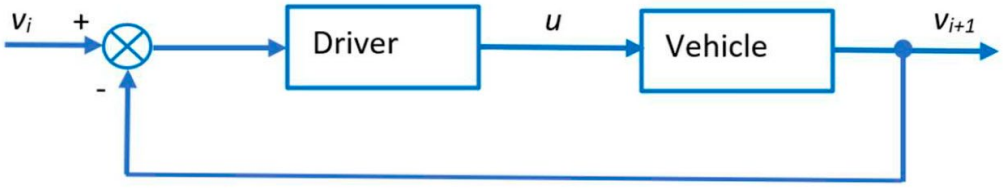


Figure 3.4 Diagram of the system driver-vehicle for the front vehicle tracking

Starting from the equation of rectilinear motion of the vehicle, the following equation can be deduced.

$$v_{i+1}^{\cdot} = k \cdot \left[v_f(t-T) - v_s(t-T)\right] \tag{3.1}$$

were: v_i is the velocity of the vehicle in front; v_{i+1} is the velocity of the vehicle in the rear; t is the current time, T is the driver reaction time and k is a constant.

The numerical integration of equation 3.1 is performed using the Signal&Control library in AMESim, as shown in Figure 3.5. The model also contains a calculation of the relative distance between vehicles to determine possible collisions.

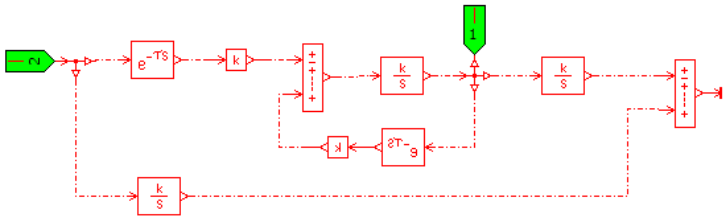


Figure 3.5 Linear model for leader-follower for a single vehicle

Starting from the first vehicle, by successive integration (Figure 3.6), it is possible to obtain the speed profiles of vehicles in a column of vehicles that are not in a coordinated convoy.

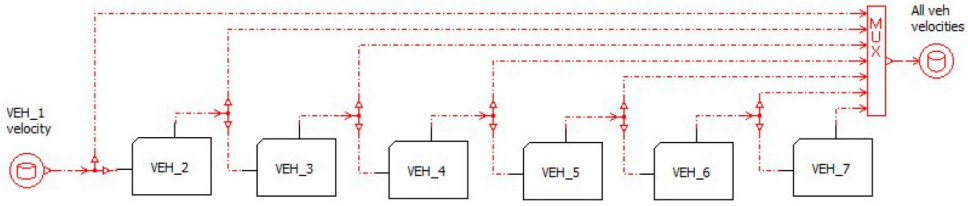


Figure 3.6 Leader-follower model for a convoy of 7 vehicles

By visualizing the evolution of speed profiles in an uncoordinated convoy of 6 vehicles (Figure 3.7), it is evident that the speed of the vehicles deteriorates the further they are behind the convoy, which will lead to higher CO_2 emissions.

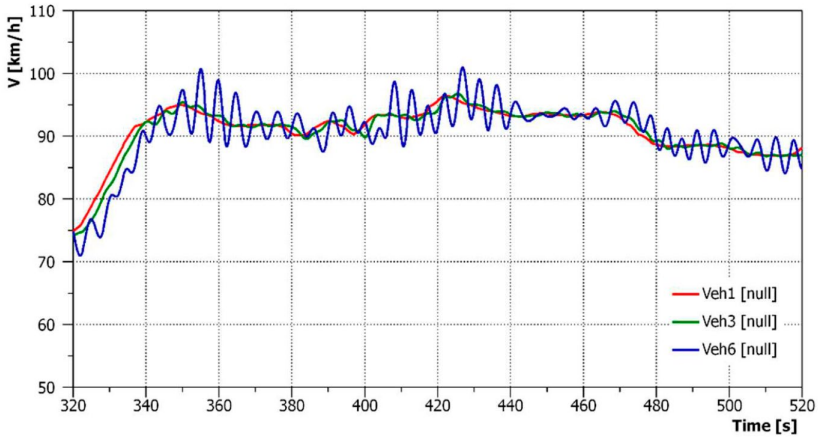


Figure 3.7 The speed variation of vehicles 1, 3 and 6 from the uncoordinated convoy

The simulations were performed for a single vehicle and for platoons with close distances between vehicles (1 meter), consisting of 2, 3, 4, 5 and 7 identical passenger vehicles. Three constant vehicle speeds were considered for the simulations: 70 km/h, 100 km/h and 130 km/h.

As can be seen in Figure 3.8, for the studied application, the improvement starts from 3.5% for 2 vehicles at 70 km/h and reaches 18.7% for 7 vehicles at 130 km/h compared to a minimum C_x improvement of 8.8% and a maximum of 24.2%. It can be concluded that a simple comparison using the average drag coefficient is not sufficient to draw a conclusion regarding the reduction of CO_2 emissions.

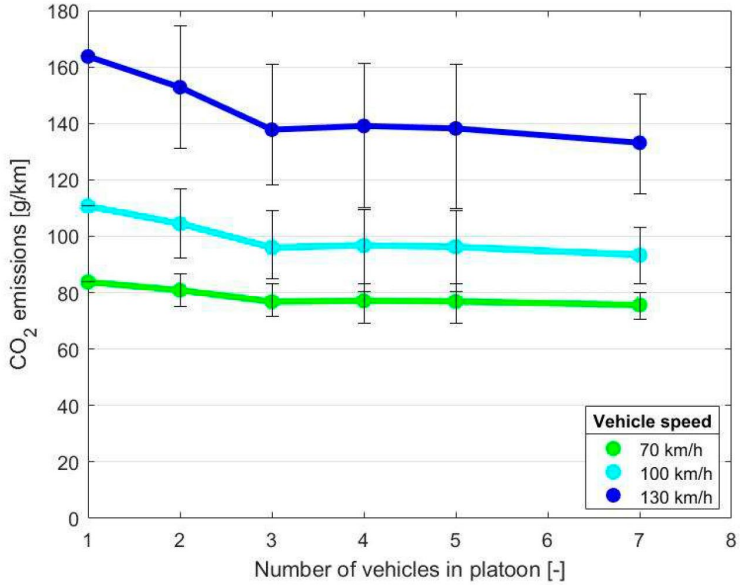


Figure 3.8 CO_2 emissions reduction for platoon driving at high stabilized speed

For the high-speed standard cycle (HWFET) the average CO_2 emissions for convoys of 2 to 7 vehicles are shown in Figure 3.9.

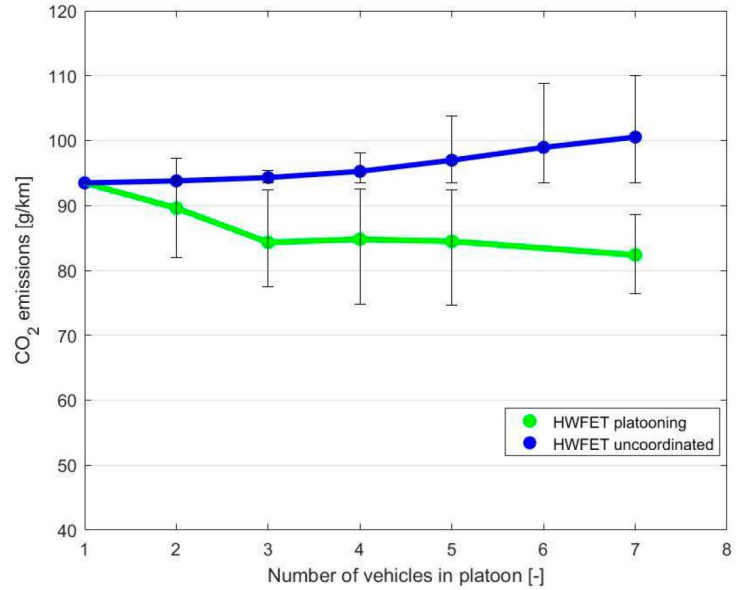


Figure 3.9 CO_2 emissions reduction for platoon driving in HWFET cycle

It is important to consider the influence of the speed variation in the convoy for a variable speed cycle, in order to obtain a more realistic average CO_2 emission. This influence can reach more than a third of the total improvement for a platoon of seven vehicles. Compared to an isolated vehicle, a CO_2 emission reduction of 11.9% (7 vehicles) was achieved and compared to an uncoordinated convoy, 18.1% (7 vehicles). The use of convoys with short distances between vehicles, consisting of three vehicles, is very efficient from an aerodynamic point of view, but it is important that they coordinate with each other to maximize the reduction of CO_2 emissions by uniforming the speeds of the vehicles.

3.3 Study of the impact of coordinated convoy driving on the energy consumption of electric vehicles

Following market trends, the study is conducted for an electric SUV vehicle through dynamic modeling and simulation, using a model developed in LMS Imagine.Lab AMESim. The vehicle specifications were chosen to resemble the average electric SUV market, having a mass/power ratio of 9. The characteristics of the Nissan Ariya model were selected: vehicle mass: 2200 kg, drag coefficient (Cd): 0.297, frontal area: 2.6 m² and usable battery capacity: 87 kWh. To carry out the study, the model presented in Figure 3.10 developed in LMS Imagine.Lab AMESim was developed.

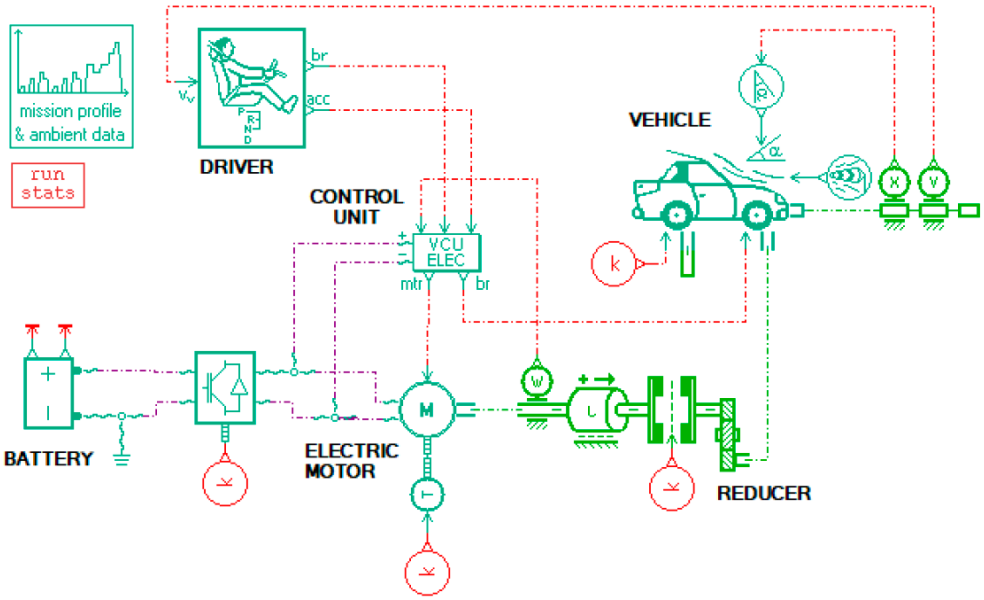


Figure 3.10 Model design of an electric vehicle for the energy consumption study

The simulations were performed for a single vehicle and for platoons with small distances between vehicles (1 meter), consisting of 2, 3, 4, 5 and 7 identical passenger vehicles. The variation of the air resistance coefficient (Cx) was taken from the literature and applied to the studied vehicle.

Three constant vehicle speeds were considered for the simulations: 70 km/h, 100 km/h and 130 km/h. The results are presented in Figure 3.11 where the upper and lower limits for each vehicle in the convoy are marked for each case.

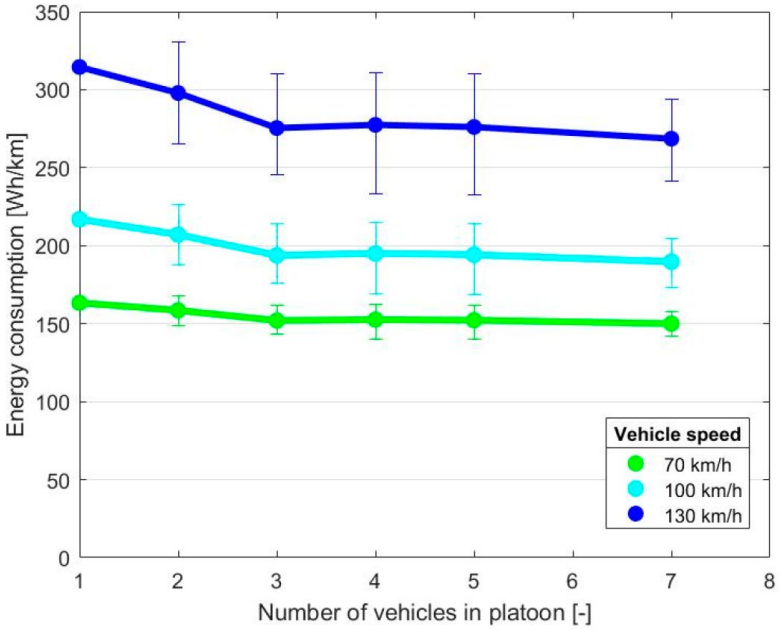


Figure 3.11 Energy consumption for platoon driving at high stabilized speed

The position of the vehicle in the convoy has a significant influence on energy consumption. The largest gains are obtained for the first vehicle, with savings of 26% compared to an isolated vehicle, while the last vehicle achieves only 6.5%. For stabilized speeds, the improvements range from 2.9% for 2 vehicles at 70 km/h to 14.6% for 7 vehicles at 130 km/h. These gains are lower than those obtained for a conventional propulsion system, which start from 3.5% for 2 vehicles at 70 km/h to 18.7% for 7 vehicles at 130 km/h, as shown in the previous subsection.

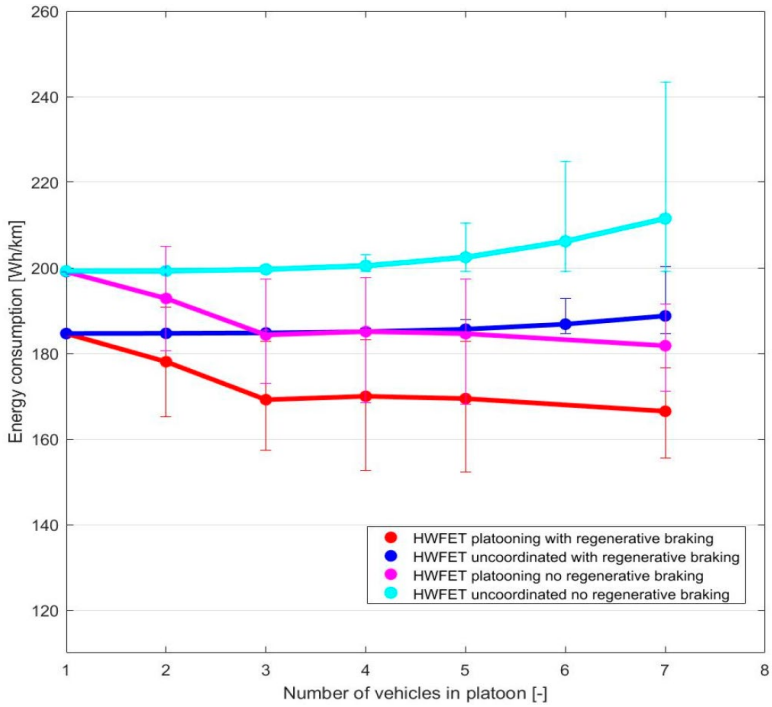


Figure 3.12 Comparison of energy consumption for HWFET cycle

The greatest improvements are achieved when using a 3-vehicle convoy, which is the most efficient configuration using the fewest number of vehicles. Driving in a convoy offers real benefits where electric vehicles have their weaknesses, especially at high sustained speeds, and delivers tangible results, such as an increase in range of up to 17.6% at 130km/h.

Although electric vehicles do not use fossil fuels, there are CO_2 emissions associated with the production of the electricity used to charge the batteries. We can therefore estimate the CO_2 emissions produced by electric vehicles using formula 3.2:

$$E_{ev} = \frac{E_{mix} \cdot C_{ev}}{\eta_t \cdot \eta_{\hat{i}}} \quad (3.2)$$

where:

- E_{ev} - the equivalent CO_2 emissions produced by the electric vehicle [g/km],
- E_{mix} - CO_2 emissions per kWh obtained from the production of electricity from the European mix [g CO_2e/kWh],
- C_{ev} - energy consumption of the electric vehicle [kWh/km],
- η_t - electric current transport efficiency (92%),
- $\eta_{\hat{i}}$ - battery charging efficiency (80%).

To achieve the most accurate equivalence, in the case of internal combustion engine vehicles, we must also take into account the fuel refining and transportation efficiency, which varies between 86% and 90%. The energy consumption results for the HWFET cycle with regenerative braking were converted into equivalent CO_2 emissions (in Table 3.2).

Table 3.2 Equivalent CO_2 emissions of electric vehicles (with regenerative braking) and conventional ones for the HWFET cycle

Number of vehicles	**Equivalent CO_2 emissions [g/km] – EV vehicle**		**Total CO_2 emissions [g/km] – vehicul ICE**		**Improvement over ICE vehicle [%]**	
	Coordinated convoy	Uncoordinated convoy	Coordinated convoy	Uncoordinated convoy	Coordinated convoy	Uncoordinated convoy
1	52,67	52,67	106,25	106,25	50,43	50,43
2	50,79	52,70	101,82	106,59	50,12	50,56
3	48,28	52,73	95,80	107,16	49,60	50,79
4	48,51	52,81	96,36	108,30	49,66	51,23
5	48,33	52,96	96,02	110,23	49,66	51,96
7	47,51	53,87	93,64	114,20	49,26	52,83

Simulations have shown that the equivalent CO_2 emissions of an electric car over its lifetime reach approximately 50% of those of a car with an internal combustion engine. The geographical region has a high impact on these results due to the different percentage of green energy in the total mix. As a result, if a 50% reduction in CO_2 emissions is achieved for Europe and the United States, for China this drop to 32%. We must however take into account the fact that electric cars have higher initial CO_2 emissions due to the elaborate and polluting battery manufacturing process, therefore, if we include them, the reduction in CO_2 emissions drops to 36%.

3.4 Impact of real driving cycles on CO_2 emissions

Driving a conventional vehicle on real roads, with a free gearshift strategy, a variable driving style, varying altitude and uncontrolled ambient conditions, is expected to generate different emission values, including CO_2, compared to those obtained in a controlled laboratory experiment following a standardized speed profile.

The driving style is practically defined by the gearshift strategy and driving dynamics. Driving dynamics during the trip can be evaluated using specific global parameters such as: VSF (Vehicle Speed Fluctuation), Mean Positive Acceleration, RMS acceleration (Root Mean Square Acceleration), RPA (Relative Positive Acceleration), etc.

The impact of driving style, characterized by driving dynamics, on CO_2 emissions of a passenger car equipped with an internal combustion engine will be investigated.

The recordings were made with a class C passenger car, over a period of 27 days, totaling a total of 920 km of combined driving in urban, rural and motorway areas. The data are post-processed according to the European Union RDE procedure and analyzed to select the most relevant trip segments to be evaluated using a detailed model developed in the Imagine.Lab AMESim LMS, previously validated.

The recordings were made using a DAWN OBD Mini Logger device presented on a Dacia Logan passenger car. It connects to the vehicle's OBD port (Figure 3.13) and records when it detects activity on the CAN bus.

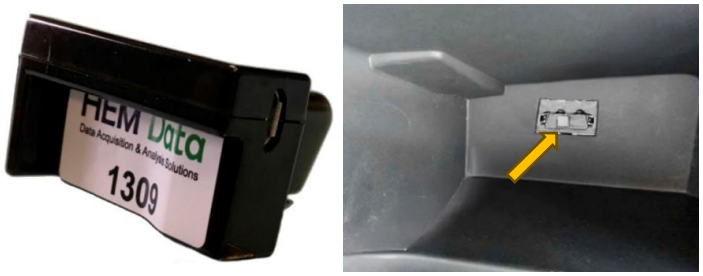


Figure 3.13 DAWN OBD Mini Logger device

The recording (Figure 3.14) lasted 27 days during which the car was operated under normal conditions reflecting its daily use. During this period, 920 km of travel was recorded in 46 trips over 11 days of combined urban, rural and motorway driving.



Figure 3.14 Recorded vehicle route

The post-processing of the trips in terms of driving dynamics and classification was performed according to the RDE procedure, by coding in Matlab the conditions of this procedure. Next, for each trip segment, the 95% percentile value of $v \cdot a_{pos}$ is calculated using the following method. The values $(v \cdot a)_i$ with $a_i \geq 0.1$ m/s^2 for each trip segment are ordered and their total number, Mk, is determined. Subsequently, each value $(v \cdot a_{pos})_j$, is assigned a percentage weight starting from the lowest 1/Mk, continuing with 2/Mk, 3/Mk and so on, up to the highest value for which Mk /Mk =100 %.

The average speed, 95% percentile of $v \cdot a_{pos}$ and RPA for each trip segment are calculated and presented in Figures 3.15 and 3.16, together with the average of each trip segment class and the limit imposed by the RDE procedure.

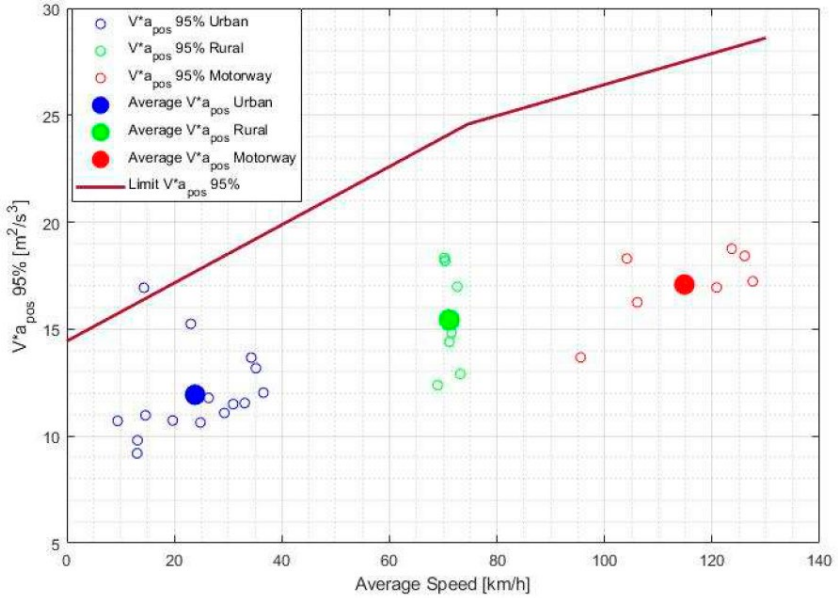


Figure 3.15 The 95th percentile of the $v \cdot a_{pos}$ and average velocity of each trip segment.

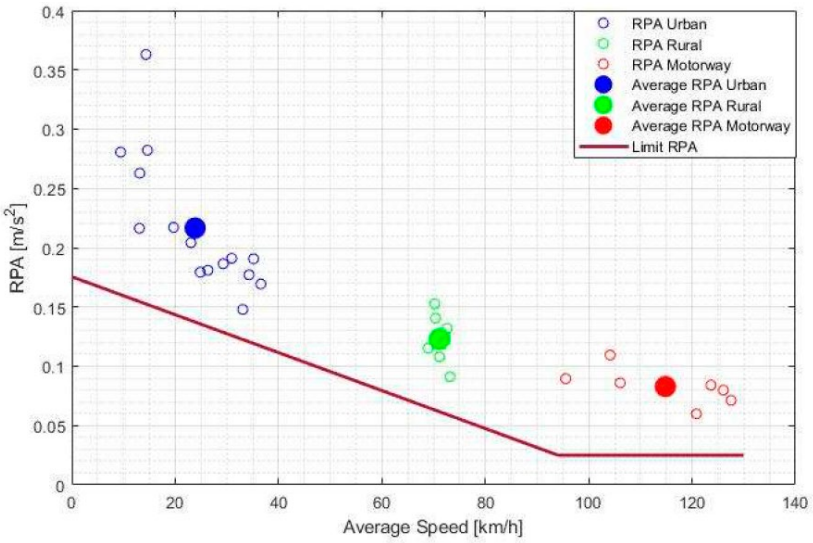


Figure 3.16 The RPA and average velocity of each trip segment.

The calculations left 15 urban travel segments (v ≤ 60 km/h), 6 rural travel segments (60 km/h < v ≤ 90 km/h) and 7 motorway travel segments (v > 90 km/h). The concatenated speed profiles for each trip type are available in Figure 3.17.

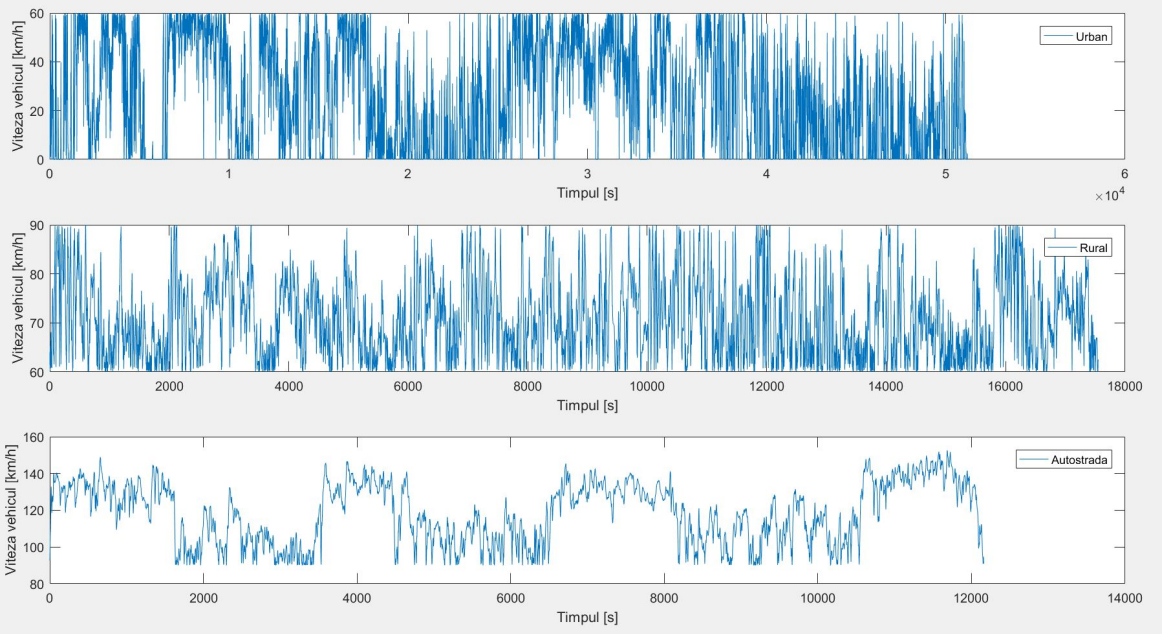


Figure 3.17 Speed profiles of concatenated routes for each type of travel

The speed profiles for the relevant trip segments are used as input data for the test cycle in a complex model of a class C SUV developed using the Imagine.Lab AMESim LMS. Using the model presented in Figure 3.1, CO_2 emissions were determined for low and high dynamic cycles in each category (urban, road and motorway) to assess the influence of using the proposed classification criteria.

Table 3.3 CO_2 emissions for low and high dynamic cycles.

Segment	Dynamicity	RPA [m/s²]	(v·a_pos)_[95] [m²/s³]	V_med [km/h]	CO₂ Emissions[g/km]		CO₂ emissions ratio [-]
					For segment	For v_med	
Urban	High	0,363	16,94	14,87	194,1	151,2	1,284
	Low	0,147	11,55	33,37	110,9	78,4	1,414
Rural	High	0,152	18,33	70,2	95,9	91,4	1,049
	Low	0,091	12,9	73,08	96,1	92	1,045
Highway	High	0,109	18,3	104,1	145,6	138	1,055
	Low	0,059	16,95	120,8	185,1	176,6	1,048

To compare the influence on CO_2 emissions consumption of different test cycles, we define a parameter called the CO_2 emissions ratio (CO_2_re), formula 3.9.

$$CO_2_re = \frac{CO_2_ciclu}{CO_2_v_ct} \cdot 100\ [\%] \tag{3.9}$$

where:

- CO_2_ciclu is the CO_2 emission obtained in the tested cycle;
- $CO_2_v_ct$ is the CO_2 emission obtained at a constant speed equal to the average speed of the respective cycle;

From the data in Table 3.3, we can see that there is no simple correlation between the chosen cycle dynamics parameters and CO_2 emissions. In urban driving, high dynamics corresponds to a cycle with a low average speed. The engine will operate at a disadvantage and fuel consumption (and thus CO_2 emissions) will be high, in this particular case 75% higher than in the case of low dynamics driving. For motorway driving, low dynamics corresponds to a cycle with a high average speed, which will increase CO_2 emissions. For the simulated examples, it is 27% higher when driving dynamics are low. In rural driving, the two trends compensate, and the differences between high and low dynamics driving are below 0.2%.

A limitation of the resulting trip segments is the low specific power of the test vehicle, which can influence the overall driving dynamics. Therefore, the recordings should be used for studies on vehicles with similar specific power. However, for each type of driving segment, a significant difference between the driving dynamics characterization parameters was obtained: from 67% to 145% for RPA and from 8% to 47% for v·apos 95%.

If the influence of the average vehicle speed is removed using the CO_2 emission ratio, it is observed that the influence of cycle dynamics is reduced from 75% to 9% in urban driving and becomes insignificant (less than 0.7%) in rural and highway driving.

IV. Assessing the real impact of CO_2 emission reduction measures

Next, a method is proposed to evaluate the real impact of CO_2 emission reduction measures using registration databases. These allow us to have a better representativeness of the results by providing a larger data sample, covering a wide range of vehicle usage modes.

In order to have access to such a registration database, a doctoral collaboration agreement was concluded between the 3 parties involved:

- National University of Science and Technology POLITEHNICA Bucharest (UPB), Doctoral School "Transports";
- HORSE POWERTRAIN SA, as owner of the registration database;
- Constantin Răzvan Cornel, as a doctoral student and employee of HORSE POWERTRAIN SA in the HORSE R&D CUSTOMER PERFORMANCE department.

This provides access to a database of records of over 7000 cars, personal vehicles and vans registered in over 35 countries.

It totals almost 900,000 trips over 250,000 recorded hours and 8.6 million kilometres travelled. In order to obtain relevant results for the studied vehicle (through simulation with a model developed in LMS Imagine.Lab AMESim) it will be necessary to filter the records according to the type of vehicle and its constructive solution but also according to the available recorded parameters. This will create a smaller but representative database and reduce the simulation time to a reasonable value.

In order to obtain relevant results for the studied vehicle (through simulation with a model developed in LMS Imagine.Lab AMESim) it will be necessary to filter the records according to the type of vehicle and its constructive solution but also according to the available recorded parameters. This will create a smaller but representative database and reduce the simulation time to a reasonable value.

To study the impact of Stop & Start technology on CO_2 emissions, the analysis of a segment of SUV type vehicles in the C class was chosen. The selection of records was made according to the recorded parameters available and necessary for the Stop & Start analysis, namely: vehicle speed, reverse signal, brake signal, external temperature and coolant temperature. There are also other parameters that can influence the activation of the Stop & Start system, such as: battery charge status, various electrical consumers, passenger compartment air conditioning, seat belt status, etc. However, signals for such parameters were not found in the database, therefore, the filtering of records was performed according to the parameters mentioned above. The filtering resulted in 24 records for vehicles of the Dacia Duster type with spark ignition engine, from two European countries. These together have the following characteristics: 326 recorded days, 412 driving hours, 16286 km travelled and 1562 routes.

The recorded signals come at different frequencies, usually between 50 Hz and 5 Hz, depending on the importance of the parameters and their rate of variation. To facilitate calculations and simulations on these cycles, the signals were converted to a frequency of 1 Hz according to the RDE procedure by using the tool developed within the thesis.

Using the Matlab programming language, for each vehicle selected from the registration database, data such as: the number of routes travelled, the number of days elapsed from the start of the recording to its end, the time spent driving and the distance travelled were extracted. It was

possible to observe the high variability of the recordings, from 4 to 23 recorded days, with a number of routes varying from 12 to 110 depending on the driver's habits. Also, both the actual duration of the recording (from 4 hours to 33.8 hours) and the distance travelled (117 km to 2519 km) offer significant fluctuations, with no precise correlation between them and the number of routes or days recorded. This is a good indicator of the very varied way in which drivers use their vehicles and the need to study their real-life travel.

Additionally, the percentage of time spent and distance traveled in urban, rural and motorway driving environments defined according to the RDE procedure was calculated. It was discovered that for all vehicles the majority of time is spent in the urban driving environment, which would favor the activation of the Stop & Start system and from the point of view of the distance traveled in the 3 driving modes there is a more balanced mix.

4.1 Definition and verification of different Stop & Start technologies

The Stop-Start system, also known as Stop & Start (S&S), is an engine control strategy that allows the engine to be stopped when it is idling, in order to reduce fuel consumption and pollutant emissions, especially in urban driving.

The Stop & Start system can have different developments depending on the technologies available on the vehicle on which it is implemented. Starting from the available recorded parameters, the following types of Stop & Start (Table 4.1) have been defined to evaluate the impact of each strategy.

Stop & Start strategy	Activation speed	Coolant temperature	Exterior temperature	Speed since trip started	Speed since last stop	Speed since last reverse gear	Reverse gear not engaged	Brake pedal pressed at the beginning of phase	Speed negative gradient
Simplified	0 km/h								
Classic	< 3 km/h	40°C < T_lr < 95°C	-5°C < T_ext < 35°C	> 20 km/h	> 6 km/h		yes		
Coasting Low Speed	<= 8 km/h	40°C < T_lr < 95°C	-5°C < T_ext < 35°C	> 20 km/h	>= 8 km/h	> 9 km/h	yes	yes	> 1 s
Coasting High Speed	<= 21 km/h	40°C < T_lr < 95°C	-5°C < T_ext < 35°C	> 21 km/h	>= 21 km/h	> 9 km/h	yes	yes	> 2 s
Complete	Depends on strategy	40°C < T_lr < 95°C	-5°C < T_ext < 35°C	Depends on strategy	Depends on strategy	Depends on strategy	yes	Depends on strategy	Depends on strategy

Table 4.1 The conditions of each Stop & Start strategy

Next, the number of activations of each type of Stop & Start system was calculated for each registered vehicle, the results being presented in Figure 4.1.

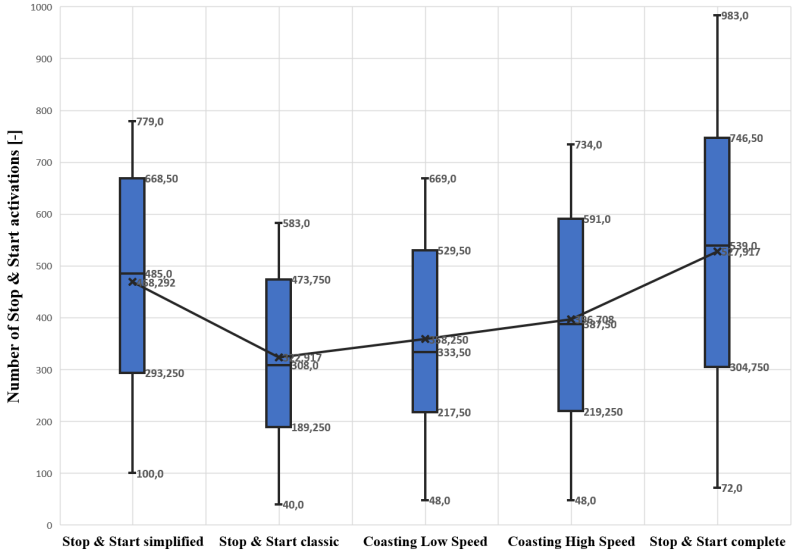


Figure 4.1 Number of activations of each type of Stop & Start system for the registered population

As the range of conditions is widened (by increasing the speed of system activation) the potential for a Stop & Start event to occur increases. Thus, a vehicle that benefits from all Stop & Start systems will be able to achieve the greatest reduction in CO_2 emissions. The large size of the box indicates a large dispersion of the data and the position of the median suggests an approximately symmetrical distribution of the data.

4.2 The model used to simulate CO_2 emissions

The study is carried out using a model developed in LMS Imagine.Lab AMESim, and allows the modification of Stop & Start strategies and the evaluation of CO_2 emissions (Figure 4.2).

To change the Stop & Start strategy, 3 signals were calculated based on the available parameters and the conditions of each of the 4 cases presented previously. For this, the MATLAB programming environment was used where the respective conditions were coded and the resulting code was run on the population of 24 records.

The respective signals are:

- the S&S signal that enters the engine control unit
- the signal for starting the starter
- the switching signal between the starter and the alternator.

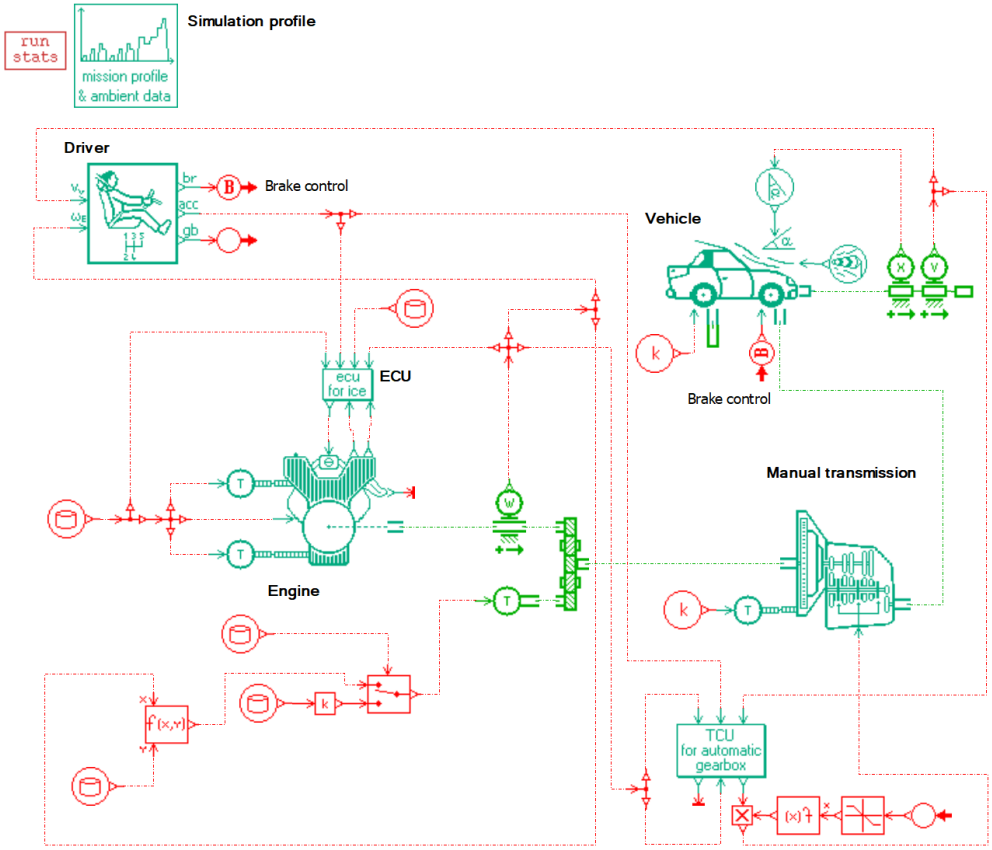


Figure 4.2 Vehicle and powertrain model for CO_2 emission calculation by implementing Stop & Start strategies

Additionally, signals for vehicle speed, reverse gear activation, outside temperature, coolant temperature and brake were saved to be used together with those calculated for Start & Stop as input data in the model. The routes of each customer were concatenated to reduce the total number of simulations required. To assess the effectiveness of Stop & Start systems, simulations will also be performed for a vehicle that does not have these systems.

4.3 CO_2 emissions results obtained through simulation

The simulation results are presented in Figure 4.3 where we can see the CO_2 emissions for each type of Stop & Start as well as for the case where the car is not equipped with this technology. The car that benefits from all Stop & Start technologies will offer the lowest CO_2 emissions, with an average value of 158 g/km compared to 169 g/km for a vehicle without Stop & Start.

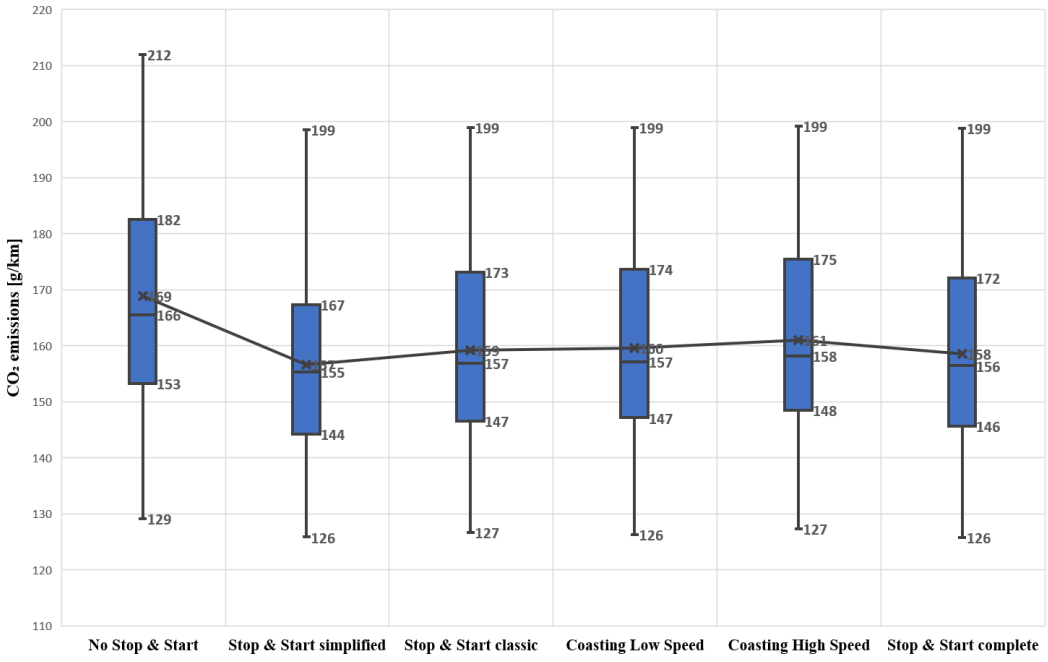


Figure 4.3 CO_2 emissions for each type of Stop & Start

However, the differences in emissions between the 4 types of Stop & Start are not as significant as we would have thought if we had only looked at the number of activations. For example, an average number of activations of the full Stop & Start system that is 36% higher than that of freewheeling at increased speed results in average CO_2 emissions that are only 1.3% lower.

We can see a large variation in CO_2 emissions between the simulation results of the 24 customers. They range between 129g/km and 212g/km for a standard vehicle and 126g/km to 199g/km for a vehicle equipped with full Stop & Start. These results highlight the need to perform recordings and simulations on real driving cycles. Comparing the results from chapter 3.1.4 where the reduction in CO_2 emissions for an SUV equipped with a simplified Stop & Start system was calculated on the WLTP cycle, we can see that the 2.4% gain obtained then has no counterpart in reality. The results obtained from the simulations on recordings produced an average value of 7%.

However, by introducing the rest of the variables that take into account the driving conditions, the value is reduced to 4.92% for a classic Stop & Start system.

Figure 4.4 shows the percentage of CO_2 emission reduction for each type of Stop & Start compared to a vehicle not equipped with this technology. The lowest CO_2 emission reduction is provided by the coasting system with an average value of 4.48%, although it is activated more often than the first two systems. This is due to the fact that, due to the imposed conditions, the system is activated very often in traffic jams, where the vehicle does not come to a complete stop. Short stops that occur under these conditions determine a large number of starts, which will lead to an increase in consumption, thus reducing the benefits of the system. Therefore, the Stop & Start strategy during coasting requires a more complex implementation that takes into account traffic conditions. The full Stop & Start system offers the greatest reduction in CO_2 emissions with an average value of 5.93%, reaching up to 16.37% for the customer with the most favourable conditions.

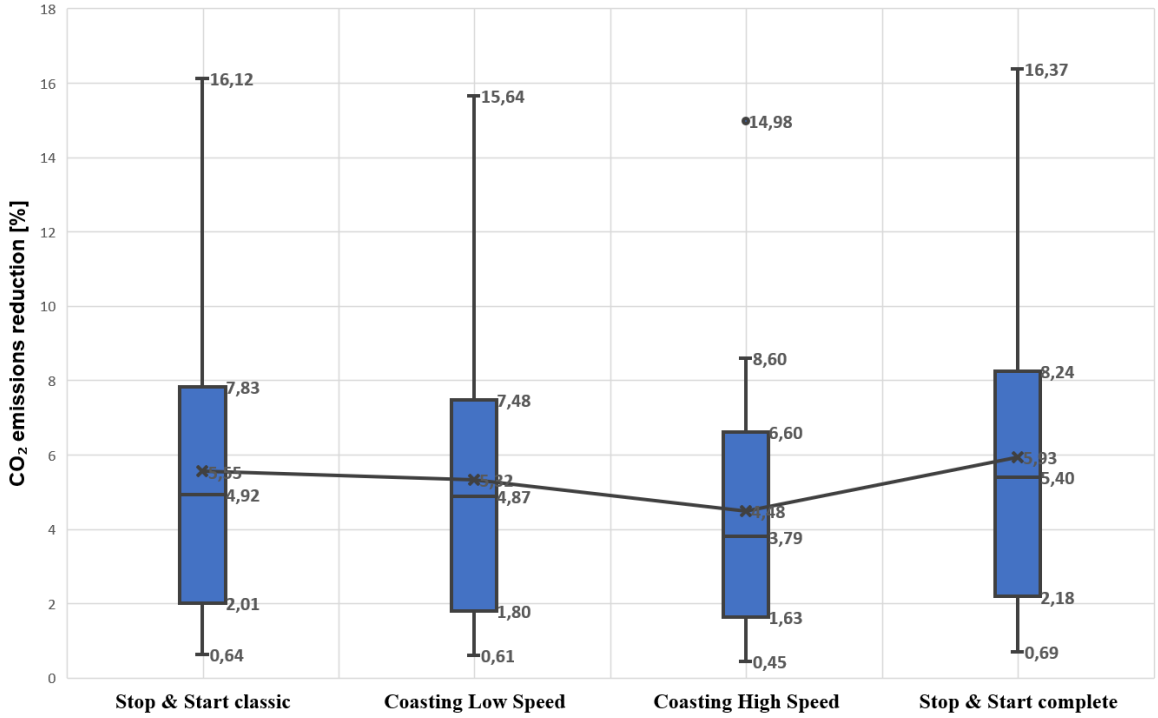


Figure 4.4 Percentage of CO_2 emission reduction for each type of Stop & Start

4.4 In-depth research of customer with extreme results

The results obtained show a large variability in the CO_2 emission gain, from 0.45% for the worst case of free running at increased speed to 16.37% for the best case with full Stop & Start. To better understand the results, we will focus on the extreme cases from the full Stop & Start simulations. As a result, vehicle 8 with a CO_2 emission reduction of 16.37% was selected as the most favourable case and vehicle 21 with a CO_2 emission reduction of 0.69% located at the opposite end.

To better understand the travel mode of these two registered vehicles we will first look at the time spent per speed class (Figure 4.5) and the number of Stop & Start activations per kilometre (Figure 4.6).

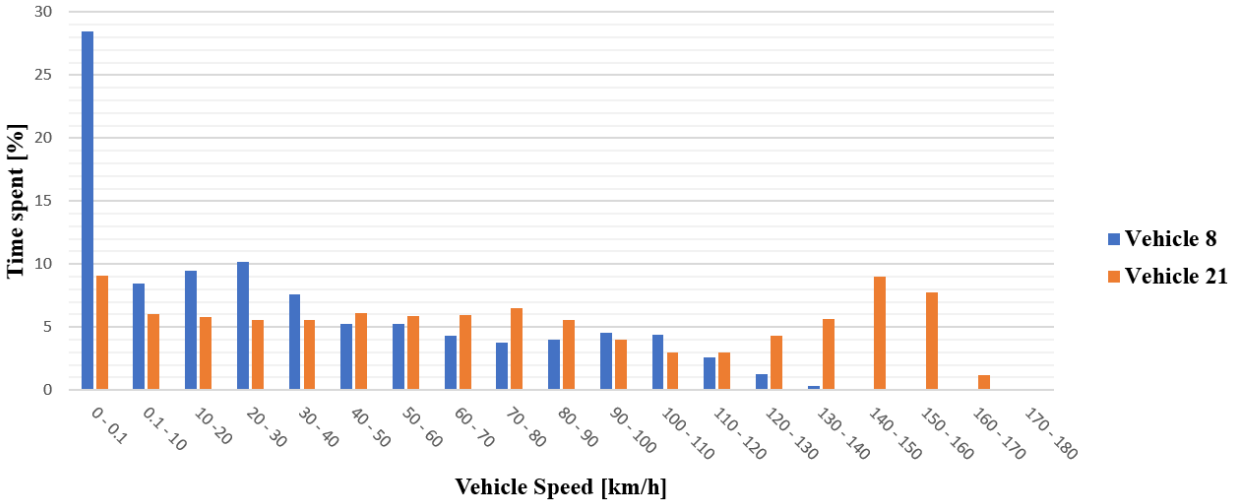


Figure 4.5 Percentage of time spent in speed classes for selected vehicles

It can be seen that vehicle 8 spent more time at low speeds, which allowed it to activate the Stop & Start system much more often than vehicle 21, which had a considerable percentage of time spent at highway speeds. It can also be seen that the classic Stop & Start system was activated 4.8 times more often for vehicle 8 and the complete one 4.2 times more often.

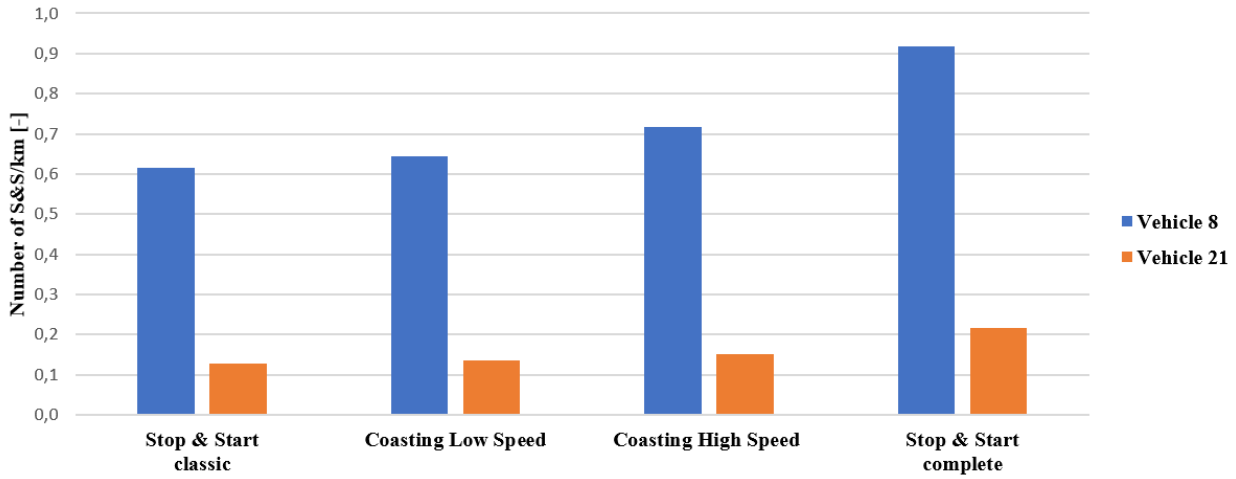


Figure 4.6 Number of Stop & Start activations per kilometre for selected vehicles

Based on these analyses, we can conclude that the results obtained on these two recordings are consistent with their driving style. It should be noted that not all parameters that influence the activation of the Stop & Start system were available for analysis (battery charge status, air conditioning, electrical consumers, etc.), therefore the real results would be even lower. Also, the external temperature of the selected recordings was within the limits of the activation of the Stop & Start system and did not have a strong impact on the results.

4.5 Calculating CO_2 emission reduction for a car fleet

To calculate CO_2 emissions at a reliability target, a method using formula 4.1 will be used. by developing a code in Matlab and applying it to previous results obtained in simulations. To ensure that the mixture is representative, the CO_2 emissions results will be multiplied only by the NCBS (New Car Buyer Survey) mileage which is a maximum of ±20% different from that of the records. The NCBS surveys contain the annual distance declared by hundreds of thousands of drivers for the 4 modes of travel but also other data related to the way of using the vehicles (number of passengers, luggage, towing, etc.)

$$R(n,p) = R(n) \cdot D(p); \qquad (4.1)$$

where:

- $R(n,p)$ represents the final result calculated for a client(n) mixed with one(p) from NCBS;
- $R(n)$ represents the result per kilometre for a simulated customer (n);
- $D(p)$ represents the distance travelled declared in NCBS for a customer (p);

The results, which are calculated for a reliability target of 1 year or 30,000 km, are sorted in ascending order and each value is assigned a weight according to the total number of results. Their graphical representation according to the percentage of participation of each value will be called an S-curve and is available in Figure 4.7. Looking in detail at the graph we can see how the curves with Stop & Start are shifted to the left compared to the results without this system. Therefore, it can be seen that the full Stop & Start system offers the best reduction in CO_2 emissions and at the opposite end is free running at increased speed.

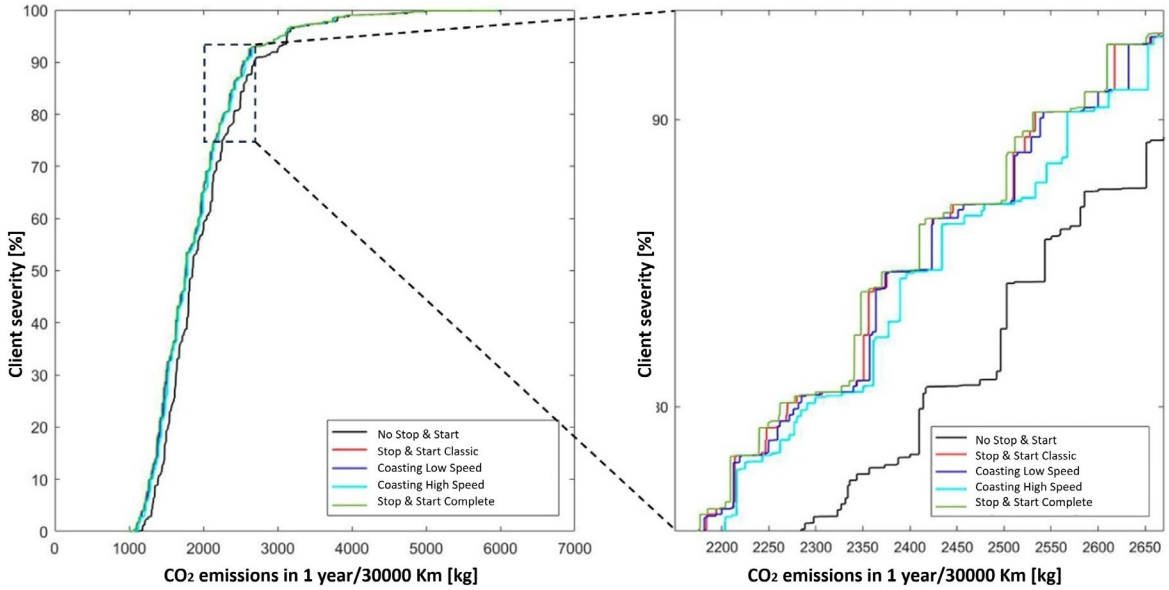


Figure 4.7 S-curves with CO_2 emissions produced in 1 year or 30,000km

To quantify these results for each type of Stop & Start, the results for severe customers 50%, 90%, 96%, 99% and the average one will be calculated as in the example in Figure 4.8 for CO_2 emissions produced without the Stop & Start system. The results will be summarized in Table 4.2.

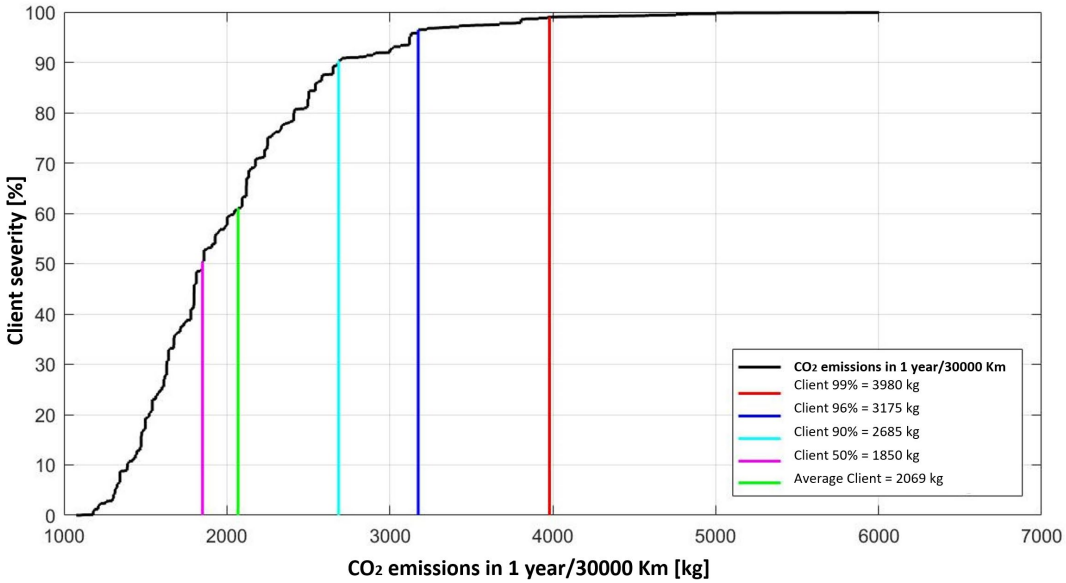


Figure 4.8 CO_2 emissions produced in 1 year or 30,000km without the Stop & Start system.

Table 4.2 CO_2 emissions produced in 1 year or 30,000km

Stop & Start strategy	CO_2 emissions [kg]				
	Average Client	Client 50%	Client 90%	Client 96%	Client 99%
No Stop & Start	2069	1850	2685	3175	3980
Stop & Start classic	1958	1767	2533	3137	3921
Coasting Low Speed	1962	1769	2539	3138	3924
Coasting High Speed	1978	1784	2567	3143	3933
Stop & Start complete	1950	1754	2531	3133	3916

Looking at the data in Table 4.4 we can see a large variability of the results between the average and the most severe customer (99%) who recorded results twice as high. On average, a car will produce 119 kg of CO_2 less in a year or 30,000km if it is equipped with a full Stop & Start system compared to a conventional car.

We can further extrapolate the results to the sales of new cars of a car manufacturer, for example Dacia, which in 2023 sold 200,633 new Duster models in Europe. If on average the gain in CO_2 emissions for the respective car fleet is similar to the one obtained above then we can conclude that in one year an average reduction in CO_2 emissions of 23,875 tons can be achieved by using a full Stop & Start system.

We can also calculate what the CO_2 emissions will be produced over the entire life of the car using formula 4.2:

$$E_{tot} = \sum_{k=1}^{m} R_n \cdot D_p \cdot \frac{100-\theta_k}{100}; \quad (4.2)$$

where:

- E_{tot} represents the total result of CO_2 emissions produced over the entire life of the car measured in years (m);
- R_n represents the result per kilometre for a simulated customer (n);

- D_p represents the distance travelled declared in NCBS for a customer (p);
- θ_k represents the coefficient from the turnover law corresponding to year k.

The results of CO_2 emissions produced over the entire life of the car are available in Table 4.2.

Table 4.2 CO_2 emissions produced in 20 years or 300,000km

Stop & Start strategy	CO_2 emissions [tones]				
	Average Client	Client 50%	Client 90%	Client 96%	Client 99%
No Stop & Start	25,52	23,97	31,62	36,24	40,26
Stop & Start classic	24,09	23,08	29,3	33,19	39,62
Coasting Low Speed	24,15	23,07	29,39	33,2	39,7
Coasting High Speed	24,36	23,26	29,81	33,26	39,79
Stop & Start complete	23,99	22,98	29,19	33,15	39,57

It can be seen that on average a car equipped with the Stop & Start system will produce approximately 24 tons of CO_2 during its operation, which will represent a reduction of 1.54 tons of CO_2 compared to a car without this technology.

For a complete balance of CO_2 emissions of a car throughout its life we must also take into account the emissions produced with the production of fuel, the manufacture of the car and its maintenance. For a SUV with a petrol engine, the emissions resulting from the production of fuel can reach 20% of the emissions resulting during operation, those from the manufacture of the car at 17% and those produced by the maintenance process at 3%. Thus, the total CO_2 emissions of an SUV car during its life can reach an average of approximately 33.6 tons.

V. Synthesis of original contributions and perspectives for further research

5.1 Main original contributions of the paper

1. The paper highlights the need to study real driving cycles in the field of reducing CO_2 emissions from automobiles and proposes a four-step solution for assessing the impact of different technologies in this field:

   a) Recording on vehicles in circulation, where signal recording solutions are presented, even bypassing CAN protection or using pre-existing databases;

   b) Storing and manipulating such recordings, as part of the paper a program is created for this purpose;

   c) Modelling the vehicle to be studied by implementing different CO_2 emission reduction technologies and simulating it on real driving cycles to calculate CO_2 emissions;

   d) Calculating the real impact of the respective measures by presenting a method for bringing the results to a reliability objective.

2. The work developed a program that facilitates the work with registrations and homologation cycles. It allows their management, conversion, visualization and analysis, as well as the calculation of different cycle characteristics or a simplified Stop & Start signal.
3. It was demonstrated that, using available technologies, a significant reduction in CO_2 emissions between 13.7% and 16.7% can be achieved, depending on the type of vehicle and the test cycle adopted.
4. The efficiency of coordinated platoon driving in order to reduce CO_2 emissions was analysed in detail, where it was shown that an improvement in emissions by 18.1% compared to an isolated vehicle is possible by using a coordinated platoon of 7 vehicles.
5. For electric cars, a method was presented for converting electricity consumption into CO_2 emissions and calculating them for different technologies for their improvement.
6. CAN recordings were made on an SUV vehicle and the RDE procedure was applied to evaluate their dynamics and analyse its impact on CO_2 emissions.
7. In order to carry out analyses on a database of customer vehicle records, a collaboration agreement was concluded between the National University of Science and Technology POLITEHNICA Bucharest (UPB), the Doctoral School "Transports" and HORSE POWERTRAIN Ltd., as the owner of the database of records.
8. A method for analysing the impact of measures to reduce CO_2 emissions by using database records was developed and was exemplified by implementing Stop & Start technology on it through simulation.
9. The driving style of the registered vehicles was analysed and the dependence between this and the efficiency of the Stop & Start system in reducing CO_2 emissions was demonstrated.
10. In order to assess the total real impact of the Stop & Start system on CO_2 emissions, a method for calculating them over the entire life of the vehicle was presented.

5.2 Prospects for continuing studies

The work steps proposed in the paper can also be used to assess the real impact of other technologies and methods for reducing CO_2 emissions. Although the paper focused on decarbonization with the aim of slowing down global warming, the methods and models used can also be used to calculate pollutant emissions or fuel consumption of motor vehicles.

The recordings management program can also be adapted to other needs. Depending on the recorded parameters, new functions or calculations can be added to meet other requirements.

Specifically, the work done in the completion of the doctoral thesis will be used within a research project with national public funding, namely "Study of the impact of energy optimization measures in road transport" (GNAC ARUT 2023 program) of the National University of Science and Technology POLITEHNICA Bucharest. As a member of this project, I will apply the knowledge acquired through the design of this work to carry out vehicle registrations, create a registration database by adapting the already developed program to new needs, and analyse the impact of the energy optimization measures that will be implemented.