Fuel Saving Potentials of HDVs through Platooning based on Real GPS Traces.

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Master’s Degree Project
Stockholm, Sweden March 2014

XR-EE-RT 2014:008
Abstract

In the last years, the increase of the fuel price and the need to reduce the greenhouse gas emissions have triggered the research on lowering the fuel consumption within the transport sector. The research not only involves the development of more efficient engines but also the exploration of new transportation paradigms. One promising approach is to create vehicle platoons, i.e., convoys of vehicles driving close to each other. Vehicles driving close behind benefit from the reduction of the air drag and hence their overall fuel consumptions are reduced.

This work focuses on studying platoons of heavy-duty vehicles (HDVs). More specifically, the work analyzes real position data of an HDV fleet from one manufacturer. The objective is to determine the potentials to reduce the fuel consumption of the fleet through platoon formations, using low sampled GPS traces obtained from the fleet management system. Map matching and path inference algorithms have been developed to reconstruct the path of the vehicles on a given road network.

The reconstructed paths are used to analyze the vehicles’ positions and inter-vehicle distances. Results show that the vehicles are widely spread. The average distance to the closest vehicle is greater than 20km, which limits the platoon opportunities. Although with limited platoon opportunities, potential fuel savings up to 0.14% of the whole fleet’s consumption have been obtained. Results suggest that fuel savings can be largely improved if the density of vehicles in the road network is increased.
Acknowledgements

First, I would like to thank Kuo-Yun Liang for the guidance and patient support during the whole project. I also want to express my gratitude to the co-supervisors Karl Henrik Johansson and Jonas Mårtensson for introducing the topic and for the useful inputs provided. Without them, this thesis should not have been possible.

The work of this thesis has been based on the data provided by Scania AB. Kuo-Yun Liang must be acknowledged again for processing the data and making the task of this thesis easier.

Last, but not least, I also want to thank the support and encouragement received from friends and family. I want to express my gratitude to the people I have met at KTH School of Electrical engineering for making every day of this thesis enjoyable.
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Chapter 1

Introduction

Intelligent transportation systems are needed to face the future challenges in transportation. One approach in this field is to form vehicle platoons, i.e., convoys of vehicles driving close to each other. Among other benefits, the vehicles platooning experience a reduction of the air drag that enables fuel savings. This work focuses on these potential benefits in fuel consumption and tries to estimate the savings for heavy duty vehicles (HDVs) on a network.

This thesis follows from other previous works in the same topic as a part of a collaborative project between KTH and Scania AB. For this reason, particular emphasis has been placed in describing the criteria and methods used to obtain the results.

1.1 Motivation

In the last years, the transportation world has been experiencing big changes in terms of consumption. The society is every day more concerned about the global warming and the fuel cost. This fact has triggered the development of low-consumption eco-friendly technologies. One promising approach to reduce the fuel consumption is to create platoons of vehicles. The fuel reduction is achieved thanks to the air drag reduction when vehicles are placed close behind. Currently, programs like COMPANION [8], SARTRE [24], PATH [21], GCDC [11], KONVOI [15] investigate the use of platoons with that objective.

Platooning is especially interesting for commercial transportation and in particular for HDVs. HDV transportation is a competitive sector where the fuel cost is a big concern. For long haulage HDVs, the cost of the fuel is estimated to be about 30% of the total life cycle cost [1]. Thus, a small reduction of the fuel consumption can lead to significant reduction of the total cost. Moreover, the common long motorway journeys of HDV have the appropriate characteristics to exploit the platoon benefits. These reasons have motivated numerous studies in that topic, by now mostly focused in inter-distance control strategies. However, the platoon coordination and its feasibility in the current road and traffic conditions still remain unclear.

1.2 Objective

In this thesis we analyze HDVs trips based on real vehicle data to determine the potential fuel savings when the vehicles are arranged in platoons. Several issues arise before the fuel savings can be quantified. The source data consists of conventional GPS positions that must be processed to remove undesired information and to enhance the accuracy of the fuel analysis. Moreover, a strategy to form platoons must be defined in order to explore the potential fuel reduction. Such a strategy will be dependent on
a fuel consumption model that takes into account the fuel benefits when the vehicles are platooning.

The work is aimed to provide a plausible approach to form platoons to reduce the fuel consumption. The aspects to consider to form a platoon are the same whatever might be the types of vehicles involved. For this reason, part of the work of this thesis has a more general scope than the specific HDV transports. The approaches developed in this work can also be applied to other type of vehicles although considering other parameter values.

The main part of the thesis will be devoted to quantifying the fuel savings based on real data of HDV positions. The source data consists on GPS positions of HDVs obtained from Scania’s fleet management system. The data will be used to determine if the type of vehicles and the characteristics of their trips allow to reduce significantly the fuel consumption via platooning. Also, the effects of the characteristics of data analyzed on the fuel savings will be studied. The results must provide an insight of the actions to develop to improve the rate of vehicles platooning and the general fuel savings.

Last but not least, the work must also enclose the necessary processing of the GPS data. The GPS positions are recorded during intervals of about 5-10 minutes. Intervals are not regular and the GPS samples of every vehicle are not synchronous. Moreover, a map source is used to identify the unknown paths between GPS samples. The approaches adopted can serve as a reference to future work in the field.

1.3 Related Work

The idea of creating platoons is not new, Shladover ([25]) already discussed the platoon benefits in 1979. Platoons were initially motivated by the need to increase the throughput and safety of the roads. There exist several studies looking for different approaches to coordinate the vehicles in order to maximize the capacity of the lanes. For example R. Hall and C. Chin ([13]) evaluated strategies to form platoons at the entrance ramps of the motorways. The objective was to maximize the distance the platoons stayed intact. In terms of fuel savings, maintaining the platoons intact can avoid maneuvers that increase the final fuel consumption and make less safe the platoons. Recently, C.M. Clark proposed an strategy to form platoons at the entrance of the road by solving an optimization problem [9].

In the last years, studies on platoons have started to focus on the additional benefits of fuel reduction rather than increasing traffic throughput. One of the first experiments on fuel reduction when vehicles are arranged in platoons was performed in California in the PATH program (Partners for Advance Transportation Technology)[19]. The study was focused only on cars and it stated fuel saving up to 10% (3 vehicles within 3m gap) obtained from field measurements on real roads. In a posterior study in the same PATH framework the experiments have been conducted with a HDV tandem[6]. The results show a fuel reduction of about 8% when the average space between vehicle was 6-10m. A. Alam ([2]) obtained similar results when measuring the fuel consumption of two platooning HDVs coupled with an adaptive cruise control in an experiment.
1.3. RELATED WORK

conducted on Swedish roads.

Little literature exists concerning strategies of platoon formation for reducing the fuel consumption. The feasibility for a HDV to catch up with a platoon is studied in [17]. In the article, platoons are formed by slightly increasing the velocity of the rear vehicle. The cost of platoon formation and the savings via platooning are studied as a function of the inter-vehicle distance, velocity and distance to destination. Another study focuses on analyzing the potential fuel savings via platooning when a coordination route system is introduced [16]. The coordination route system consists of local controllers distributed over the junctions of the road network. The local controllers induce slight adjustments in the velocity of the incoming vehicles in order to form platoons. The control scheme has been tested with simulated data. A large scale simulation on the German autobahn shows fuel savings up to 9%.

Until today, the only study involving HDVs and real GPS data the author is aware of is the one developed in [14]. The research is not on platoon formation. However, the data preprocessing of the GPS data for HDV trips is close related to this work. The article deals with identifying the possible different journeys in a set of GPS traces for a particular vehicle.
Chapter 2

Approach

This thesis studies the fuel savings when platoons of HDVs are formed based on real GPS data. Certainly, there is no unique approach to form platoons and quantify the fuel savings. The problem can be approached in different ways depending on how the problem is formulated and the assumptions taken for modeling it.

The very first task to perform, before any analysis, will be to process the source data. The source data must be processed in order to obtain useful inputs for treating the problem. Moreover, the characteristics of the working data determine how the problem must be faced and the scope of the final results.

Prior to any attempt to form platoons, a first analysis of the current HDV distribution on the road network is proposed. The analysis will give a picture of the current characteristics of the HDV journeys and it can be used for comparisons later on. An issue to tackle is how to model the fuel consumption of a HDV.

After the initial analysis, the fuel savings via platoon formation are discussed. A platoon coordination strategy is defined at the end of Section 2.5.3.

In the coming sections of this chapter, the details involving the different tasks of this thesis are analyzed. An approach based on the characteristics of every task is proposed. The different parts of the approach will be discussed in the next chapters.

2.1 Data Source Characteristics

The data available for this work consists of series of low sampled GPS traces for around 7000 trucks driving on part of the European network. The map area is about 500,000 km\(^2\) and the data has been recorded during 24 hours. The data does not contain all the HDVs in traffic. It only contains the trajectories of Scania HDVs equipped with a GPS unit. The GPS traces contain information of:

- Trajectory: Sequence of position (latitude and longitude) and the timestamp of a specific vehicle recorded from the GPS system. The data is updated at irregular intervals of 5-10 minutes approximately.

- Vehicle ID: An unique distinctive number assigned to the data of each vehicle.

- Current Velocity: The absolute value of vehicle’s velocity in each position.

The GPS precision is estimated to be around few meters meanwhile the inter-vehicle distances handled in the platoon coordinations are about few hundreds of meters. Therefore, GPS accuracy does not seem as a limitation for obtaining the inter-vehicle distance. However, GPS traces are low sampled (samples every 5-10 minutes approximately) and the path that HDVs take from sample to sample is unknown. Furthermore,
there is no information regarding the vehicle direction and the specific road on which the vehicle is driving. Thus, a platoon coordination system could wrongly form a platoon between vehicles that are not in the same road. One possible solution to these problems is to match the GPS data with an existent road map. Identify the points of the road network where a vehicle is most likely to be is known as map matching (MM). Finding the path between two distant points in a road network is called path inference (PI). There exist a wide range of proposed solutions for both MM and PI.

2.2 Fuel Model

A fuel model is needed to compare the fuel consumption with and without platooning. Fuel consumption models for HDVs take the dynamics of the vehicle into account and involve several vehicles parameters such as gear ratio and efficiency, engine and wheels inertia, etc (See [1] for an accurate description). Such models are non-linear which can complicate the task of forming platoons according to the fuel consumed. Moreover, the parameters needed are not known in this work. On the other hand, precise dynamical models are especially required when computing the fuel consumption in quickly varying accelerations. In other cases, the contribution of the dynamics of the system are less important and simpler models can give a good estimation. That is the case of the platoon scenarios, where smooth changes in velocity are expected. Furthermore, the aim of the work is to determine the differences in normal conditions or when platooning rather than to compute accurately the fuel consumption. A simple fuel model considering the main longitudinal forces can meet these requirements. By applying Newton’s second law we have:

\[ m_t \frac{dv}{dt} = F_{eng} - F_b - F_{ad} - F_g - F_r \]  (2.1)

From left to right, the different terms of the equality are the force exerted for the engine, the brake system force, the air drag, the gravitational force and the roll resistance. \( m_t \) is the accelerated mass of the vehicle that takes into account the inertia momentums of mobile parts of the vehicle. As the variations in velocity are expected to be smooth, the accelerations will not be considered. This simplification is valid when the cost due to short accelerations is small compared to the cost of traveling long distances at a constant speed. Hence, the force exerted by the engine considering that the brake system is not actuated will be:

\[ F_{eng} = F_{ad} + F_g + F_r \]  (2.2)

The gravitational force can be neglected considering the negative contribution to the movement going uphill will be compensated with positive contribution going downhill in a round trip. This assumption is valid as far as downhill slopes are small enough to avoid actuating on the brake system (typically less than -1.4% [1] for HDVs). Also, uphill slopes must be small enough for permitting a HDV to drive at a constant speed.
2.2. FUEL MODEL

(typically slopes less than 3.5% [1] for HDVs) making the air drag contribution equal going uphill or going downhill.

The air drag force is a negative contribution to the movement that can be reduced via platooning. The force can be modeled as follows:

\[ F_{ad} = \frac{1}{2} \rho A c_D v^2 \phi(d) \]  \hspace{1cm} (2.3)

where \( \rho \) is the air density, \( A \) is the cross sectional area, \( c_D \) the air drag coefficient that depends on the geometry of the vehicle and \( v \) the velocity of the vehicle. The coefficient \( \phi(d) \in [0, 1] \) takes into account the reduction of the air drag when platooning. It is a function of the inter-vehicle distance. The bigger the inter-vehicle distance, the lesser will be the reduction effects. The details of the dependence can be found in [1].

The main contribution of the roll resistance is dependent on the weight of the vehicle. For a vehicle traveling in a road with a slope of \( \alpha \) degrees, it can be modeled with a coefficient \( c_r \):

\[ F_r = m g c_r \cos \alpha \]  \hspace{1cm} (2.4)

The coefficient \( c_r \) depends on the velocity, tires, asphalt, temperature and other factors that are difficult to measure. Anderson ([3]) describes the models of the air drag and roll forces. He gives values of both coefficients for a HDV based on simulations and experimentation. A rough approximation using these values shows that both forces have the same order of magnitude for a 40t HDV driving at 80km/h. Specifically, the roll resistance accounts for the 60% and the air drag for the 40% of the force in the opposite direction to the movement.

In conclusion, the fuel consumption in a round trip at a constant speed will mainly be due to the air drag force and the roll resistance. The roll resistance depends on the slope of the road and we do not have information about that. Also, the coefficient \( c_r \) depends on the velocity and the relation is not linear. For these reason, this work does not take into account the roll resistance in a first instance. Without roll resistance, the engine force is proportional to the square of the velocity. In this way, the work exerted for the engine will be proportional to the distance driven and the square of the velocity. The factor of proportionality is not relevant because it is only pursued to derivate the ratio between platooning and not platooning fuel costs. Therefore, the fuel model can be described by:

\[ C = dv^2 \phi(d) \]  \hspace{1cm} (2.5)

Where \( d \) is the distance driven and \( v \) the velocity. The parameter \( \phi \) keeps modeling the reduction of the drag force when the vehicle is platooning. Platooning can induce reductions up to 30% of the air drag force. However, the roll resistance has been
omitted in a first instance and it remains constant when platooning. Thus, the real fuel benefits of platooning will not be directly proportional to the air drag reduction. For this reason, the fuel cost reduction when vehicles platoon considered in this work is only 10%, i.e. a value of 0.9 for $\phi$. This value is close to the 8% that some experiments with HDV platoons have obtained [2] [6].

In summary, the fuel model used in this work is the one described in 2.5 where $\phi$ takes the value 1 or 0.9 when normal conditions and when platooning respectively. Under this model, constant velocity profiles minimize the cost. Thus, whatever the vehicles distribution will be, the velocities of the vehicles will be constant until an event like a platoon formation occurs. Moreover, the neglected cost of the acceleration will contribute to make the constant velocity profile even more convenient.

2.3 Formulation of Coordination Problem

The platoon coordination system must be constricted to the specific characteristics of the real problem. However, the real problem can have multiple interpretations and different goals. In this master thesis, the problem has been modeled as follows:

Find a platoon coordination scheme for reducing the fuel consumption of the general transport network constricted to:

- None of the vehicles must be forced to consume more fuel than the amount it will originally consume.
- None of the vehicle journeys will be considerably delayed compared to the original journey without platoon coordination.
- The velocity profiles have to be close to the current traffic regulations.

The first constrain accounts the fact that the transportation network is formed mostly for individuals. The vehicles involved might look for their own benefit but not for the global. The second restriction takes into account that transports can dependent of other factors. The driver salaries, delivery deadlines or drivers’ reluctance to do longer trips are some examples of factors that may not make possible longer journeys. The third restriction should be fulfilled if the system has to become a reality. Even though the platoon inter-vehicle distances might be currently out of the traffic regulations, it is important to maintain the velocities close to the current limitations in order to create a realistic system.

This work does not consider the possibility that the vehicles can change routes where more platoon opportunities might occur. The author of the thesis believes that the extra fuel savings considering this possibility are not relevant because in the working network there are not many alternative paths with similar lengths. Usually, there are not many motorways connecting the same two spots with similar paths. Moreover, previous studies considering rerouting obtained null increasing benefits when the rerouting involves larger paths than the original [16].
2.4 Definitions

Several concepts can be defined to narrow down the problem formulation and to facilitate later explanations. These concepts are presented below and they will be used in the next chapters of the master thesis.

**Inter-vehicle distance:** Distance of the shortest path through the road that connects one vehicle position to the other.

**Platooning distance:** Inter-vehicle distance a pair of vehicles maintain when they are platooning.

**Platooning range:** Maximum inter-vehicle distance a pair of vehicles can have to be considered for platoon coordination.

**Close vehicles:** Two vehicles are close vehicles if their inter-vehicle distance is smaller or equal to the platooning range.

**Platooning group:** A group of vehicles where every vehicle has at least a close vehicle in the group.

**Platoon event:** When merging the vehicles in a platoon group, the precise time when a vehicle catch up another one (their inter-vehicle distance becomes equal or shorter than the platooning distance). Also, it is the time instant when the platoon splits.

**Active vehicle:** Vehicle driving faster than a certain velocity. In this work the considered velocity is 50km/h.

**Common destination:** The farthest point shared by the paths of two vehicles meanwhile they are active vehicles.

Unless stated otherwise, all the distances referred in this work are the distances constrained to the road network. For instance, the distance to destination of a vehicle is computed from the current position of the vehicle to the destination following the road map.

2.5 Platoon Coordination

GPS positions of the different HDVs are available for creating platoons. Information about the position, direction and road can be obtained after processing the initial data of the GPS trajectories. The inputs of the platoon strategy can be extracted form this data: the distance between vehicles and the distance to destination of each vehicle.
2.5.1 Two Vehicles Problem

The first issue to tackle towards creating a complete platoon coordination system is when two close vehicles traveling alone should form a platoon. This problem has already been treated in [17], where none of the vehicles is forced to slow down. In this thesis, this strategy is referred as Strategy 1.

**Strategy 1**: The rear vehicle speeds up to catch the front vehicle. During the process, the front vehicle does not modify its velocity.

The underlying idea of the problem is that, although a fuel reduction is obtained for the follower vehicle when the platoon has formed, an additional cost of platoon formation exists because the follower is forced to speed up to catch up the vehicle ahead. Under these circumstances, a break-even ratio can be defined. The break-even ratio is defined as the ratio between the initial inter-vehicle distance and the distance to destination that makes that platoon formation beneficial. The expression for the break event ratio has been obtained from [17]:

\[
\frac{d_d}{d_p} \geq \frac{r_v}{r_v - 1} \left( \frac{r_v^2 - \phi}{1 - \phi} \right)
\]

(2.6)

Where \(d_d\) is the distance to the *common destination* for the follower vehicle, \(d_p\) is the initial inter-vehicle distance, \(r_v\) is the ratio in which the velocity of the rear vehicle is increased respect to the velocity of the lead vehicle and \(\phi\) is the air drag reduction coefficient. In the same article is defined an incentive factor \(\kappa\) as follows:

\[
\kappa = 1 - \frac{d_p}{d_d} \frac{r_v}{r_v - 1} (r_v^2 - \phi) - \phi
\]

(2.7)

The incentive factor accounts for the fuel saved due the air drag reduction through platooning. The value of \(\kappa\) is positive when fuel savings are achieved and negative otherwise. One interesting point is to see how the \(\kappa\) value depends on the velocity and the distance ratio. The function \(\kappa(r_v)\) in the range of interest for different values of \(\frac{d_d}{d_p}\) (considering the air drag reduction \(\phi = 0.68\) as in [17]) is plotted in Figure 2.1. The function has a maximum in \(r_v \approx 1.3\), which does not depend on the distance ratio. In conclusion, the optimum velocity to catch up (the one with higher fuel savings) does not depend on \(\frac{d_d}{d_p}\).
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Figure 2.1: Incentive factor $\kappa$ as function of the velocity ratio $r_v$. Different curves account for different distance to the common destination and inter-vehicle distance ratios.

But what happens when first vehicle slows down such that the follower does not need to accelerate? This situation contradicts one of the constrains imposed in this work: the travel time of any vehicle must not be longer than the original. Thus, after merging, the two vehicles must be forced to speed up to make up for lost time and fulfill the constrains of the problem. The strategy has been called Strategy 2 in this work.

**Strategy 2:** The front vehicle slows down in order to merge with the rear vehicle. The rear vehicle does not modify its velocity. After merging, both vehicles speed up to make up the lost time during the merging process.

The fuel implications of the Strategy 2 compared to the Strategy 1 can be summarized with the next two points:

- **The front vehicle consumes more fuel:** The velocity profile that minimizes the cost keeping the time constrains is a constant velocity. Any other velocity schemes, like the initial slow down suggested, increases the cost.

- **The rear vehicle saves fuel:** The rear vehicle will have to speed up anyway to reach the destination at the same time of the first strategy. The difference is that it will speed up when platooning.

The costs of the Strategy 2 and 1 are not directly comparable. The costs depend on the velocity profiles chosen in each strategy. For comparison purposes, it is defined an scenario where both strategies leaves to similar timings. We consider the following scenario:
• All the vehicles drive at the same speed $v$ when they are not catching up or slowing down.

• The same velocity difference $\Delta v$ exists in the platoon formation in Strategy 2 (front vehicle slows down) and the platoon formation in Strategy 1 (rear vehicle speeds up).

• Strategy 2 increases the velocity of both vehicles with the same velocity difference $\Delta v$ for making up lost time.

In the previous scenario, the time required to form a platoon is the same between Strategy 2 and Strategy 1. Also, the rear vehicle spends the same time speeding up in both strategies, but at different time intervals. In these conditions, we compare the cost of both strategies. Figure 2.2 depicts the relevant distances for the comparison. $d_{p0}$ is the initial inter-vehicle distance, $d_{c1}$ is the distance where the vehicle $b$ catches the $a$ with the Strategy 1, $d_{c2}$ is the distance where the $b$ catches the $a$ with the Strategy 2, $d_{su}$ is the distance required to make up the lost time when speeding up and $d_n = (d_{c2} + d_{su}) - d_{c1}$. Applying the velocity scheme explained above the distances can be expressed as:

$$d_{c1} = d_{p0} \frac{v + \Delta v}{\Delta v}, \quad d_{c2} = d_{p0} \frac{v}{\Delta v}, \quad d_{su} = d_{p0} \frac{v + \Delta v}{\Delta v}, \quad d_n = d_{p0} \frac{\Delta v}{\Delta v}. \quad (2.8)$$

The cost of the pair of vehicles to reach the point X in Figure 2.2 is given by:

$$C_1 = \frac{d_{p0}}{\Delta v} \left( (v + \Delta v)^3 + v^3 \phi + (v + \Delta v)v^2 + v^3 - \Delta vv^2 \right)$$

$$C_2 = \frac{d_{p0}}{\Delta v} \left( v^3 + (v + \Delta v)^3 \phi + v(v - \Delta v)^2 - \Delta v(v - \Delta v)^2 + (v + \Delta v)^3 \right) \quad (2.9)$$

The cost difference of both strategies can be expressed as a function of the velocity ratio $r_v = (v + \Delta v)/v$:

$$C_2 - C_1 = d_{p0} v^2 \left( -(r_v - 1)^2 (1 - \phi) + (r_v - 1) (3 + 3\phi) - (3 - 3\phi) \right) \quad (2.10)$$

The sign of the cost difference is dependent of $r_v$. Figure 2.3 shows the relative difference in cost between Strategy 1 and Strategy 2 as a function of $r_v$ and for different values of $\phi$. The results show that Strategy 2 is preferable for low fuel savings and for low increasing velocity ratio. With the specific values of $\phi$ and $r_v$ used in [17] ($\phi = 0.68$ and $r_v \approx 1, 3$) the strategy 1 consumes less fuel under the comparison clauses.

There is no more relevant strategies for the two vehicle problem. However, a combination of Strategy 1 and 2 is also possible when the coordination involves more than two vehicles. Then, a rear vehicle can slow down and, after a certain time interval, decide
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Figure 2.2: Platoon formation fuel cost comparison between Strategy 1 and 2

Figure 2.3: Relative difference in cost of Strategies 1 and 2 for platoon formation as a function of the velocity ratio \( r_v - 1 \). Each curve accounts for a different value of air drag reduction coefficient \( \phi \).

to catch up a vehicle ahead. In the two vehicle problem, this strategy makes the cost greater for the rear vehicle meanwhile the cost of the lead vehicle remains the same compared to the Strategy 1. For instance, in a 3 vehicle group this happens between the first and second vehicle when the second vehicle slows down in order to form a platoon with the third.
2.5.2 Generalization to N Vehicles

After the arguments discussed in the previous section, the following premises can be stated:

- Accelerations are neglected due to the big distances involved.
- Under specific time constraints, a constant velocity profile gives the lower fuel cost.
  The velocities remain constant until another platoon event occurs.
  A vehicle slowing down has always higher fuel consume if the time deadlines are maintained, but it can contribute to reduce the global cost of the platooning group.
- The optimum velocity ratio to catch up does not depend on the initial inter-vehicle distance and the distance to the common destination.

Problem Formulation

The previous premises will be used to formulate the cost of platoon formation for a general case. The most general case is a group of N vehicles with different inter-vehicle distances and different destinations, as depicted in Figure 2.4. The variables chosen to describe the problem are:

\[ x^k_i : \text{Distance from vehicle } i \text{ to the platoon leader at the beginning of the time interval } k \]

\[ v^k_i : \text{Velocity of the vehicle } i \text{ at the beginning of time interval } k \]

\[ d^k_{di} : \text{Distance from the platoon leader to the destination of the vehicle } i \text{ at the beginning of time interval } k \]

\[ \eta : \text{Air drag reduction. Equivalent to } 1 - \phi. \]

\[ \Gamma^k_i : \text{Binary variable indicating if the vehicle } i \text{ is platooning (} \Gamma^k_i = 1 \text{) or not (} \Gamma^k_i = 0 \text{) during the time interval } k \]

\[ T_k : \text{Duration of the time interval } k. \]

Figure 2.4: General case of a platooning group
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A time interval \( k \) starts when a platoon event has occurred. The index \( i \) denotes the initial position in the group, being \( i = 1 \) the leader of the group and assigning increasing numbers in increasing position in the platoon. Neglecting the distance between vehicles when platooning, the value of \( \Gamma_i^k \) is given by:

\[
\Gamma_i^k = \begin{cases} 
1 & \text{if } \exists j \mid x_j^k = x_i^k, \ j < i; \\
0 & \text{otherwise.}
\end{cases}
\]  

(2.11)

The expression for \( \Gamma \) assumes that the order in which the vehicles are coordinated preserves the initial order. An optimum platoon formation where all the vehicles in the group must merge in the same platoon this situation will always occur. Not preserving the order implies that a vehicle catching up another vehicle looses the opportunity to reduce the cost of platoon formation through platooning with the vehicles that are in between.

On the other hand, the value of each \( x_i \) at the beginning of every time step will be given by:

\[
x_i^{k+1} = x_i^k + (v_1 - v_i)T_k
\]

(2.12)

The cost of the platoon formation using the variables defined above can be written as:

\[
Cost = \sum_k \sum_i (v_i^k)^3 \left( 1 - \Gamma_i^k \eta \right) T_k
\]

(2.13)

where the sum \( k \) is the sum for all the time intervals until no more platoons are formed.

The platoon event \( k+1 \) will occur depending on the velocities set up in the time interval \( k \). The velocity values must be set in order to form a platoon with all the vehicles in the group if possible and cost convenient. That objective will be accomplished when \( x_i = 0 \forall i \in N \) if the platooning distances are neglected. The time at which the events occur is determined by the length of the intervals \( T_k \). The length of the intervals is given by:

\[
T_k = \min \left( \frac{x_m^k - x_n^k}{v_n^k - v_m^k} \right) \text{ for } n > m
\]

(2.14)

Coordination Strategies for the Platooning Groups

In this work, the group of vehicles considered to form a platoon are the vehicles of a platooning group (see Section 2.4). For discussing the strategies, we consider that all the vehicles travel at a same typical velocity if they are not trying to form a platoon. The same typical velocity will be the final velocity of the platoons once formed. Meanwhile, the vehicles trying to form the platoons can modify their velocity.
The velocity values should be limited not only because they must be realistic but also because every vehicle must not consume more fuel than the original trip (constraints of the thesis). For instance, the extra cost a vehicle has when slowing down (later speeding up) must be compensated by the future platoon opportunities. This fact implies that velocity values of a step \( k \) are affected by the values of the previous steps and also that they determine the values at future steps. The problem turns out to be difficult to formulate if we do not impose other restrictions.

A simple restriction that avoids the previous problem is not allowing vehicles to slow down. Imposing that condition, every vehicle will drive at the typical velocity or greater. Following a proper strategy, vehicles will only drive faster when forming a platoon if the break event ratio is positive. Thus, the possibility to expend more fuel than the original trip can be avoided checking the incentive factor. However, the example explained in the next paragraph illustrates how the fuel savings for every vehicle in a platooning group are not always guaranteed only by checking the incentive factor for every platoon formation.

Imagine a platooning group of 3 vehicles as the one in Figure 2.5. The incentive factor \( \kappa_{2,3} \) is positive because the vehicles 2 and 3 are very close in spite of having their common destination very close. The incentive factor \( \kappa_{1,2} \) is also positive because the common destination of the pair is very far. The remaining incentive factor \( \kappa_{1,3} \) is negative. In that situation, both platoons might not be possible to form. Vehicle 3 cannot form a platoon with vehicle 2 if vehicle 2 also form a platoon with vehicle 1.

If all the incentive factors between the vehicles in a group are positive, a way to form a unique platoon where all the vehicles save fuel is guaranteed. This strategy ends up with the problem of how to define the optimum platooning groups. There might be a vehicle \( a \) with positive incentive factor with vehicle \( b \) and \( c \) meanwhile the incentive factor between \( b \) and \( c \) is negative. Moreover, finding the groups that maximize the incentive factors involved in the catch up process will not give the optimum solution. The incentive factors account for the cost of forming platoons when vehicles catch up alone. However, in a group there might be opportunities to catch up when platooning.

### 2.5.3 Adopted Strategy

Finding the optimum coordination strategy to the most general problem has turned out to be difficult. As far the author is aware, there is no work facing the same type of problem. Previous works deal with minimizing the total fuel consumption when platooning and rerouting are considered [16]. However, the analysis in [16] is discrete.
paths but not with the continuous real paths of the vehicles. Keeping the paths continuous is interesting in this work for representation purposes of the coordination strategy used. Moreover, the discrete network directly defined by the road map used is not uniform and can induce big errors (see Chapter 3) so the discretization of the map should be redefined. That is why this work deals with the continuous problem.

An heuristic strategy has been adopted inspired with the one used in [16]. The strategy consists of analyzing the fuel savings potentials of all the possible combinations of vehicles in a platooning group. For a platooning group of N vehicles, the fuel savings achieved forming platoons between all the $N(N-1)/2$ possible different pairs are analyzed. The pair of vehicles that can save more fuel are set to form a platoon as long as the fuel savings are positive. The analysis is iteratively repeated until there is no pair in the group that can save fuel forming a platoon. During the iterative process, the vehicles that are already speeding up to form a platoon cannot be considered for other platoons. Likewise, vehicles waiting to merge in a platoon with other vehicles cannot speed up to form an alternative platoon. More details of the strategy are given in Chapter 5.

The Strategy 1 described in the "Two vehicle problem" Section is adopted to form the platoons between the pair of vehicles. Figure 2.3 shows how this is the strategy with highest fuel savings considering that the air drag force decreases in about 30% driving in a platoon. Thus, the platoons between a pair of vehicles are formed due to the rear vehicle speeds up to catch the front vehicle.
Chapter 3

Data Processing

In this chapter, we first present the map source and filtering tools used for obtaining a working map. Once the map has been characterized, we describe the methods used to convert the low sample GPS data to a continuous path through the MM and PI processes. Finally, a brief explanation about the input data format for the initial analysis and the platoon coordination is given.

Due to the scope and the time constrains of the thesis, the MM and PI algorithms developed have not finally been used to process the GPS data. The processed data has been obtained from the supervisor of this thesis. The data is more precise and complete than the one obtained in this work. However, the own MM and PI process developed are currently working. The details of the algorithms are explained in this chapter and the results presented in Chapter 6.

3.1 OpenStreetMap

There is a high availability of road map sources most of them with private licenses. For this thesis we use OpenStreetMaps (OSM) [20], a suffice open source map for our purposes. OSM is a collaborative initiative devoted to create a free editable worldwide map. Founded in 2004 by Steve Coast, OSM has compiled map information from very disparate sources as government agencies and users’ ground surveying routes. Currently, OSM has over a million of registered users. The map data is available in a web site under the Open Database License. Although the quality of the maps varies depending on the geographical region, studies have stated the quality being more than acceptable compared to other privative map sources [12]. Moreover, Europe is the most accurate and complete mapped region in general.

3.1.1 OSM Data Format

OSM uses a topological data structure composed of four elements (data primitives):

- **Node**: Geographical position described by its GPS coordinates according to WGS-84. A node can represent a point of interest, a position describing road or a polygon, etc. Each Node has a unique id number in the map.

- **Way**: List of ordered nodes building an open or close path that can represent a road segment, a river or any other linear real feature. Each way has an unique id number in the map and they refer to the nodes through tags containing the node id.
- **Relation:** List of ordered nodes, ways and relations. A relation is used for representing relationship between their members. An example is a relation containing a group of ways that generate a specific route or road.

- **Tag:** An element composed of two string variables: key and value. It is used to define characteristics of the other data primitives. For instance, a way can have a tag with key='oneway' and value='no' indicating that it is a two-way road.

The information of the OSM map, once decompressed, is stored in the human readable xml format. The OSM maps use a specific xml tree named osm format.

### 3.2 Map Source and Map Filtering

The OpenStreetMap Foundation maintains a web server where users can download the desired map areas. However, the web application cannot gather the big regions needed for this work (about 500,000 square km). For this reason the map source used has not been obtained from the official web page. The source used is a web called Geofabrik where the geodata of the OSM is available in different files according to the geographical region.

The entire Europe map has been download from Geofabrik (9th of November of 2013). However, the working GPS data is limited to a part of that map and the Europe map is unnecessary big. That is why the map is bound to the specific region of interest using the open tool *osmconvert*. Furthermore, *osmconvert* also removes some preliminary information out of interest: relation data primitives and the author references.

Another open tool called *osmfilter* permits to select the data primitives according to the tags’ information. Additionally, *osmfilter* can also be used to remove additional tags with no useful information. This tool has been used to select the ways belonging only to high speed roads and the links between them. This process is done by selecting the ways whose value of the key='highway' is:

- motorway
- motorway link
- trunk
- trunk link

The filtering process permits to identify roads where the HDVs are able to platoon. Platooning will be only feasible and convenient when the vehicles travel in high speed roads. In high speed roads, HDVs usually do long trips and they have higher air drag, i.e. conditions favorable to platoon formation. Moreover, the lane characteristics of the roads make platooning maneuvers safer.
3.3 About the Software

All the work of this thesis uses the programming language Python due to its simplicity, easy to use, extensive libraries and extensive documentation. For instance, Python has libraries to read osm files and the appropriate object class definitions to deal with the data primitives of osm.

Maps with osm format can be plotted and edited using JOSM (Java OpenStreetMap editor). Nevertheless, Google Earth is more powerful when it comes to representation. Google Earth allows to easily make animations of the trajectory of the vehicles. Also, the positions are represented directly on the Google maps what facilitates the interpretation of the results. The software needed to change from osm format to the Google kml format has been developed in this work.

3.4 Map Matching

Map matching is an ongoing field of research where currently exists different solutions with varying complexity and accuracy [23]. Some authors have developed open source map matching algorithms. This is the case of the algorithm developed in [22]. However, the lack of knowledge of the external sources and the particularities of the problem faced make the adaptation of these algorithms in a reasonable time complicated. Moreover, the existent algorithms usually deal with high frequency GPS data (10-30s) on urban dense networks, which is the opposite case of this work. For this reason, a simple map matching algorithm has been developed according to the needs of the work.

3.4.1 Definitions

Before going into the details of the MM problem, some necessary definitions are presented:

- **GPS set**: Collection of GPS points \( P = p_1, p_2, ..., p_n \). Each point \( p_i \in L \) has attributes of latitude \( (p_i.lat) \), longitude \( (p_i.lon) \), timestamp \( (p_i.t) \) and velocity \( (p_i.v) \). The set is ordered in increasing order of time, that is, \( p_i.t < p_{i+1}.t \).

- **Matched GPS set**: Collection of GPS points \( M = \{m_{p_1}, m_{p_2}, ..., m_{p_n}\} \). Each point \( m_{p_i} \in M \) is a point belonging to the road network that has been matched to the point \( p_i \). Thus, each \( m_{p_i} \in M \) keeps the attributes of velocity and timestamp of the original \( p_i \) meanwhile the longitude and latitude belong to the road network.

The elements describing the road map in the MM process will be called nodes and links. Their relation to the data primitives of the OSM map is the following:

- **node**: OSM nodes of the map source described for its GPS coordinates.
- **link**: Straight line that connects two consecutive OSM nodes.
3.4.2 Map-matching Process

The process of map matching finds the set of matched points $M$ most likely to fit with the real path of the vehicle. In other words, a set of $M$ where the vehicle has truly traveled. The choice of each of the matched points $m_{p_i} \in M$ can be based on:

- Geometry and topology of the network
- Statistical methods
- Temporal constrains
- Additional data of the network

Furthermore, the approaches to determine which $M$ fits better $P$ can be global or local. Local approaches try to find the $m_{p_i}$ that fits each $p_i$ (or a subset of $M$ and $P$) best. On the other hand, global approaches look for a set of $M$ that fits the whole $P$ best. An example of global approach is the Average-Fréchet-Distance ([5]), which measures the similarity between the curves described by $P$ and $M$. The results of the global approaches tend to be more accurate but with higher computational cost. This work presents a local solution considering only the geometry and topology of the network and the velocity constrains.

Geometrical analyses take into account the distance between the points $p_i$ and the road network. One possibility is to perform a point to point matching. Point to point matching consists on identifying the closest node to the point $p_i$. Nevertheless, situations like the one depicted in Figure 3.1a are common and induce errors when using this technique. In Figure 3.1a, point to point matching wrongly selects the node in red when it is not in the correct path. Another method called point to curve matching can solve this problem.

The point to curve method looks for the closest link to the position being matched. Strictly speaking, the working map is on a spherical surface so the shortest paths are
3.4. MAP MATCHING

arcs and not straight lines. The arc differences separating the different points will be small. Then, the surface of the sphere can be approximated by a plane. With this objective, the GPS coordinates are transformed to a point in a Cartesian system with origin in the center of the sphere. If $\theta$ is the latitude of the point and $\varphi$ the longitude, each coordinates in the Cartesian system will be given by:

$$x = r \cos(\theta) \cos(\varphi), \quad y = r \cos(\theta) \sin(\varphi), \quad z = r \sin(\theta).$$

If $C_1 = (x_1, y_1, z_1)$ and $C_2 = (x_2, y_2, z_2)$ are the map nodes that define the link line and $P = (x_3, y_3, z_3)$ the point whose shortest distance to the line is calculated, then the distance will be given by:

$$d = \frac{|P\vec{C_1} \times \vec{C_1C_2}|}{|\vec{C_1C_2}|}. \quad (3.1)$$

Note that the distance found is the minimum distance between the GPS point and the infinite line defined by $C_1$ and $C_2$. Other more accurate algorithms take into account that the link is finite. Also, precise MM algorithms find not only the link but the point on the link line that is closest to the GPS position being matched. The algorithms developed in this work only find the closest link and then the vehicle position is related to one of the two nodes connected by the link.

The spatial orientation of the links has also been used. For example, imagine a matching algorithm that relies exclusively on the distance from the GPS position to the closest link of the road network. The algorithm fails when it tries to match the GPS point depicted in the Figure 3.1b. The algorithm assigns the wrong link because it is the closest one. However, if the direction of the road and the trajectory described by $P$ are taken into account, then the correct link can easily be identified. Thus, just considering the point $p_i$ being matched is not enough to find the $m_{p_i}$ that fits it best. The miss-matching of Figure 3.1b can be avoided if a reduced set $P' \in P$ is considered. For a given point $p_i$, the developed algorithm computes the bearing angle of the trajectory using the next GPS point $p_{i+1}$. An edge of the road is set to be a map matching candidate only if:

$$|\beta_{\text{link}} - \beta_{\text{heading}}| < 30^\circ \quad (3.2)$$

$\beta$ states for bearing angle: the angle in clockwise direction starting from north. $\beta_{\text{link}}$ is the bearing angle of the edge and $\beta_{\text{heading}}$ is the bearing angle of the trajectory between $p_i$ and $p_{i+1}$. The bearing angle between two points is given by:

$$Y = \sin(lon_1 - lon_0) \cos(lat_1)$$
$$X = \cos(lat_0) \sin(lat_1) - \sin(lat_0) \cos(lat_1) \cos(lon_1 - lon_0)$$
$$\beta = \arctan2(X, Y) \quad (3.3)$$
where coordinates with subindex 0 are from the departure point. The function \( \text{atan2} \) is the two argument version of the arctangent, commonly used in informatics. The function uses two arguments to return the solution in the corresponding quadrant. The formula 3.3 returns the value according to the usual convention of North latitudes and East longitudes positive and South and West negative.

The velocity information can also be used to improve the MM. For instance, Y. Lou et al. ([18]) use the speed constrains of the roads to determine if one position can be matched to a particular link of the network. The same idea has implicitly been done in this work but with two steps. First, the working map is filtered as explained in Section 3.2. As a result, the map consists in only unidirectional high speed roads. After filtering the map, a velocity threshold is applied to the positions \( p_i \) being matched. The result is a MM process according to the velocity constrains of the roads. Using this method, the GPS positions with low velocity are ruled out because platooning has no sense when the velocity is low.

In this thesis, geometric analysis and velocity constrains are applied in a true/false or best value scheme. Threshold values are established for the distance between point and link, the difference between the bearing angles and the velocity of the GPS sample being matched. A link is considered to be a matched link candidate if it accomplishes all the thresholds. From all the possible candidates, the final matched node is the one belonging to the link closest to \( p_i \). If there is no candidate, then there will not be any matched node for \( p_i \).

There exist weighted algorithms that weight the contribution of each of the values involved in the match decision. Also, the weights can take into account more GPS points rather than the \( p_i \) being matched. Moreover, there are more advanced statistical models based on predictors. In this work, these methods has been omitted because they are time consuming and map-matching is not the goal of the thesis.

### 3.5 Path Inference

The results of MM are sets of GPS positions belonging to the road network. These GPS points still do not define a specific path but there can be more than one possible path between a pair of matched nodes. The previous possibility is especially relevant in the working case due to the low sampled GPS data. Thus, the correct path between matched nodes has to be chosen. The criteria to choose the correct path can consider many variables as distance, traffic situation, type of the road, accidents, etc. A cost function must be defined in order to weight all the variables. The remaining problem to solve is to find a path that minimizes the cost. This is equivalent to the well known problem called shortest path problem where the distance plays the role of cost.

Shortest path algorithms have been studied for over 50 years. A review of the optimal faster algorithms can be found in [7]. In practice, heuristic algorithms perform better than the optimal ones. A review with the state of the art of that algorithms can be found in [10].
3.5. PATH INFERENCE

3.5.1 Definitions

PI does not need the geometry of the road network but only the topology. The topology of the road can be described with a graph. A graph \( G(V, E) \) is a set of vertices \( V \) together with a set of edges \( E \). Edges are two-element subsets of \( V \), i.e. relations between a pair of vertices. The working road network is the so-called "directed graph" because all the roads have only one possible direction. A convenient graph can be generated with the following elements of the road:

**vertices:** Junctions that connect more than one road. Described for the OSM node id that forms the junction.

**edges:** Paths that link to different junctions. In the road network used, all of them are unidirectional. They are described by their length and the ids of the OSM nodes defining them.

**graph:** Road network.

The density of nodes in the OSM map meets the needs of geometric precision. The roads have few nodes if they are straight because the straight link connecting two nodes can describe the road segment properly. The opposite happens with curved paths. The graph only needs to contain information of the road junctions and the connections between them to describe the topology of the road. That is why not all the OSM nodes are considered as vertices of the graph.

The PI process of this thesis is based exclusively on distances so there is only need to associate the correct distance value at every edge. The node ids forming an edge are kept just for later representation purposes.

The problem to be solved can be stated as follows. For a given set of matched points \( M \), we must find a graph subset \( G'(V', E') \in G(V, E) \) where the edges in \( E' \) define the shortest path between any pair of points \( m_{p_i}, m_{p_{i+1}} \in M \).

The criterion of only considering distances is simple and seems good enough because the shortest path is usually taken in normal conditions. Moreover, there is no other information available such as traffic conditions. Like the distances are defined positive and the edges are unidirectional, the working graph is a directed graph with nonnegative lengths.

From the existent different algorithms, the one used in this work has been the Dijkstra’s algorithm. This algorithm is the optimal fastest known algorithm to find the shortest path from a single source. Nevertheless, heuristic versions of Dijkstra’s algorithm like A* perform better in computational time [7]. Dijkstra’s algorithm simple implementation runs in \( O(|V|^2) \). However, the bound can be reduced using different data structures that help to identify the closest vertex. The most used one is the Fibonacci heap where the bound is reduced to \( O(|E| + |V| \log(|V|)) \) [7].
The algorithm developed in this work uses a priority queue and it runs on $O((|E| + |V|) \log |V|)$. The pseudocode of the algorithm can be seen in Algorithm 1.

```plaintext
for u in V do
    if u \neq \text{source} then
        dist[u] = \text{Inf}
        prev = \text{Undef}
    else
        dist[u] = 0;
    end
    p_queue.add(dist[u], u)
end
while p_queue do
    m = p_queue.extract_min()
    if m = \text{goal} then
        break
    end
    for u in V do
        if dist[u] > dist[m] + D(m, u) then
            dist[u] = dist[m] + D(m, u)
            prev[u] = m
            p_queue.change(dist[u], u)
        end
    end
end
k = \text{goal}
while prev[k] \neq \text{Undef} do
    path.append(prev[k])
    k = prev[k]
end
reverse path
```

**Algorithm 1:** Dijkstra’s algorithm using a priority queue

In the code, $\text{source}$ and $\text{goal}$ are the starting and ending vertex whose shortest paths have to be computed. The variable $\text{dist}[u]$ is the distance value of the shortest path from $\text{source}$ to $u$ that have been found until the moment. $D(m, u)$ is commonly called adjacency matrix and contains the distance of every edge. $\text{prev}[u]$ stores the previous vertex of the path that gives the shortest path to $u$. $\text{p}_-$queue is the priority queue where the vertex of the graph are ordered in increasing order of $\text{dist}[u]$. There are three methods defined on the priority queue. The method $\text{add}(\text{dist}[u], u)$ adds the element $u$ to the queue $\text{p}_-$queue with priority $\text{dist}[u]$. The method $\text{change}(\text{dist}[u], u)$ changes the priority of the element $u$ to the new value $\text{dist}[u]$. Finally, the method $\text{extract}_\text{min}()$ returns the vertex of the queue that currently have the lowest value of $\text{dist}[u]$. 

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3.5. PATH INFERENCE

Figure 3.2: Examples of dead end roads

A very brief explanation of the code is the following. In the first "For" loop all the \( \text{dist}[u] \) are initialized with an infinite value except the \( d[\text{source}] \) that is assigned to zero. They are placed in the priority queue according to the value of \( \text{dist} \). In the "While" loop, it is checked the distance of the neighbors of the current vertex. The distance is updated (also the position in the queue) if it is shorter than the previous known path. The loop repeats until there is no more vertices to explore or the target has been found. Finally, the last while loop goes over the inverse direction pointed by the previous nodes stored \( \text{prev}[u] \) and reconstructs the shortest path.

The Dijkstra’s algorithm is a single-source shortest path algorithm that returns the shortest distance from one source to all the vertex of the graph. We are only interested in finding the path to a specific goal. That problem is named single-pair shortest path problem. It turns out that the most efficient way to solve the problem is using the more general single-source shortest path algorithms. Thus, the time bounds can be seen as a worst case. In the pseudocode of Algorithm 1, it can be seen how the algorithm is stopped when the vertex found is the goal.

3.5.2 Creating the Network Graph

The adjacency matrix \( D(u, v) \) is required for implementing the Dijkstra’s algorithm. In other words, the distance of each edge connecting two vertices must be known. Using the OSM nodes as vertices of the graph creates an unnecessary big graph. There are too many nodes for very few real road junctions. The source map used has 639,516 nodes that will give an adjacency matrix of about 380GB, numbers that are not tractable for a conventional hardware.

The graph should be formed for only the real junctions of the roads. One easy way to identify junctions is to look for the OSM nodes connecting two vertices must be known. Using the OSM nodes as vertices of the graph creates an unnecessary big graph. There are too many nodes for very few real road junctions. The source map used has 639,516 nodes that will give an adjacency matrix of about 380GB, numbers that are not tractable for a conventional hardware.

The graph should be formed for only the real junctions of the roads. One easy way to identify junctions is to look for the OSM nodes connecting more than two OSM ways. However, the process of filtering based on the type of the road has generated a map with short dead end roads (see Figure 3.2). The dead end ways are mostly segments of connections to other low speed roads not interesting for this work. Thus, a node connected to this type of roads should not be considered as a real junction of the high speed network. A depth-limited search algorithm (DLS) is used to determine if the
OSM ways arising from a specific node connect to a relative long paths (see pseudocode in Algorithm 2). If there are three different paths with a considerable amount of nodes, then the source node is considered as real junction of the network.

```
num = N
stack = (start_node, N)
while stack not empty do
    (node, num) = stack.pop()
    if num > 0 then
        if node not in discovered then
            discovered.add(node)
            next_nodes = find_neighbors(node)
            num -= 1
            for next_node in next_nodes do
                stack.add((next_node,num))
            end
        end
    else
        return True
    end
end
return False
```

**Algorithm 2: Depth-limited search algorithm: Non recursive implementation**

In Algorithm 2, `node` is the current node in the exploration and `num` is the number of nodes that have been needed to reach that node from the starting point `start_node`. The algorithm explores the road network until the maximum number of nodes \( N \) have been reached (return True) or until there is no more nodes to explore (return False). The procedure uses a `stack` where the new node neighbors and the `num` counter value are added and popped with the `add()` and `pop()` methods. The exploration of the vertices is done with the particular order the vertices have been stored in the map. The function `find_neighbors` return the vertices following this order.

The edges are identified once the vertices are known. The process is done using an iterative depth-limited search algorithm. This algorithm calls repetitively the previous DLS algorithm with increasing depth limit \( N \). The iteration is repeated until another junction (vertex of the graph) is found. The path to this junction is returned for the algorithm and assigned to the edge. This path will be the path with smallest number of nodes (or one of them in case there are several possible paths with the same number of nodes). The process is done for every road the node connects. The final result is a set of edges each of which has associated a collection of OSM nodes. The nodes will be used to compute the edge’s distance according to the GPS positions. The iterative depth-limited search algorithm assumes that the correct path will be the one that contain less nodes. This is not a bad assumption considering the observed characteristics of the map.
3.6 Data Processing after Map Matching and Path Inference

As mentioned at the beginning of this chapter, the data used for analyzing the HDV trajectories has not been obtained from the MM and PI algorithms developed in this work. It has been provided by the supervisor of this thesis. From the initial 7000 HDVs of the source data, the MM and PI process leads to approximately 1800 HDVs driving on high speed roads. In this section, the details of the data and the data processing applied are explained briefly.

The data used for the rest of the work consists of two files. One file contains a set of matched positions referred to the OSM nodes. Each of these positions has a timestamp according to the time of the original GPS points being matched. The positions have been generated with a MM process that selects several link candidates. Later, a PI process identifies the collection of links that generates the shortest path. From the links selected, the matched positions are the closest point of the links to the GPS samples being matched. Thus, the final matched position cannot be just a node of the OSM map but can be anywhere in the line defined for the link connecting two nodes. That closest point is described in terms of the preceding OSM node and the distance from the node to the closest point. In that way, it is possible to have a more precise estimation of the vehicle position in the map than the discrete map nodes, which leads to more accurate results and better representations.

On the other hand, the MM and PI also generate a file with the path between the matched positions. The path data consists of a set of visited nodes in which no information of the time is included. The information of time is recovered from relating the previous explained matched positions to the path.

Path and matched points contain not only the node id but also the way id. The way id is needed to identify whether there are vehicles or not in a particular path. Figure 3.3 depicts an example of the way id need. If we are interested in determining if the vehicle 1 has some vehicles ahead, we should only look for vehicles on the same way. Otherwise, we wrongly will determine that both vehicle 2 and vehicle 3 are ahead of vehicle 1 because their positions are associated to the same node. In other words, the way information tells us the link in which the vehicle is.

Figure 3.3: Example of the way id information need
CHAPTER 3. DATA PROCESSING

3.6.1 Synchronization

The path of each vehicle is a discrete set of positions (visited nodes). The nodes are linked with straight lines and the vehicles’ positions are defined on that links. Thus, the information about the trajectory consists on discrete time samples of the vehicles’ positions on a continuous path. However, the time samples of each vehicles are not synchronous. The vehicles’ positions are recorded at very different times and hence they are not directly comparable at a specific time. For this reason, a regular time samples are defined and the position of the vehicles are defined at these times.

There are no unique way to define the positions of the vehicles at the regular time samples. The most straightforward way to proceed is to compute the average velocity between two consecutive matched points. The velocity average is used to interpolate the position of the vehicle at the regular time samples in between to original timestamps (see Figure 3.4a).

The previous way to proceed makes the velocity changing at the original timestamps of the GPS data. However, velocity changes at irregular time can be problematic. The problems come when the platooning vehicles update their velocity according to the lead vehicle of the platoon. The update is done at defined regular time samples. Thus, if the velocity value is not maintained between the regular intervals, then the vehicles will no longer maintain the precise platooning distance between them. The distance varies at every velocity change.

In order to make the velocity changes regularly, the final synchronization is done as follows:

For every matched node of each vehicle:

- An algorithm follows the path to the next matched node keeping track of the time according to the distance driven and the velocity the vehicle had when it reached the current node.

- When the next regular time sample is reached, the velocity is set to a new value. The value is the average speed the vehicle should have to reach the next known matched sample coming from the current position.

An example of implementation and the comparison between the method used and the simple average velocity method can be seen in Figure 3.4. Note that in both methods the trajectories reach the matched points at the same original time.

The GPS samples of the original data have been recorded at intervals of about 5-10 minutes. The time interval used for this work to generate the synchronous data of the HDVs has been 2 minutes. Therefore, the distances between vehicles and the platoons coordinations studied in the next chapters will be updated every 2 minutes. That time interval is small enough to not lose precision in the results. A shorter time sample could have been used but without expecting significant differences. The platoons will be approximately the same regardless of whether they are formed every 2 minutes
3.6. DATA PROCESSING AFTER MAP MATCHING AND PATH INference

Figure 3.4: Example of synchronization for (a) average velocity and (b) synchronous velocity

or every 1 second. New vehicles do not appear every second but every 5 minutes in average.
Chapter 4

Analysis of the Potential Platoon Opportunities and Fuel Savings

A first analysis of the traffic characteristics and the potential platoon opportunities is done. The analysis is based on the inter-vehicle distances of the real vehicle trajectories. With that information the potential HDV platoons and the potential fuel savings are identified. Furthermore, the first analysis is also used to identify the vehicles that can platoon without the need of any coordination.

Two main things must be specified to determine the fuel savings: when do we say that vehicles are platooning? and how much fuel do they save when platooning? The first question is going to be answered in this section. The last question has already been answered when the fuel model was presented, which is 10%.

4.1 Vehicles Platooning

Fuel savings obtained from a platoon formation depend on the relative distance of the vehicles, the velocity and the distance to the final common destination (see Chapter 2). Only the separation of the vehicles is taken into account in this first rough estimation. Two matrices $C$ and $P$ are defined to store the inter-vehicle distances and the platooning status respectively.

Matrix of the close vehicles $C$:

The $C(t) \in \mathbb{R}^{N \times N}$ stores for each vehicle the distances to all the vehicles that are closer than a given platooning range.

\[
C(t)_{i,j} = \begin{cases} 
  d_{i,j} & \text{if } (d_{i,j} \leq d_{\text{platooning}}) \text{ and } (v_i > v_{\text{ref}}) \text{ and } (v_j > v_{\text{ref}}); \\
  \infty & \text{otherwise.}
\end{cases}
\] (4.1)

$d_{i,j}$ corresponds to the distance between the vehicle $i$ and the vehicle $j$. If the vehicle of index $j$ is in front, then the distance is positive and negative otherwise. $d_{\text{platooning}}$ is the platooning range set in the specific calculation. $v_i$ is the velocity of the vehicle $i$ at the time $t$ and it must be greater than a reference value $v_{\text{ref}}$. The $v_{\text{ref}}$ condition limits the search to those vehicles most likely to platoon and eliminate the vehicles that have stopped for some reason. The value used for this work has been 50km/h so the platoons search only considers the active vehicles.
CHAPTER 4. ANALYSIS OF THE POTENTIAL PLATOON OPPORTUNITIES AND FUEL SAVINGS

Matrix of the platooning vehicles $P$:

The matrix $P \in \mathbb{R}^{N \times N}$ has possible entries values of 1, -1 and 0. The value of elements of the matrix are defined as:

$$P(t)_{i,j} = \begin{cases} 
1 & \text{if } C(t)_{i,j} < \infty \text{ and } C(t-1)_{i,j} < \infty \text{ and } C(t)_{i,j} > 0; \\
-1 & \text{if } C(t)_{i,j} < \infty \text{ and } C(t-1)_{i,j} < \infty \text{ and } C(t)_{i,j} < 0; \\
0 & \text{Otherwise.} 
\end{cases}$$

The definition of the matrix $P$ is the scheme used to determine if two vehicles are platooning. We say that two vehicles have been platooning from $t-1$ to $t$ if they are closer than the platooning range during the two consecutive time samples. From the pair of vehicles, the vehicle $j$ in front of the vehicle $i$ at $t$ has the value $P(t)_{j,i} = -1$, which means that it is the leader of the group and it does not benefit from platooning. Instead, for the vehicle $i$ the value of the entry will be $P(t)_{i,j} = 1$, which implies potential fuel saving from $t-1$ to $t$. In the other cases the value is 0.

In Section 2.4 we define the concept of a platooning group as the group of vehicles each of which are separated for less than the platooning range from at least one vehicle of the group. Using the definition of the matrix $P$, it can be said that a vehicle $i$ and $m$ are from the same platooning group if, although being $P^t_{i,m} = 0$, it exists at least one vehicle $k$ that fulfills $P^t_{i,k} \neq 0$ and $P^t_{k,m} \neq 0$. An algorithm has been developed to search for those conditions and generate the platooning groups.

Once the platooning groups have been identified, the leader of the platoon will be the vehicle that has no other vehicle ahead closer than the platooning range. It can be determined by simply identifying which of the vehicles index corresponds to a row in the matrix $P$ without any 1 (equivalent to not have any -1 in the column with the same index).

The interpretation of the platooning groups can be different depending on the value set as the platooning range. If the platooning range is very small, then the platooning groups can be considered as vehicles in real conditions of forming a platoon. In those cases, no coordination process is needed and an adaptive cruise control could couple the vehicles. The platooning range chosen to define these situations has been 100m in this work.

4.2 Identifying Vehicles within the Platooning Range

The distance between vehicles is determined using the road map information instead of calculating the separation of the GPS positions of the vehicles. The method allows to identify vehicles ahead of a specific HDV and avoids computing the inter-vehicle distances for all of the N vehicles. Also, we gather information about which is the vehicle in front and which is in the back with the road position. This information cannot be determined using absolute distances between GPS points.
Given a specific vehicle, the close vehicles can be determined looking forward on the road. There is no need of looking backwards because the inter-vehicle distance with the rear vehicles will be the same, with opposite sign, than the one obtained when the rear vehicles perform their search.

The search for vehicles ahead is done with the same type of depth-limited search algorithm used in the Chapter 3 (See Algorithm 2). The algorithm performs a limited search but this time the limit is the traveled distance and not the number of visited nodes. For this reason, the algorithm keeps track of the traveled distance. The algorithm stops and starts exploring another branch of the road when the distance is greater than the platooning range. The exploration is done node by node (OSM nodes). The distance offsets of the vehicles from the nodes are taken into account. Thus, the inter-vehicle distance can be precisely determined in spite of the discrete nodes defining the map.

### 4.3 Computing Fuel Savings

A set of different platooning groups at every time interval is generated. This information can be rewritten in a different way to facilitate the process of computing the fuel cost of each vehicle. We are interested in knowing, for each vehicle, the time intervals in which a vehicle has platooned. Then, a possible solution used in this work is to define a matrix $V \in \mathbb{R}^{N \times M}$ where $N$ is the number of vehicles and $M$ is the number of time intervals between the regular time samples. The values of the elements of this matrix are:

$$V_{i,t} = \begin{cases} 
1 & \text{if } i \text{ in one platooning group at } t \text{ and } i \text{ not the leader;} \\
0 & \text{otherwise.} 
\end{cases} \quad (4.3)$$

After building $V$, computing the cost of a vehicle with and without considering the potential platoons is straightforward. We just keep track of the trajectory and the time traveled of every vehicle. The fuel model must be adapted to the condition of platooning or not given for the elements of the matrix $V$ for the regular time intervals. Taking into account a fuel model proportional to the distance driven multiplied by the velocity squared, then for the interval between $t - 1$ and $t$ the cost will be:

$$Cost(t) = \left( d_{\text{driven}}^2 v_t^2 (1 - V_{i,t} \eta) \right) \quad (4.4)$$

Where $\eta$ is the fuel reduction when the vehicle is platooning and $d_{\text{driven}}(t)$ is the driven distance between $t - 1$ and $t$. 
Chapter 5

Analysis of the Fuel Savings after Platoon Coordination

The analysis of Chapter 4 neglects the cost of platoon formation and only considers the initial inter-vehicle distance. In this Chapter, the feasibility to form a platoon between a pair of vehicles according to their velocity, the distance between them and the distance to the common destination is studied. Furthermore, in the previous analysis there has not been any modification of the timing of the vehicles. At least one of the vehicles must modify the velocity in order to form a platoon and this modifies the original journey timing. All these considerations are taken into account in the next part of the work.

5.1 Platoon Coordination

In a general situation the platooning groups can contain more than one vehicle. The possible strategies to develop for an arbitrary platooning group are discussed in the Section 2.5. We decided to form platoons following an heuristic scheme for simplicity. Moreover, this work already uses a simple relation to model the cost with or without platooning. We believe that, after both simplifications, the work still keeps the general behavior and magnitudes of the real problem so a meaningful estimation of the fuel savings can be obtained.

The heuristic scheme to coordinate platoons treats the vehicles in pairs. All combinations of two vehicles in a platooning group are analyzed. The Strategy 1 of Chapter 3 is the one adopted to modify the velocity profiles in order to merge a pair of vehicles in a platoon. The fuel costs with and without forming platoons will be based on the velocity profiles of the Strategy 1.

Following the coordination scheme of this work, the pair of vehicles in the platooning group having higher fuel savings are set to platoon. The process is iteratively repeated until all the vehicles are platooning or there is no pair that can save fuel. The pseudo-code of the Algorithm 3 explains the details of the procedure used.
update catch_list, plat_list, lead_list according to the time;
for group in platooning groups do
    \( f_{\text{min}} = 0 \);
    while \( f_{\text{min}} < 1 \) do
        for \( \text{veh}_f, \text{veh}_b \) in group do
            if \( \text{veh}_f \) not in catch_list and \( \text{veh}_b \) not in (lead_list + plat_list) then
                \( f = \text{cost\_calculation(veh}_b) \);
                \( \text{path} = \text{change\_timing(veh}_b) \);
                if \( f < f_{\text{min}} \) then
                    \( f_{\text{min}} = cf \);
                    \( \text{path}_{\text{min}} = \text{path} \);
                    \( \text{veh}_{\text{b}min} = \text{veh}_b \);
                    \( \text{veh}_{\text{f}min} = \text{veh}_f \);
                end
            end
            if \( f_{\text{min}} < 1 \) then
                \( \text{path} = \text{path}_{\text{min}} \);
                update catch_list with \( \text{veh}_{\text{b}min} \);
                update plat_list with \( \text{veh}_{\text{b}min} \);
                update lead_list with \( \text{veh}_{\text{f}min} \);
            end
        end
    end
end

Algorithm 3: Platoon Coordination Algorithm

The algorithm takes into account that a given vehicle can platoon if:

- It is not already platooning (not in the Platt_list)
- It is not the leader of a platoon (not in the lead_list).

Likewise, a vehicle can be a leader of a platoon if:

- It is not catching up another vehicle (not in catch_list)

If the vehicle in front \( \text{veh}_f \) and the vehicle in the back \( \text{veh}_b \) satisfy the above conditions the algorithm proceeds. The coefficient \( f \) is the ratio between the cost with and without platoon coordination for the vehicle in the back \( \text{veh}_b \). The vehicle in the back is the only one that modifies its journey if the platoon forms (see Strategy 1). If this coefficient is less than 1, then the rear vehicle can save fuel via platooning.

The previous procedure is done for each pair in a given platooning group. The pair of vehicles that gives the smallest \( f \) coefficient (greatest fuel savings) are coordinated to form a platoon as long as \( f \) was less than 1. Once decided to form a platoon, the lists catch_list, plat_list and lead_list are updated with the information of the vehicles catching, platooning or leading and with the time at when each process ends. \( f \) is
5.2 Distance to the Common Destination

The common destination of a pair of vehicles is the farthest shared point of their paths meanwhile they driving at a reasonable speed. If vehicles form a platoon, then the platoon will split at this point. The steps to determine the common destination used in this work are:

1. Determine the initial position of the vehicles according to the time sample.
2. Move along the path of the rear vehicle until reaching the same node position of the front vehicle.
3. Move simultaneously along both paths until the algorithm reaches a node whether the velocity of one of the vehicles drops below a reference value $v_{ref}$ (no active vehicles) or where the two paths are different.
4. The node of the previous step is considered the common destination.

Note that the velocity considered in the third step above is the original velocity in a specific point of the path of both vehicles. That velocity corresponds to the same road point but to a different timestamps for every vehicle. When the velocity drops below the threshold $v_{ref}$ the platoons are ended. The journey of the vehicles may have some deliveries and breaks that make the velocity decrease and the platoons no longer possible. The threshold used in the work is 50km/h.

5.3 Velocity Profiles when Platooning

The original velocity of the vehicles must be modified for platoon formation and maintenance. For platoon formation, the rear vehicle speeds up to catch the front vehicle. The front vehicle maintains its own original velocity profile all times. The specific velocity profile that is set to the rear vehicle is explained in the next paragraphs.

Catching process

The velocity of the rear vehicle is set to the value in equation 5.1 meanwhile the distance from the vehicle ahead is greater than the desired platooning distance.

$$v_b = \begin{cases} 
  v_f + v_{inc} & v_f + v_{inc} \leq v_{lim} ; \\
  v_{lim} & \text{if } v_f + v_{inc} > v_{lim}.
\end{cases}$$ (5.1)

The subindex $b$ and $f$ refer to the vehicle in the back or in the front respectively. $v_{inc}$ is the increment of the speed set to the vehicle in the back to catch up the header and $v_{lim}$ is a velocity limit that must not be exceeded. The velocity increment chosen in
CHAPTER 5. ANALYSIS OF THE FUEL SAVINGS AFTER PLATOON COORDINATION

this work is 20km/h and the velocity limit is 100km/h that is slightly higher than the common speed limits in the European highways (90km/h).

Sometimes two vehicles are closer than the considered platooning distance before forming the platoon. If that is the case, there is no attempt to increase the distance between them. Both vehicles keep the same initial distance between them.

Platooning

The velocity of the vehicle in the back is instantaneously set to the same value of the front vehicle’s velocity just after the vehicles have merged (inter-vehicle distance equal to the platooning distance). The velocity is not modified at the regular time samples in order to place the vehicles with the exact platooning distance. Thus, the synchrony between the different vehicles’ velocities generated in the data processing is lost. However, the synchrony is only lost during the catch-up process when no more platoons are formed.

When the vehicles are currently platooning, the vehicle in the back simply follows the same velocity of the front vehicle. The velocity is updated at the regular time samples so the distance between vehicles is maintained.

After the common destination

After reaching the common destination, the front vehicle simply keeps unchanged its path, velocity and timing as it has been doing during the whole process. The vehicle in the back recovers its own original velocity profile for the remaining path.

5.4 Time Constrain

The velocity scheme explained above does not guarantee that the back vehicle will not spend more time than the original journey. The back vehicle initially speeds up to catch the front vehicle but then it copies the velocity of the platoon leader. If the journey of the platoon leader is slower than the original journey of the trailer vehicle, then the trailer vehicle may be delayed compared to the initial journey. Longer trips are in contradiction of one of the constraints of this thesis.

Furthermore, time constrains are needed to guarantee that the obtained fuel savings come from the platooning process and not because vehicles have slowed down. The velocity profiles are different between the original journey and the potential platooning journey of a vehicle. The differences not only come from the catch-up process but when the back vehicle copies the velocity of the leading vehicle. If no time restrictions are imposed, then some of the fuel savings of the platoons can also be due to traveling at a lower speed. In fact, this approach has been implemented showing that fuel savings are mostly due to the lower velocity rather than the platooning process.

Longer trips are avoided comparing the time at the end of the platooning process with the time of the original journey. If the platooning vehicles spend more time than the original, then the platoons are not formed. Thus, the platoons only will be formed when the vehicle in front originally drives faster than the rear vehicle or when the
catch up process compensate the lost time when traveling slower.

Forcing platoons to strictly fulfill the time constrains implies to lose approximately half of the platoon opportunities. In average, only half of the times the lead vehicle will drive faster or at the same speed than the rear vehicle. The reduction of the platoon opportunities may be too big to have significant fuel savings. For this reason some relaxation to the tight time constrains is done in this work. Two minutes delay is allowed when reaching the common destination. If the time relaxation is not very wide, then we still can consider that the fuel savings are due to platooning and that the delays can be accepted for drivers.

5.5 Computing Fuel Savings

The fuel cost is computed applying the cost reduction coefficient once the vehicles have merged. The fuel reduction for vehicles driving behind another vehicle in a platoon is 10%. When platoon formation is not considered, we simply compute the cost of the rear vehicle from the starting point to the common destination considering the original velocity. Both costs are compared. If the cost considering the platoon formation is smaller, then the two vehicles form a platoon. Every time two vehicles form platoon, the position on the road where the vehicles merge and the position of the common destination is stored. This information is used to follow the path with the criteria:

- If the merge point is reached, the cost model change to the platooning model until reaching the common destination.
- Once reached the common destination, the cost model change to the idle state (no fuel reduction).

The displacement through the path is made by OSM node meanwhile the program keeps track of the distance driven and the cost of the vehicle. Once reached one node where the distance driven overcomes a merge point or a common destination, the cost is recalculated considering that the merge/destination is in between that node and the previous one. The same happens with the velocity changes at every synchronous time. Thus, the computation is accurate and it always takes into account the distance offsets respect to the nodes.
Chapter 6

Results and Discussion

The results of this work have been divided into three sections. In the first section, the results of the map-matching and path inference algorithms are presented. In the following section, the analysis of the data characteristics and a first estimation of the potential platoons based on the observed inter-vehicle distance are presented. Finally, the fuel savings obtained after implementing a platoon coordination system are given and the relation between the results and the traffic characteristics is discussed.

6.1 Map Matching and Path Inference

As a part of the data preprocessing, we have developed the tools for map matching and path inference. Thanks to these tools, the GPS traces of the vehicles can be related to the roads of OSM network. In the following two sections, the results obtained are described. The characteristics of the map after applying customized filtering processes are presented. The map is used for the map matching and path inference algorithms to generate the path of the vehicles. Some examples of the matched nodes and inferred paths are presented showing the strengths and weakness of the algorithms developed.

6.1.1 Map Filtering

The map size was significantly reduced after applying the open software tools for OSM `osmconvert` and `osmfilter`. The whole Europe map of 12GB was reduced to a 100MB map of the specific regions containing only high speed roads. This initial filtering process is limited for the characteristics of the OSM format. The filtered map has lots of very short dead end roads that connect to low speed roads, which are not interesting for the work. Also, the process of PI requires a reduced graph describing the network and not the graph directly defined for the OSM nodes. Thus, a map preprocessing before MM and PI is needed. The details of map processing have been explained in the Chapter 3 of this work. The results are presented in this section.

Identifying the Road Junctions

The vertices of the graph used in PI are the road junctions. A program has been developed to find the nodes of the OSM accounting for the road junctions. Because of the presence of short dead end roads, the length of the roads is checked to see if they are alternative paths or they just end few meters later. The node that connects to more than two relative long paths forward or backwards is considered to be a road junction. The results can be seen in figure 6.1.

A intersection is depicted in Figure 6.1a. The intersections are the points of the road where the junctions are. The results show how only 22 of the 263 OSM nodes represented in the figure are road junctions. The process is applied to the whole
CHAPTER 6. RESULTS AND DISCUSSION

Figure 6.1: Nodes that are road junctions (colored)

Figure 6.2: Edges of the graph (green) and vertices of the graph (red)

working map concluding that only 7,692 of the 639,516 nodes of the graph are road junctions. The graph simplification compared to considering all the OSM nodes as road junctions is clear.

Figure 6.1b shows how the dead end roads are not taken into account when looking for junctions. The only node considered as a junction is the one connecting to a parallel road. The other nodes connecting to very short roads are not taken into account. The paths that have less than 30 nodes are not considered as alternative paths in this work. The reason of choosing 30 nodes is that most of the dead end road have less than this number of nodes.
6.1. MAP MATCHING AND PATH INFERENECCE

**Paths Connecting Road Junctions**

The graph is completed by determining which vertices (road junctions) are directly connected and which is the edge (path) that connects them. The iterative DLS algorithm explained in Section 3.5.2 performs this task. Every possible path form every road junctions is explored until finding another node labeled as junction. The exploration is done in a way that the paths with less nodes are the first found and the ones considered. The collections of nodes forming the paths are used to compute the distance from one junction to the other: the edge length.

In Figure 6.2a, the green lines are the paths linking the road junctions. Figure 6.2b shows how the two alternative paths in black are avoided because they have a higher number of nodes.

The total number of paths between junctions found in the road network is 11,020 compared to the initial 109,813 OSM ways. Unfortunately, not all the paths between road junctions are found. There are some OSM roads that end without connecting to other high speed roads.

**6.1.2 Matched Positions and Inferred Paths**

The following figures present the results of MM and PI. The map-matched nodes are represented in blue and the original GPS samples are represented in green. The path inferred between the matched points is plotted with a white line, which links all the OSM nodes identified as the path of the vehicle. All the results are presented on the top of the Google Earth image, which facilitates the interpretation.

Figure 6.3 depicts an example of successful MM and PI of one of the vehicle’s GPS

![Figure 6.3: Example of MM and PI. Blue and green place marks are the matched positions and original GPS samples respectively](image)

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CHAPTER 6. RESULTS AND DISCUSSION

Figure 6.4: Example of unsuccessful MM and PI

traces. The developed algorithms identify the OSM map nodes that match the real path of the vehicle. The right zoomed image shows that GPS and matched nodes do not exactly coincide in position. The MM process only identify a close OSM node but not the exact point of the road for simplicity. On the other hand, the PI identifies the shortest path connecting the pair of matched positions. The correct directions are taken in the road junctions as it can be seen in the zoomed image on the left.

Not all the paths are correctly discovered. That is the case presented in figure 6.4. The figure shows how some of the GPS samples cannot be matched. A vehicle driving out of a high speed way can cause the error. However, it turns out that the road is actually a high speed road. The error is caused by an incomplete map. The map filtering has removed some roads not belonging to any discovered path between road junctions. The filtering process should be improved because not all the roads are discovered.

Another drawback of the MM and PI developed is the high sensitivity to errors of the MM process. If one GPS sample is matched to the wrong road, then the PI algorithm will try to find the path to this point, which can be very long and induce significant errors in the distance driven. Usually, conventional MM algorithms solve the same problem not only choosing one matched point but different candidates. Then, the PI process find all the possible paths between the candidate points and selects the shortest or the one with minimum cost. This step has been omitted in this work. As a consequence, the thresholds imposed to a node to be a matched node are very tight (only 3 meters difference from GPS point the road matched) to avoid wrong matched nodes. In exchange, some low accurate GPS samples may not be matched.
6.2. ANALYSIS OF THE POTENTIAL PLATOON OPPORTUNITIES AND FUEL SAVINGS

A possible way to improve the algorithms is limiting the length of the inferred paths. If the time stamp of the GPS positions is known, then only the path that can be done in a realistic velocity must be considered. Otherwise, the path must be ruled out. Due to lack of time, the algorithms do not incorporate the functionality.

6.2 Analysis of the Potential Platoon Opportunities and Fuel Savings

There may be correlations between the fuel savings and the vehicle distribution in the road network. For this reason, in this section the characteristics of the source data are analyzed. The analysis is completed with a first estimation of the platoon potentials based on current inter-vehicle distances. As mentioned, the data consists on the trajectories of Scania HDVs on the European roads. Moreover, the original data has been filtered in order to obtain data only from HDVs driving on high speed roads. Then, the obtained results concern only those vehicles of interest.

6.2.1 Inter-vehicle Distance

Inter-vehicle distance is one of the parameters playing a major role in the platoon formation. That is why the distance to the closest front vehicle has been determined for all the HDVs and the results are depicted in the next figures.

As a starting point, the number of vehicles that have its closest vehicle within certain distance intervals is computed. The computation is done for every vehicle and at every 2 minutes during 24h. An average of the obtained data is done for all the active vehicles and time samples. Figure 6.5 presents the percentage of vehicles that have its closest vehicle within the intervals specified. The percentage is not from the total of active vehicles but only for the vehicles that have their closest vehicle within 20km.

The results of Figure 6.5 will be used in the next section for comparison purposes once the platoon coordination system has been applied. Note that the number of vehicles in the non-uniform intervals chosen increases the farther is the distance interval. Thus, the length of the chosen intervals increases faster than the probability to find a vehicle in that intervals. However, these intervals still permit showing differences between them at the same time that are typical distances easy to figure out for the reader. That is why these intervals are the ones considered when the platoon coordination is applied.

The analyzed vehicles are not close to each other. Figure 6.6 shows the percentage of vehicles from the total number of active vehicles that have their closest vehicle in a certain range. The distance intervals are the same used in figure 6.5 but this time the percentages are accumulative. In other words, the percentage in the bar from 1000m to 2000m is the percentage of the vehicles whose closest vehicle is closer than 2000m, but not only between 1000m and 2000m as before.

The percentage of vehicles whose closest vehicle is within 20km upstream is about 30%. The low percentage was expected because the source data only has 1773 vehicles
CHAPTER 6. RESULTS AND DISCUSSION

Figure 6.5: Distance to the closest vehicle distribution. Average from samples every 2 minutes during of 24h.

Figure 6.6: Percentage of vehicles from the total of active vehicles whose closest vehicle is in the range depicted. Average from samples every 2 minutes during of 24h.
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![Graph showing active vehicles over time]

Figure 6.7: Number of active vehicles during the day

on a road with more than 15000km. In fact, a rough approximation of the average minimum distance to the closest vehicle gives a distance of 45km. The estimation is done considering that vehicles are placed randomly on a straight line accounting for the road network. In these conditions, the value of the average distance to the closest vehicle is given for:

$$d_{closest} = \frac{L}{N-1}$$  \hspace{1cm} (6.1)

$L$ states for the longitude of the line that in this case is set to 16382km, the total longitude of the map once filtered. $N$ states for the number of vehicles and the value considered is 365, the maximum simultaneous active vehicles during the day.

The low percentages observed in Figure 6.6 permit that the platooning groups maintain relatively small even considering long platooning ranges. If the traffic density was higher, then the constrains to belong to a group should be more restrictive in order to have manageable platooning groups. Shorter distances and higher potential fuel saving should be imposed. That is not the case of this work.

Another thing to point out is the percentage of vehicles whose closest vehicle is closer than 100m. Vehicles in that situation could form a platoon without need of any coordination system. Thus, that percentage of the vehicles accounts for the current platooning rate. The average value during the 24h is 0.4%. The obtained values are very low and justify the need of a platoon coordination system.

Additionally, the traffic density varies depending on the day time. Figure 6.7 plots the number of active vehicles as a function of the day time and it shows big variations. The relationship between the average inter-vehicle distance and the number of active vehicles is analyzed. Figure 6.8 plots the average inter-vehicle distance during the day. Again, the average distance only takes into account the vehicles closer than 20km.

From the figure 6.8 cannot be concluded any relation between the average distance and the number of active vehicles. The average distance maintains approximately constant during the day meanwhile the number of active vehicles strongly varies. Certainly,
there must exist a strong relation between them. The inter-vehicle distance must be inversely proportional to the number of active vehicles. Even though the average distance computation of Figure 6.8 is truncated at 20km, we should be able to see the dependence on the number of the vehicles. However, the author believes that the vehicle density on the road is too low that the statistics are poor and the dependences cannot be observed. The same lack of dependency has also been observed for the distance distribution, but not depicted in this work.

### 6.2.2 Platoon Potentials

A method to determine the platoon potentials based exclusively on the inter-vehicle distances has been described in Chapter 3. The method identifies if two vehicles have not been more than a distance limit (platooning range) apart during a certain time interval. A rough estimation of the possible platoons and fuel savings are obtained through this method. Table 6.1 shows the results considering different platooning ranges and for a time intervals of 2 minutes. The value of the general fuel savings and the savings for platooning vehicles are depicted in Figure 6.9.

The values of the first column of the table are the platooning range used to obtain the data of the specific row. The second column contains the percentage of the total distance that has been traveled for vehicles when they were platooning. The values of the third state for the same platooned distance but computing the percentage from the distance traveled only for the vehicles that at least have platooned once. The fourth and fifth columns contain the percentage of the fuel saved from the total cost of the journeys. The fourth column contains the percentages from the vehicles that have platooned and the fifth column the percentage of savings from the total cost of the vehicles analyzed.

The results show how the fuel savings are proportional to the considered platooning range. The relation seems linear for the distances considered. Certainly, this relation
6.2. ANALYSIS OF THE POTENTIAL PLATOON OPPORTUNITIES AND FUEL SAVINGS

Table 6.1: Results of the estimated platoon potentials

<table>
<thead>
<tr>
<th>platoon range (m)</th>
<th>% total platooned distance</th>
<th>% platooned distance for platooning vehicles</th>
<th>% platooning vehicles</th>
<th>% fuel reduction for platooning vehicles</th>
<th>% total fuel reduction</th>
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</table>

Figure 6.9: % of the fuel saved respect to the total fuel consumed
cannot maintain linear because the fuel savings must be limited. The top value of fuel savings is 10% considering the platooning groups are big and the non-platooning leader can be neglected. The top value is achieved when all the vehicles are platooning all the time. The maximum observed value in the analysis is 2.5%, corresponding to the situation where 26.6% of the total distance traveled is done when vehicles are in platoons. In conclusion, a platooning range of 20km with the low vehicle density studied is not large enough to have platoon opportunities during all the time. However, increasing the platoon opportunities with larger a platooning range may not increase significantly the real platoons because of the cost of the platoon formation. The issue will be discussed in the next Section 6.3.

Another factor that shows the low density of vehicles is the total platooned distance. Vehicles maintain closer than 20km from their closest vehicle during only 26% of the whole driven distance. These values must be used to weight the platoon savings when the coordination is done.

### 6.2.3 Number of Vehicles per Platooning Group

The number of vehicles per platooning group will obviously increase when the platooning range increases. The percentage of platoons with the specific number of vehicles are plotted in Figure 6.10. Again, the numbers are obtained from the 24h average. The results plotted have been obtained setting a platooning range of 20km. The number of vehicles in the platooning groups maintains low due to the previous described low density of HDVs. Even for a 20km platooning range, the maximum number of vehicles in a platoon is 19 and platooning groups larger than 4 vehicles happen in very few cases.

![Figure 6.10: % of platooning groups with the specific number of vehicles](image_url)
6.3 Analysis of the Fuel Savings after Platoon Coordination

In contrast to the previous Section, here the initial trajectories of the HDV are modified applying the platoon coordination system described in Chapter 3. The platoon coordination system allows us to define precisely when the vehicles are platooning. Hence, the cost of platoon formation due the speed up can be considered. At the same time, the trajectories of the vehicles are more realistic because they take into account when vehicles adapt the velocity to form platoons.

In the following paragraphs are presented the fuel savings after the coordination scheme is applied. The results are compared with the initial estimation. Also, how the inter-vehicle distances reflect the formation of platoons and how the density of the vehicles affects the platoon formation is discussed. Additionally, some statistics of the formed platoons are provided.

6.3.1 Fuel Savings

The main goal of this thesis is to quantify the fuels savings when a platoon coordination strategy is applied. In this section, the results are presented with the same parameters of the previous initial estimation (see Section 6.2.2). Table 6.2 lists the values obtained when allowing 2 minutes delay respect to the original HDV journeys.

Table 6.2 main values are those of the lasts column that are related to the fuel savings. The other values are given to understand the scenarios that give the specific fuel savings. Figure 6.11 and Figure 6.12 plot the percentage of the fuel savings as a function of the platooning range considered. Figure 6.11 shows the percentage from the total fuel costs and Figure 6.12 the percentage from the costs of vehicles that have platooned.

<table>
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<tr>
<th>platooning range(m)</th>
<th>% total platooned distance</th>
<th>% platooned distance for platooning vehicles</th>
<th>% platooning vehicles</th>
<th>% fuel reduction for platooning vehicles</th>
<th>% total fuel reduction</th>
</tr>
</thead>
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</tbody>
</table>
Figure 6.11: % of the fuel saved respect to the total fuel consumed

Figure 6.12: % of the fuel saved respect fuel consumed for platooning vehicles
6.3. ANALYSIS OF THE FUEL SAVINGS AFTER PLATOON COORDINATION

**Dependences**

Determining the dependence of the fuel savings with the chosen *platooning range* has an especial importance. The proper *platooning range* that gives significant fuel savings can be derived from the dependence. Results show how the fuel savings increase when considering larger *platooning range*. This is obviously due to the fact that more vehicles are considered for the potential platoons and hence the final number of platoons created increases. The fourth column of Table 6.2 shows how the number of vehicles that have platooned at the end of the day effectively increases when the distance considered for coordination is larger.

The fuel saving curves in Figure 6.11 strongly increase when larger become the distance in consideration. The larger is the *platooning range* the higher is the number of potential vehicles to form platoons. For small *platooning ranges*, the vehicles considered are close so the cost of the platoon formation is low and the fuel savings strongly increase when more vehicles are taken into account. If the *platooning ranges* keeps increasing, then the number of vehicles keeps increasing too, as it has been seen in Figure 6.5. However, the inter-vehicle distance becomes larger and so the cost of the platoon formation until no longer the platoons are fuel beneficial. For this reason, the general fuel savings saturates. This behavior is the one expected intuitively.

Remarkably, the general fuel savings for larger *platooning ranges* not only saturates but also slightly decrease in some cases. This behavior may seem surprising when all the platoons formed save fuel. Considering larger distances should only increase the number of the platoons. However, the formation of platoons with low fuel benefits can avoid the later formation of other platoons with higher benefits. For instance, imagine one HDV set to catch up another vehicle far away when the final fuel benefit is very low. Once the vehicle has started the catch-up, the coordination system does not take into account other platoons until the platoon is split. The fuel savings driving in a platoon could have been higher with the last appeared vehicle. In conclusion, very large *platooning ranges* do not contribute to save more fuel and they can be counter-productive in some cases.

A *platooning range* of 5km seems to be the most convenient based on the curve of Figure 6.11. Considering a higher distance will increase the complexity of the platoon formation without affecting significantly the fuel savings. This result is independent from the density of the vehicles because it only depends on the distance traveled for the trucks in the journeys. The working data has not many journeys but they still can be considered representative of the average characteristics of the HDV journeys.

**Fuel Saving Values**

So far, only the functionality of the fuel savings has been discussed but not the magnitude of the results. Regarding the absolute values, the maximum fuel savings obtained are around 0.14% of the total cost of the HDV fleet. Fuel savings obtained are very low compared to limit value of 10%. The low fuel savings are due to the limited opportunities to form platoons at a low cost. Only 8% of the vehicles end up forming a
platoon from the 86% of vehicles that have at least one platoon opportunity (see Table 6.1 and Table 6.2).

The platoon fuel savings after the coordination are lower than the potential fuels savings computed in Section 6.2.2. The cost of platoon formation considered in this point explains the differences. However, for short platooning ranges the savings are slightly better. After coordination, the platoons maintain vehicles close to each other. Vehicles remain closer for longer distances meanwhile the inter-vehicles distance could fluctuate when the potential platoons were estimated.

If with the fuel reduction ratio is only taken into account the vehicles that have platooned, then the average fuel benefits is around 1.3%. The average benefits for platooning vehicles seems to decrease when considering longer platoon ranges (See Figure 6.12). The new platoons considered increasing the platooning range have higher cost of platoon formation so lower fuel benefits that reduce the average benefit of the platoons. That is why in general the fuel savings reduce when increasing the platooning range. However, the platoons formed at every platoon range are different so the results are quite random due to not many platoons are considered in the statistics.

### 6.3.2 Inter-vehicle Distance

Figure 6.13a shows the distance to the closest vehicle distribution (time average) when platoon coordination has been applied with a platooning range of 20km. For comparison, Figure 6.13b shows the results obtained in the previous Section 6.2.1. The percentage of vehicles whose closest vehicle is closer than 100m notably increases after coordination. The platooning distance is set to 10m so all the vehicles that have formed a platoon will be within this distance interval. The interesting point is to see how the percentage of vehicles in each distance interval reduces. The reduction informs about the impact of platoon formation depending of the inter-vehicle distances.

![Figure 6.13: Distance to the closest vehicle distribution](image)

(a) With coordination  
(b) Without coordination

The plots in Figure 6.13 show how the vehicles closer than 5km are substantially affected for the platoon formation. This is not the case of vehicles more than 5km.
6.3. ANALYSIS OF THE FUEL SAVINGS AFTER PLATOON COORDINATION

away. The behavior is consistent with the results of table 6.2 where the fuel savings do not increase significantly when platooning ranges larger than 5km are considered. Moreover, the repetition of the analysis performed in Figure 6.6 shows how 3% of the active vehicles have their closest HDV within 100m after the platoon coordination.

6.3.3 Platoon Statistics

The previous results gave general information but not details of the platoons. Here, the number of vehicles per platooning group, the time spent in a platoon, the number of times a vehicle form a platoon and the catch up distance are analyzed. The platoons’ characteristics are presented to give a general overview of the platoons that may be expected between HDV. The characteristics are analyzed only for the results with the larger considered platooning range (20km). The largest platooning range contains platoons with different initial inter-vehicle distances but the main behavior will be mastered for the platoons formed between very close vehicles, which are the most common.

The results of the number of vehicles per potential platooning group have been presented in the previous section. Not all of those vehicles will finally form a platoon because the cost of platoon formation neglected. Thus, the number of vehicles in a coordinated platoon is expected to be smaller. The results after implementing the platoon coordination system are depicted in Figure 6.14.

Figure 6.14 shows how the number of vehicles per platoon after the coordination is very small. The largest platoon during the 24h is made of only 4 vehicles compared to the 19 vehicles observed in the potential platooning groups (see Figure 6.10). Moreover, platoons with only two vehicles are by far the ones more common, occurring 90% of the times. The platoons with three vehicles account for the approximately the

![Figure 6.14: Percentage of platoons with the specific number of vehicles](image)

57
9% meanwhile the platoons with 3 vehicles account for the remaining percentage. Therefore, there is no need to put more constrains to limit the number of vehicles per platoon for the data analyzed. The platoons formed during the simulation are small and they could have been formed in a real scenario. Moreover, the result demonstrates that the approach followed in this work will not give values that differ significantly from an optimal platoon coordination. The final platoons are small, which means that the chances to coordinate more than two vehicles at the same time are also small.

The number of times a vehicle has platooned is represented in Figure 6.15 considering a platooning range of 20km. The figure plots the percentage of vehicles that have platooned the specific number of times. The percentages are from all the vehicles analyzed. Thus, the bars of the histogram of Figure 6.15 sum up 100%. Likewise, the duration of the platoons is depicted in Figure 6.16 also considering the platoon range of 20km. The percentage corresponding to 0 minutes has been omitted. There are many vehicles that have not platooned making the percentage for 0 minutes high, which prevents to see in detail the other time intervals in the same graph.

Less than 10% of the vehicles have platooned and most of them have only platooned once. Less than 1% of the vehicles have platooned twice meanwhile none of the vehicles have platooned more than two times with the working data and the platoon coordination applied. The results are in part due to the low traffic density and platoon chances but also because the time platooning is relatively large as it can be seen in Figure 6.16.

Figure 6.16 shows for how long HDVs have been platooning at the end of the simulation. The results can be interpreted as the portability a platoon produce for the specific durations. The functionality observed is that the longer is the time platooning the lower is the probability. Nevertheless, platoons up to 120 minutes in duration are still quite common in the working data. The limited paths and directions a HDV can
6.3. ANALYSIS OF THE FUEL SAVINGS AFTER PLATOON COORDINATION

Figure 6.16: Distribution of the platoon duration

Figure 6.17: Distribution of the catch up distances

take in the high speed roads contribute to make these long trips possible. The longest platooning time observed is 4h, which is an indicator of the chances to form large platoons.

Finally, the catch up distance involved in the platoon formations can also be characterized. Figure 6.17 plots the accumulate percentage of times a platoon formation have been done within the catch up distances specified. The results are obtained computing all the platoon formations during the 24h. The percentage of the catch-ups done with less than 100m is around 13%. The percentage increases significantly if there are also
considered catch ups at 500m, 1000m 2km and 5km. The percentage of platoons done with catch ups less than 5km is quite close to 100%. Few platoons have formed with the back vehicle speeding up more than 10km and no one has formed with speeding up during distances larger than 20km. This is obviously due to the cost of the platoon formation. The results of Figure 6.17 quantify the behavior expected and put the typical catch up distances behind the 10km.
Chapter 7

Conclusion

The objective of this thesis was to quantify the potential fuel savings of a HDV fleet when vehicles form platoons. A platoon coordination strategy and a fuel model have been defined according to intuition and previous related works. Several assumptions and simplifications have been made in these definitions in order to model the real problem meanwhile keeping it tractable. The final approach used is a simplification of the reality but still takes into account the theoretical dependencies as well as the magnitudes close to the experimental values.

The real GPS data available for this work has been analyzed to characterize the typical inter-vehicles distances that play a major role in platoon formation. The results show how the considered vehicles are widely spread. Only 30% of the vehicles driving faster than 50km/h have another vehicle within 20km in average during the day. This strongly limits the platoon opportunities. When vehicles closer than 20km are considered to be in a platoon, a theoretical maximum value of 2.5% fuel savings can be achieved neglecting the cost of the platoon formation.

During all the day, an average of only 0.7% of the HDVs driving faster than 50km/h have a neighbor closer than 100m. We say that the vehicles within this distance are in conditions to platoon so the percentage can be interpreted as the current platooning range of the Scania vehicles. The platooning rate is increased up to around 3% when the platoon coordination system is applied, which demonstrates the effectiveness of the system designed.

Low fuel savings are obtained when the platoon coordination is implemented. Only a 0.14% reduction of fuel consumption is achieved when allowing 2 minutes delay respect to the original journeys. The value obtained is not very high but it could be achieved only with vehicles of the same manufacturer. That implies that no agreements within manufactures and standardizations of the system are needed. In contrast, the percentages of fuel savings only for the vehicles that have platooned at the end of the day are more significant. A platoon coordination can achieve fuel savings around 1.3% for the platooning vehicles without affecting the current journeys of the other HDVs.

The low percentage of fuel savings might be largely improved if the density of vehicles were higher. The number of platoons formed was not high because the platoon opportunities were limited for the low density of the vehicles. A higher number of vehicles will increase the platoon opportunities and so the final platoons formed. On the other hand, the results show how vehicles that platoon save in average a significant 1.3% of the fuel. HDVs travel relatively long distances when they are in a platoon. The analysis of the platooning time confirms this behavior. Moreover, increasing the density of vehicles will make long duration platoons more probable because there will be more platoon opportunities to choose for a same vehicle. Vehicles of other manufactures
can contribute to increase the number of platooning vehicles. In fact, Germany has an area about 2/3 of the area considered in this work and it has over 400,000 registered HDVs [4] compared to the 7000 HDVs analyzed in this work. Also, the increase of the transportation needs in the future can lead to higher HDV density on the road.

The MM and PI algorithms developed in this work should be improved. The results have been presented in this report showing that the algorithms are working. However, some improvements are needed in order to make the matched data useful for the fuel saving analysis. The work to do involves improving the filtration process and post-processing the matched data. The filtering process should recover some missing roads for which no connection to other roads has been found. Post-processing must remove the matched paths that are unfeasible according to the known time sampling of the GPS points.
Chapter 8

Future work

Low fuel savings have been obtained through analyzing the working data. However, the results obtained suggest that the fuel benefits can be largely improved if the density of the vehicles increases. For this reason, the author believes that the next immediate step should be to repeat the same analysis but gathering information of more vehicles. Another option is to create simulated data to extrapolate the results to a scenario with higher density of vehicles.

The strategy to form platoons used in this work is not unique. Many other strategies can be defined playing with the time constrains of the problem. For instance, one possibility to explore is to slow down the vehicles, once the platoons have split, in order to reach the destination at the same original time. Another possibility is to allow greater delays if higher fuel savings can be achieved. Furthermore, the general problem of optimizing the cost of a platoon formation in a continuous space still remains to be resolved. Define more fuel efficient strategies to form platoons will be needed to enhance the platoon benefits.

Future more accurate analyzes of the platoon fuel savings are possible if the fuel model is improved. There are other more complex and accurate models that the one used in this work. In this direction, the slope information of the road can contribute to better differentiate the different contributions in the fuel consumption of the vehicles.

This work has performed an off-line analysis assuming that the current positions and the destinations of the vehicles are known. If a platoon coordination system comes to a reality, then there must exist some IT infrastructure gathering that information. Current projects on platooning are developing such on-line systems. Future potential fuel saving analysis must take into account the communication capabilities of the current frameworks or design the necessary infrastructure according to the needs.
Bibliography


