

# MASTER EN INGENIERÍA DE SISTEMAS Y DE CONTROL



## Traffic Simulation of Autonomous Vehicles in Swarm Configuration

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## **Dedication**

Thanks to my wife and little daughter for their time and valuable support on this work.

## **Acknowledgments**

There are many who have contributed to the work presented in this report. First of all, I would like to give my sincere gratitude to my supervisors Matilde Santos and Manuel Romana at UCM for guidance and feedback during the final stage of this project, and also for invaluable insights and recommendations on papers.

Secondly, I will like to thank ZF Friedrichshafen AG for the valuable help on getting access to valuable documentation about the latest technology developed by the company for advance driving assistance functions which gave me some insights on the future driving strategies that the automotive market will demand in the near future.

## Abstract

Autonomous driving is becoming an increasing trend in the automotive industry as vehicles are more and more smart while information is shared among them and with the infrastructures via wireless communication.

Vehicle organization in swarms is considered an interesting approach in future traffic management. An intelligent and better organization of the vehicles in the roads could significantly improve road efficiency and safety. Current practical exercises of swarm approaches such as platooning support this conclusion.

In this work, different car-following models and one lane changing algorithm have been implemented using Matlab software. The behaviour of swarms of vehicles under different road and driving conditions has been analysed. The result of this research can help to better understand how the vehicles driven in a swarm configuration can effectively maximize the traffic flow.

This final project also goes in depth in the study of the parameters that define the autonomous vehicle swarm behaviour such as its size, desired speed, inter-vehicle distance, etc., and how it will depend on the application of the swarm (high way, traffic jam assist, ...). It also analyses in detail the swarm application called platooning.

To the best of our knowledge, this is one of the first attempts of applying swarm intelligence in the automotive market.

**KEYWORDS:** Swarm intelligence, artificial intelligence, platooning, car-following, autonomous vehicle, traffic management

## Resumen

La conducción autónoma se está convirtiendo en una tendencia creciente en la industria automotriz; los vehículos son cada vez más inteligentes y se comparte más y más información entre ellos y con las infraestructuras a través de la comunicación inalámbrica.

La organización de vehículos en enjambres, por lo tanto, se considera un enfoque interesante para futuras estrategias de gestión del tráfico; una mejor organización de los vehículos dentro de las carreteras podría mejorar significativamente la eficiencia y la seguridad vial.

En este Proyecto Fin de Máster se han implementado diferentes modelos de seguimiento de automóviles y un algoritmo de cambio de carril en Matlab para estudiar el comportamiento de un enjambre de vehículos autónomos en diferentes condiciones de conducción y carreteras. El resultado de esta investigación puede ayudar a comprender cómo los vehículos que se conducen en una configuración de enjambre podrían maximizar efectivamente el flujo de tráfico.

Este trabajo también profundiza en los parámetros que definen el comportamiento del enjambre, tal como su tamaño, la velocidad deseada, la distancia entre vehículos, etc., y cómo depende de la aplicación del enjambre (autopista, asistencia para atascos de tráfico, ...). Se analiza con detalle la aplicación de enjambre llamada platooning (convoy).

Este es uno de los primeros intentos de aplicar la inteligencia de enjambres en la industria automotriz.

**PALABRAS CLAVE:** Inteligencia de enjambres, inteligencia artificial, convoy, seguimiento de vehículo, vehículo autónomo, gestión del tráfico.

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## List of Acronyms

IDM	Intelligent Driver Model
MOBIL	General Lane Changing Model for car following models
OVM	Optimal Velocity Model
CC	Cruise Control (CC)
ACC	Adaptive Cruise Control
CACC	Cooperative Adaptive Cruise Control
GUI	Graphical User Interface
V2V	Vehicle To Vehicle
V2I	Vehicle To Infrastructure
ADAS	Advance Driver Assistance Systems
OEM	Original Equipment Manufacturer
SAE	Society of Automotive Engineers
CTG	Constant Time Gap
CVS	Constant Vehicle Spacing
NREL	DOE's National Renewable Energy Laboratory
PSO	Particle Swarm Optimization
ACO	Ant Colony Optimization

## Symbols Used

$\delta$	Acceleration exponent
$\Delta V_\alpha$	The velocity differential between $v_{\alpha-1}$ and $v_\alpha$
$a$ ( $m/s^2$ )	Acceleration
$b$ ( $m/s^2$ )	Comfortable deceleration
$l_\alpha$ ( $m$ )	Length of car $\alpha$
$s_0$ ( $m$ )	Linear Jam Distance
$s_1$ ( $m$ )	Nonlinear Jam Distance
$s_\alpha$ ( $m$ )	The bumper-to-bumper gap between $x_{\alpha-1}$ and $x_\alpha$
$t_0$ ( $sec$ )	Beginning of time interval
$t_f$ ( $sec$ )	End of time interval
$T$ ( $sec$ )	Safe Time headway
$V_{\alpha-}$ ( $m/s$ )	The velocity of the car ahead
$\dot{v}$ ( $m/s$ )	Initial velocity of the car
$V_0$ ( $m/s$ )	Desired vehicle speed
$x_\alpha$ ( $m/s$ )	Position of the car ahead
$\dot{x}$ ( $m$ )	Initial position of the car

*Table 1: Symbols*



# CHAPTER 1: Introduction

## 1.1 Motivation

Traffic jams/heavy traffic has become an increasing common situation over the last years generating high levels of frustration and unhappiness. On the other hand, traffic intelligent management can be seen as gold opportunity for researching in this field by the scientific community.

With gaining popularity of autonomous cars, it is only a matter of time before hundreds of self-driven cars will flock our roads. The current system associated with such cars would drastically reduce the efficiency, as each car would be required to compute its own course. With safety being one of the highest priorities, a single wayward car could compromise the security of all cars on the roads. New and alternative traffic management strategies must therefore be developed for this new scenario.

One of the traffic management solutions that can potentially be adopted to prevent congestion and increase road efficiency would be the swarm intelligence. This approach would consider the “same” type of vehicles collaborating with each other to reach the same goal. This requires that driverless cars will need to work, communicate and learn collectively rather than as individual units. Researchers around the world see some promise in preventing traffic jams (Nunen, 2012) by learning from social insects like ants, deriving the so-called swarm intelligence (Prakash, 2014). The interactions among vehicles will lead to an "intelligent" global behaviour which has its natural example in ant colonies, bird flocks, animal herding, bacterial growth, and fish schooling.

However, cars are not the same as insects after all. They will not, for example, tell each other where the sources of food are. Cars will instead, 'communicate' about traffic congestion and warn against other problems to help the vehicle's navigation or inform drivers about road circumstances not yet seen, etc ... Thanks to the advanced sensors that the new vehicles will be equipped with such as LIDAR, Radar, GPS, Wireless Comm, etc, any information that will help autonomous cars get a notice of the driving conditions in the future will thus allow to reduce traffic issues and achieve higher levels in automatization. However, while logistical systems like these are being implemented, it still lacks a swarm 'mentality', per se.

Autonomous driving on public roads is currently restricted by law. According to the Vienna Convention of Road Traffic, which is ratified by over 70 countries as the foundation for international road traffic regulation, a driver must be present and in control of a moving vehicle always.

However, this convention dates back from more than 45 years, and clearly road transportation issues have moved on since then! In May 2014, an expert committee of the United Nations added a new rule to the Vienna Convention: “Systems that autonomously steer a car are permissible if they can be stopped by the driver at any time”.

This recent addition represents a significant step forward in the development of automated driving, and several countries are now reviewing national legislation to allow self-driving vehicles in specific circumstances where automated technology is proved to be sufficiently mature and safe. Early policy reviewers –and therefore the countries that are likely to feature early adoption– include USA, UK, and New Zealand.

According to the latest research projects in traffic management (Nunen, 2012), there are several swarm applications on which this cooperative intelligence could be applied to the traffic scenario:

1. On free-way traffic conditions, when trucks with maximum load have a uniform speed and does not require to overcome other vehicles. Swarm configurations can then be adopted to help the individual members drive in a safe and efficient way.
2. On free-way traffic conditions, trucks with non-maximum load that potentially could achieve higher speeds than in 1) and therefore, could overcome other vehicles.
3. On free-way traffic conditions, trucks and vehicles with same goals (e.g. destination). The swarm configuration in the case would help the individual members to drive safer as the swarm structure would provide constant driving conditions.
4. On urban driving, when any type of vehicles is together in a traffic jam condition. Constant variation of the position in traffic causes other drivers to brake abruptly which may even cause accidents. Cities already choking with exhaust fumes and traffic cannot cope with more. That is where the swarms come in: thousands of cars "thinking" together to find a common solution.

Based on the above examples, it could be assumed that all the vehicles within the swarm maintains the same structure. However, in real-life, vehicles are usually assigned with different transport missions and have different origins or destinations. In this project, we aim to answer questions such as:

- What are the conditions to form a swarm of vehicles?
- How is the swarm defined (type and number of vehicles, shape of the swarm)?
- How is the permeability of a swarm managed and how does it affect the traffic management?
- How traffic management benefits from a swarm type of driving?

In this work, we have focused on the platooning driving concept as a preliminary swarm driving strategy. It is currently under investigation in the automotive market due to its theoretical benefits in terms of safety and road efficiency (Deng, 2016). Experimental tests so far confirm the expectations with vehicles of the same type. Latest research projects are pointing to apply this technology to a multi-brand platooning configuration with the idea of increasing the impact on the overall traffic management.

This report will dive into the multi-brand platooning concept idea and its influence on the traffic management with novel proposals.

## 1.2 Project Objectives

The flow of autonomous and connected cars into our roads is a close reality. It may be important at this moment to explore the possibilities that optimize the use of road infrastructures, users driving comfort and the communication requirements among them to understand how this new technology may improve road safety and efficiency.

This project aims at the following general goals:

- a) Search on traffic flow management studies related to autonomous cars and its application to swarm configuration
- b) Analysis of the state of the art in swarm intelligence applied to autonomous vehicles
- c) Analysis of different traffic flow models and the development of a model that allows to implement swarm configuration of vehicles.
- d) Simulate traffic flow models, based on the individual behaviour of each vehicle, but in a swarm structure, to see its advantages and disadvantages
  - a. Develop a simulation tool for traffic flow modelling including different types of vehicles and roads
  - b. Implement functionalities in the simulation tool such as driving, overtaking and swarm cooperation
  - c. Propose potential swarms of vehicles according to different scenarios
  - d. Analysis of the advantages and disadvantages of swarms versus individual behaviour in traffic flow management

Additionally, the project also has the following specific objectives that will be drawn from the analysis of the simulation:

- a) Understand the most logical approach to define a swarm
- b) Study whether driving in a swarm may improve road safety and efficiency
- c) Understand when swarm approximation may benefit overall traffic safety and efficiency

## 1.3 Project Structure

The report of this project is organized with the following structure:

- In chapter 2, the state of the art about the swarm intelligence in the automotive market is presented. Current research projects in traffic management using swarm

intelligence are discussed and evaluated. Particularly, this Final Project mainly focuses on the platooning driving architecture as a future application of the swarm intelligence on the freeway traffic condition.

- In chapter 3, some of the most relevant microscopic traffic models that are in use nowadays are introduced, in order to get a better understanding of the traffic flow. New traffic management strategies have been proposed and implemented in this work.
- In chapter 4, a new simulation tool for platooning traffic architecture has been developed using MATLAB. The tool integrates the IDM car following model and the MOBIL lane change model to simulate current human driving behaviour and will be used as the baseline code to simulate a platoon of vehicles. The tool reports most of the relevant metrics used in traffic management to evaluate the swarm performance during the simulation time and make a comparison with the current human driven approach.
- In chapter 5, the simulations carried out with the tool presented in chapter 4 and its results are shown and discussed.
- In chapter 6, the conclusions and potential future works are discussed.

# CHAPTER 2: State of the Art

## 2.1 Introduction

Autonomous cars are becoming an increasingly important feature of modern life. State-of-the-art computer technology is striving to simulate how our brains work and, if possible, improve upon them so that overall traffic management is benefit from. With the help of this technology and the application of the swarm intelligence, this is closer to be real. It is foreseen that the swarm intelligence applied to the autonomous vehicle could potentially prevent current accidents on congestion situations and increase traffic flow in free-way driving (M.S. Kanitkar, 2015).

Congestion in large cities surroundings is being approached in two different ways. One of the approaches most adopted nowadays is to work on the infrastructure side, trying to provide information about the road traffic conditions and advising drivers on travel times to permit rerouting, as well as managing the flows of vehicles onto highway on-ramps. On the other hand, other projects focus on the vehicles, developing intelligent systems able to adjust vehicles speeds based on the preceding vehicles velocity, modifying the dynamics of the traffic response (Milanés, 2014).

This means that upcoming autonomous vehicles must cooperate among them and learn from the collective behaviour. Some of the current investigations foresee the swarm of autonomous vehicles working collectively as examples of real application of artificial intelligence to prevent traffic jams and improve road capacity and safety. The concept behind this is to learn from other societies like the ants to create a collective or swarm intelligence.

In the case of cars, by means of swarm intelligence they will be able to communicate between them about traffic congestion and to warn about other traffic issues. For example, heavily laden trucks will know when they are approaching a hill thanks to digital maps and satellite navigation. The intelligence of the truck will be able to schedule that the journey will be slowed down. This information could be transmitted to other vehicles so that they can accommodate their driving behaviors (e.g, quick overtake).

There are several applications of swarm intelligence to autonomous cars that have been used as background knowledge for the development of this work such as, for example, papers focused on truck platooning and traffic jam assistance.

Trevor Hill, head of Audi's South African operations, says in (Furlonger, 2017): "The car of the near future will be constantly collecting masses of data to facilitate automated driving in a type of traffic-swarm intelligence. One car on its own knows little; many cars know a lot. Each individual car can enhance the overall performance of all cars by providing data via the cloud." By relaying information back and forth amongst each other, vehicles on the road will be able to alert drivers of potential traffic incidents before they can see it coming. Future systems will allow vehicles to send braking, speed and direction information to other cars, helping to sort out hairy situations immediately.

Several OEMs (Original Equipment Manufacturer)) are currently working on the concept of swarm applied to autonomous driving to increase road safety and safe human lives. For instance, Honda is applying its so-called Safe Swarm, that may improve safety of driving using vehicle-to-vehicle (V2V) communication based on a dedicated short-range

communication standard and thus providing assistance to the human driver. Safe Swarm essentially means that cues picked up by one vehicle equipped with connective communication technology can pass through information to others in proximity, far before a driver is aware of anything. Cars can shuttle their collected knowledge down the line, propagating information about a pile-up potentially miles ahead in near real-time to make it easier for human drivers to act avoiding problems before they happen.

Other car companies are working using similar technology; Mobileye's REM system works on a very similar basis, connecting vehicles equipped with Mobileye sensor technology so that they can share real-time traffic and road condition information, to inform ADAS and other autonomous driving features. It is a bit like a fully automated Waze that does not require driver inputs.

## 2.2 Autonomous Vehicle Technology

An autonomous car (also known as a driverless car, self-driving car) is a vehicle that can sense its environment and navigate without any human input (Wikipedia, Self-driving car - Wikipedia, 2019). The autonomous cars are equipped with a variety of sensors that perceive their surroundings. They use different control strategies to define the appropriate navigation path and drive the corresponding actuators (Figure 1).

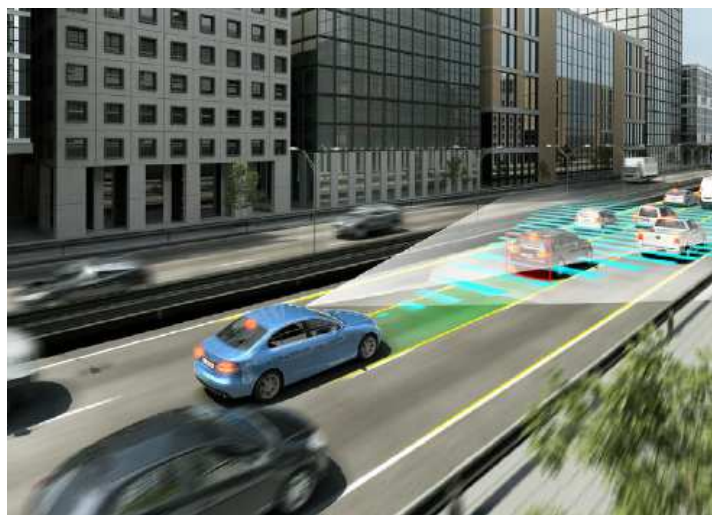


Figure 1. *Autonomous vehicle sensors*

As an example, a driver-less car may be equipped with the following components:

- 1) Lidar sensor that tracks road edges and map vehicle surroundings
- 2) Radar that monitors vehicle position
- 3) Video camera that checks traffic signals and pedestrians
- 4) Ultrasonic sensors mounted on the vehicle laterals to track for vehicle surroundings while parking
- 5) A central computing system that gathers all the sensors information to control the vehicle longitudinally and laterally via the braking and steering systems actuation.

This technology shall be developed to meet the automatization levels defined by the SAE (Society of Automotive Engineering) organization towards the full autonomous vehicle (Figure 2):

		Monitored Driving			Non-monitored Driving		
		Level 0 (Driver Only)	Level 1 (Assisted)	Level 2 (Partial Automation)	Level 3 (Cond'l automation)	Level 4 (High Automation)	Level 5 (Full Automation)
		Eyes-ON	Eyes-ON	Eyes-ON	Eyes-OFF	Eyes-OFF	Eyes-OFF
		Hands-ON	Hands-ON	Hands temp. OFF	Hands temp. OFF	Hands-OFF	Hands-OFF
Safety Requirements	Vehicle role ← → Driver role	Driver is continuously exercising longitudinal <u>and</u> lateral control.	Driver is continuously exercising longitudinal <u>or</u> lateral control.	Driver <u>has to</u> monitor the system <u>at all times</u> .	Driver <u>does not</u> have to monitor the system at all times; must always be in a position to resume control.	Driver is not required during <u>defined use case</u> .	System can cope with all situations automatically during the entire journey. No driver required.
			Lateral or longitudinal control is accomplished by the system.	System has longitudinal <u>and</u> lateral control in a specific use case.	System has longitudinal and lateral control in a specific use case. System recognizes the performance limits and requests driver to resume control within a sufficient time margin.	System can cope with all situations automatically in a <u>defined use case</u> .	
				Add DAS sensor(s) and electronic control of actuator(s)	Improve robustness in detection of scenarios requiring driver to retake control	Add <u>redundant</u> sensing, control and actuator capabilities in case of system failure while driver has hands off wheel	Add <u>fully redundant</u> sensing, control and actuator capabilities in case driver unable to retake control in emergency
Traditional passive safety and chassis systems are the foundation for all automated driving functions							

Figure 2. SAE Automatization Levels

The levels can be simplified by rephrasing them in terms of the driver role in relation to today driving:

- Level 0: driver fully in charge (today driving)
- Level 1: driver may be “feet off” if using Adaptive Cruise Control or “hands off” if a Lane Keeping Assist system is engaged
- Level 2: allows for both hands-off, feet-off driving – eyes must stay “on” the road
- Level 3: enables hands-off, feet-off, and eyes-off. Brain on (driver is able to resume control fairly quickly)
- Levels 4 and 5: human driver has no responsibilities

According to the SAE Automatization levels, the following ADAS (Advance Driving Assistance Systems) can be developed within the different levels with the use of the technology presented above (Figure 3):

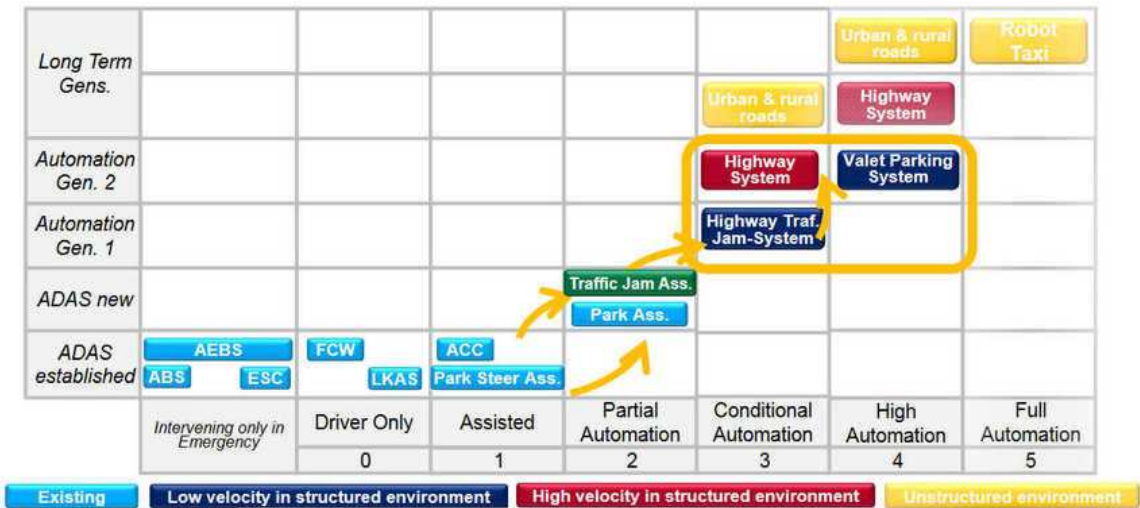


Figure 3. Advance Driver Assistance Functions

An example of a truck with driver-less technology is presented in Figure 4, with all the necessary components to bring full automatization.

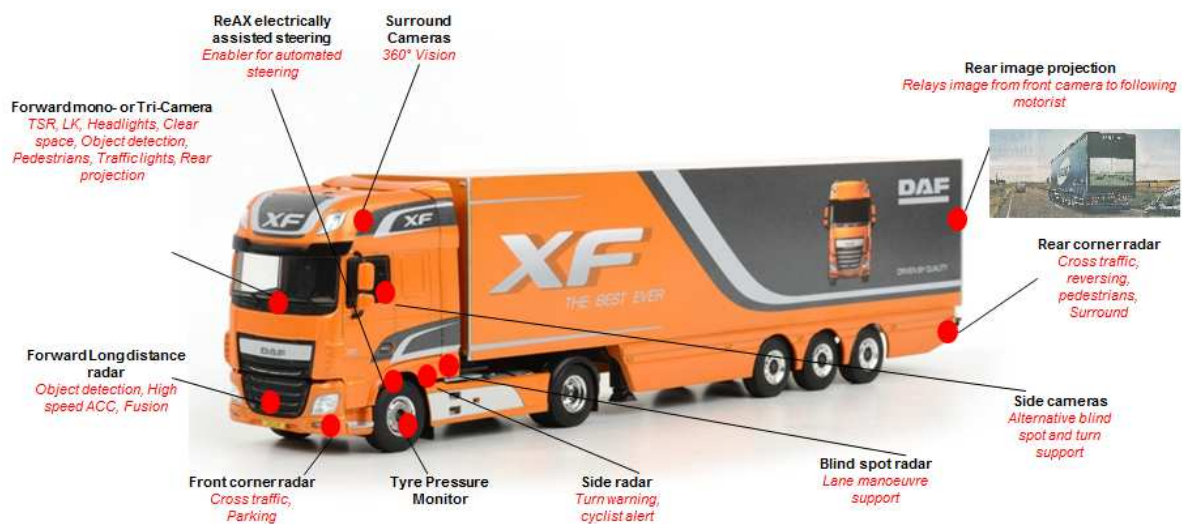


Figure 4. Example of driver-less truck set of components (ZF confidential)

Additionally to the technology developed for the vehicle itself, new communications protocols such as V2V (Vehicle to Vehicle) and V2I (Vehicle to Infrastructure) would enable the cars to "talk" to the road and with other vehicles, gathering and sharing information on traffic build-ups, weather, road conditions, vehicle status and other issues.

The fusion of driver-less technology and V2V and V2I communication protocols are therefore, the basis for the potential application of swarm intelligence into the vehicles and to implement better traffic management strategies.

## 2.3 Swarm Intelligence in Traffic Management

### 2.3.1 Swarm Intelligence

Swarm intelligence is defined as “The emergent collective intelligence of groups of simple agents.” (Bonabeau et al, 1999) or a system which works in real time conditions and where the members of a group interact with each other in a decentralized way to achieve an objective via self-organization (M.S. Kanitkar, 2015).

In many real-life situations, there are a large number of tasks and a large number of autonomous agents which can solve these tasks. The problem is how to best match agents and tasks. This problem can be found in manufacturing, robotics, cooperation and computing among others.

In general, if we want an optimal matching, then this problem is difficult to solve. One of the natural solutions is the biology. Insects, for example, are usually small, so it is difficult for an individual insect to perform complex tasks. Instead, they swarm together and perform tasks in collaboration. The group is organized in a so-called swarm configuration that has some qualities that exceed those of the individuals. Swarm intelligence thus means that the behaviour of the swarm is more intelligent than that of the individuals.

Since the existing social insects are the result of billions of years of evolution, it is expected that all the features of their collaboration have been optimized. Thus, it is reasonable to copy the way social insects interact. The resulting multi-agent systems are called swarm intelligence (Iourinskiy).

The main characteristics of a swarm can be summarized as follows:

- distributed, no central control or data source
- perception of environment, i.e. sensing
- ability to change environment

Most well-known algorithms to implement Swarm Intelligence are Ant Colony Optimization and Particle Swarm Optimization.

- 1) Ant Colony Optimization (ACO): The ant colony optimization is based on the collective behaviour of the ant colony. Considering the collective work of an ant colony and not an individual ant suggests how problems of survival can be solved (M.S. Kanitkar, 2015).
- 2) Particle Swarm Optimization (PSO): Particle Swarm Optimization is mostly associated with the bird flocking analogy. Imagine a flock of birds circling over an area where they can smell a source of food. The bird that is closest to the food source chirps louder and all other birds fly around his direction, as soon as another bird comes even more closer to the target, it will chirp louder than the first bird and hence will result in all the other birds flying in his direction. This pattern continues until one of the birds reaches the target (food). Using this analogy PSO is explained, over a number of iterations, a group of variables (birds) have their values adjusted, such that with each adjustment a more efficient solution (target food) is obtained (M.S. Kanitkar, 2015).

### 2.3.2 Application of Swarm Intelligence to Traffic Management

Autonomous driving technology can bring new functionalities to the vehicles that will increase road safety and could potentially be of use on new traffic management strategies.

The increasing volume of traffic results in higher congestions problems, so new approaches for traffic management have been proposed from different disciplines. One traditional solution generally adopted is the coordination of traffic flow by means of the synchronization of the traffic lights so that the traffic flow is oriented in the desired directions and speeds. This solution works correctly when constant traffic flows are considered but it fails for traffic patterns that are not the expected, for example, rush hours, accidents and human driving “natural” perception.

Swarm Technology is considered as a potential improvement for traffic flow routing since it can solve the lack of intelligence from previous traffic approaches.

Swarm traffic simulation is based on micro models (i.e., Intelligent Driver Model, IDM) in which the interactions between agents determine the swarm intelligence. Stigmergy (Heylighen, 2016) is a method of communication in emergent systems in which the individual parts of the system communicate with one another by modifying their local environment. As an example, ants communicate to one another by laying down pheromones along their trails. Cars, like ants, leave pheromones to other cars as perception signals (braking lights, speed changes, etc ...). Cars read signals dropped by other cars and adjust the speed and direction accordingly.

Pheromones dropped by cars have some numerical properties that can be expressed according to defined rules:

- Pheromones fade over time
- Faster cars leave longer tails of pheromones
- Stronger pheromones are dropped when:
  - Car changes lanes
  - Car brakes
  - Car stops

Figure 5 illustrates some pheromones in traffic flow simulation of driving, changing lanes and stopping conditions, respectively (from top to bottom):

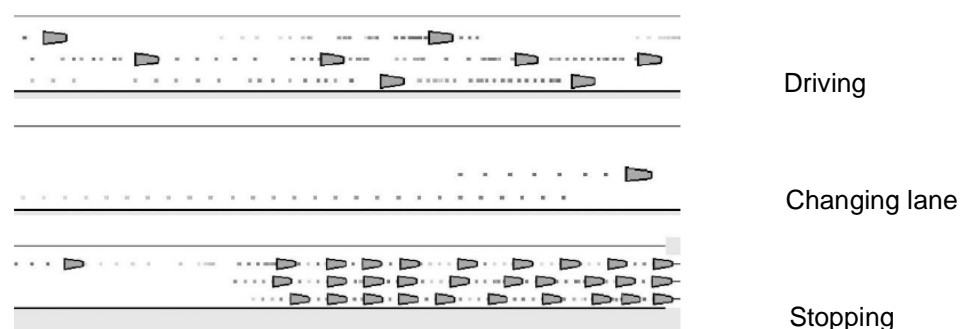


Figure 5. Example of pheromones in traffic flow (Popiv, 2006)

A basic algorithm to simulate pheromones can be described as follows:

1. “Sniffs” pheromone in front if it has not arrived at destination point yet
2. Decelerate, if tailing distance to the next car is less than what the strength of the pheromone suggests
3. Accelerate, if there is no pheromone or the tailing distance is greater than suggested by pheromone strength
4. Stop, if needed
5. Make a decision about upcoming turn (change lanes?)
6. Drop single pheromone, or a trail of pheromones
7. Update car position

Besides the interaction among agents, there are external factors that also influence how traffic behaves, such as the shape of the road, traffic signals and driving rules. The relationship between vehicle agents and environment defines where vehicles can go, the speed limit and how to act under an intersection, for example.

In the literature, there are some recent research project which are applying swarm intelligence to the traffic management such as:

- The Collective Cognitive Robots (CoCoRo) project, funded by the EU, that is researching how autonomous units can find their way around like ants. Phosphorescent dye on the ground serves as a substitute for the scent trails ants used in nature (Commission, n.d.).
- The German Research Centre for Artificial Intelligence (DFKI) is currently researching how to avoid the exclusive use of deep-learning for AI vehicles. Accidents tend to be rare events, thankfully, so machine learning utilizing mass data is of little benefit (German Research Center for Artificial Intelligence, n.d.).

### **2.3.3 Swarm Definition**

The following parameters may be considered when defining a swarm:

- **Size**

The number of individuals that belongs to a swarm. It must be big in order to increase its efficiency as better forecast of local driving conditions can be achieved when a large number of inputs are used. However, it depends on the task that the swam has been defined for.

- **Flexibility**

The swarm shall be able to work in a mixed traffic conditions, i.e. there may be some individuals that “swim” along the swarm with no cooperation with its members or with different swarm targets. The swarm members shall adapt its behaviour to “accept” these new individuals as, for example, increasing the safe gap distance.

- **Target**

The purpose of a swarm determines its definition. Traffic jam assistance swarm would need to have more flexibility and probably fewer members than a highway pilot swarm since traffic conditions and efficiency targets are different.

- **Heterogeneity**

In most of the works on swarm organization it has been assumed that all the vehicles within the swarm have the same parameters. In real practice, this could not be the case and therefore, strategies must be implemented to deal with different vehicle dynamics and with different parameters setting, allowing vehicles heterogeneity.

- **Spacing Policy**

An important factor which has a strong influence on a swarm configuration is the spacing policy (Deng, 2016), which refers to the desired gap a platoon follower needs to maintain from its predecessor in steady state. Figure 6 shows an example of three trucks in a platooning configuration and the spacing policy in comparison to the scenario where trucks are not driven in platooning.

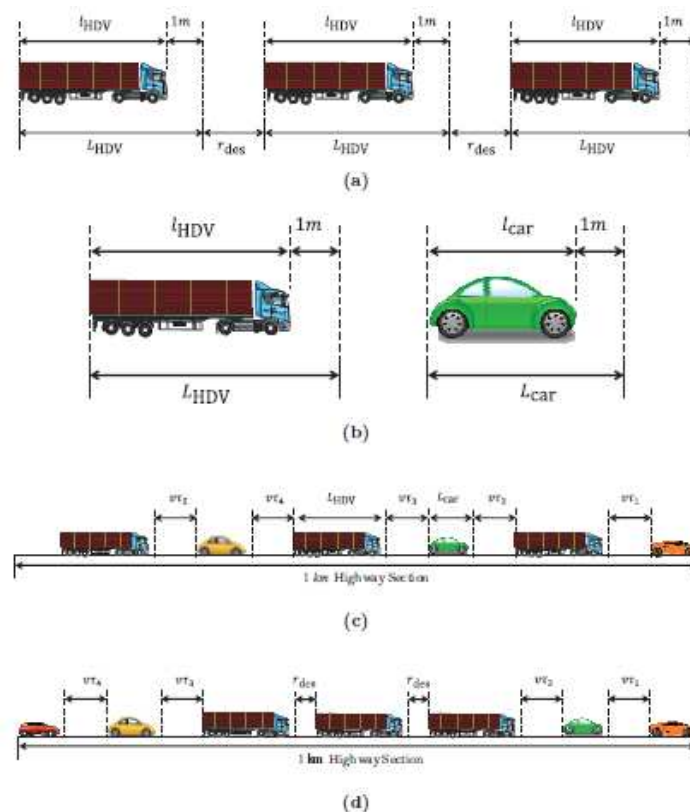


Figure 6. (a) Three-HDV platoon and CVS spacing policy; (b) Extended vehicle length; (c) reference scenario - no HDV platooning; (d) study scenario - all HDVs operating in one platoon with uniform spacing policy (Deng, 2016)

The common approach is to assume constant distance or constant time headway between vehicles for reference. Constant distance policy leads to an increase of traffic throughput, as distance error between vehicles is independent of vehicles velocity. Constant time headway policy, however, is assumed to improve string stability and safety.

Large spacing policy meets safety requirement of vehicles at the cost of decreasing lane capacity; conversely, small desired spacing policy can increase traffic flow rate and reduce air-drag, but it requires strong acceleration and braking capability to maintain safety and control stability (Deng, 2016).

In the case of swarms like platoon of vehicles, the spacing policy of a platoon may be a constant value, or typically a function of vehicle speed of platoon follower, or even a function of other variables (Deng, 2016). A variety of spacing policies have been proposed and studied. Ideally, small spacing policies improve highway capacities from a traffic flow point of view. The goal for most platooning policies is thus to achieve smallest spacing as possible that the final application can achieve in terms of acceleration and braking to meet the safety requirements (rear-end collisions).

At present, there are two common used space policies:

- Constant Vehicle Space (CVS) policy: the desired inter-vehicle distance is constant. This fact has many advantages: on the one hand, it guarantees global asymptotic stability and string stability on the other hand, it is easy to implement in practice. Moreover, different CVS policies can be applied for various traffic facilities, for instance, large CVS policy would be required when a platoon approaches on-/off-ramp to enhance safety of other vehicles. After passing the ramp area, the inter-vehicle distances of the platoon will be reduced to enhance air-drag reduction and fuel saving.
- Constant Vehicle Gap (CVG) policy: the desired inter-vehicle distance adapts to current vehicle speed with constant time gap. CTG policy is also capable of maintaining a stable vehicle string in a platoon. In order to achieve global asymptotic stability, platoon leader must operate at constant speed; otherwise the desired inter-vehicle distance needs to be updated continuously in real-time and spacing error between two consecutive vehicles will not converge.

#### **2.3.4 Advantages and Disadvantages of swarms on autonomous vehicles**

The application of swarm intelligence on autonomous vehicles has been studied from several points of view. Its impact on today traffic management and its potential application in the near future have been also analysed. Recent investigation by Prakash (Prakash, 2014) summarises some of the benefits of implementing some kind of swarm intelligence in autonomous vehicles:

1. If autonomous cars move in swarms, constant average speed would be maintained, thereby ensuring constant traffic.
2. Higher safety; in case of failure of an individual sensor, the probability of collision both within the swarm and outside with pedestrians or obstacles is reduced.
3. Higher efficiency as workload of collision detection and navigation is divided among larger number of autonomous cars.
4. Higher efficiency as independent navigation and creation of 3D data models is required individually only when a car is not part of a swarm.

- Better response to traffic situations as cooperation between cars would result in faster clearing of roads with traffic.

Figure 7 summarises these conclusions in the case of truck platooning as a way of swarm intelligence applied to autonomous cars (Williams D., 2015):

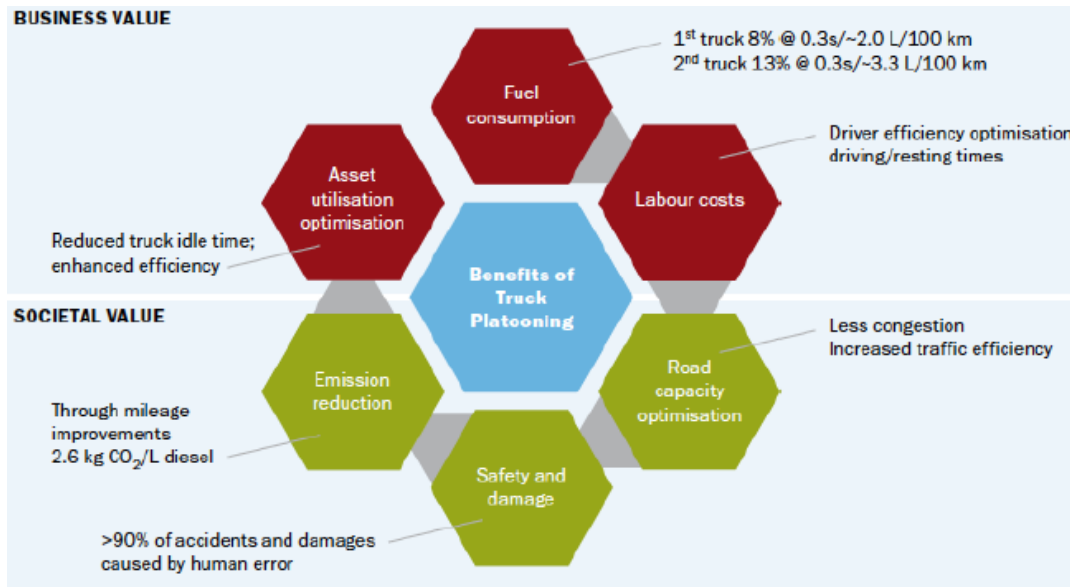


Figure 7. TNO summary of high-level truck platooning benefits

The Dutch research group TNO published an extensive study on two-truck platooning in early 2015. To maximize benefits, they introduce the concept of a Platooning Service Provider (PSP) to support *ad hoc* formation of platoons (Williams D., 2015). The platooning will allow a more optimal use of the available road capacity. In a typical scenario, they calculate that two trucks platooning at a 0.3 second gap (9 m at 60 mph) would decrease the length of those two trucks by 46%, from 82 to 44 m. Thus, the amount of road space taken by the two trucks is essentially halved.

Additional conclusions from the investigations confirm that there are some disadvantages when a swarm approach is adopted and should also be considered (Williams D., 2015):

- An upper limit of the number of robots in a swarm could be a disadvantage as merging on or off the swarm could be a factor.
- If any of the robots in the swarm causes a deadlock, it may pose a threat
- The security mechanism in a swarm is inefficient
- Multiple swarms meeting each other may create problems
- The inter-vehicle gap setting must consider several factors to set a safe gap. Key factors are:
  - Engine horsepower
  - Estimated mass of each vehicle
  - Estimated braking ability of each vehicle (measured in real time conditions (road, weather, vehicle status).
  - Ability to cool the engine with adequate flow

- Driver acceptance
- Traffic conditions
- Road configuration

If above conditions do not meet the safety requirements of the swarm, the swarm is considered not advisable.

## **2.4 Swarm Intelligence Application in Commercial Vehicles**

All ants, fish and amoeba have something in common with humans, they can work perfectly in tandem to solve a common problem. Considering the same approach applied to the autonomous vehicles within the so-called swarm intelligence, some of nowadays traffic problems such as congestion, road hogs and even traffic lights, could be drastically solved.

As an example, Singapore's drivers are spending 126 hours a year on average waiting in traffic, and this costs the economy more than S\$1 billion in wasted time, according to Professor Euston Quah, Head of Economics at Nanyang Technological University (Koh, 2016).

One of the major causes for this is that human drivers are just unable to put aside their own interests to make traffic smoother as they do not collaborate among them sharing the information they have. By adopting swarm intelligence, the information available at any individual member is shared with the rest of members of the swarm so a more objective solution is taken for the defined goals. If additionally, this information is exchanged with a centrally controlled network, predictions for traffic routing can be made, thus increasing the traffic flow efficiency. The technology, therefore, will help to reduce the number of accidents linked to human error. By delegating vehicle control, drivers take advantage of their time to do something else while remaining in a position to take back control.

There are several aids based on swarm intelligence that have been already implemented in commercial vehicle and are available. Some of the most common ones are the following.

### **2.4.1 Driver Assistive Truck Platooning**

The term "vehicle platooning," in its broadest sense, uses radar and vehicle-vehicle communications to form and maintain a close-headway formation between at least two in-lane vehicles, controlling the vehicles both longitudinally and laterally at highway speeds, implying at least Level 2 automation (Figure 2).

The use of this systems is intended for highway use. They provide only longitudinal control based on an Adaptive Cruise Control (ACC) strategy so that the driver is responsible for the steering action. Braking and other relevant information is sent from the front truck to the rear truck to enable close following.

There is a low speed application of the driver truck platooning in which the system only provides longitudinal control while braking remains the driver responsibility. This function will be developed to reduce driver's boring within a slow-moving queue similar to traffic jam assist function deployed for cars. It is called Driver assistive movement in queue.

### 2.4.2 Highly Automated Platooning

The term “highly automated vehicle platooning” uses radar and vehicle to vehicle communication (V2V) to form and maintain a close headway formation between at least two in-lane vehicles, controlling the vehicles both longitudinally and laterally at highway speeds, implying at least Level 2 automation (Figure 2). The use of Cooperative Adaptive Cruise Control (CACC) strategies allow that the vehicles can follow each other with a closer distance, thereby, improving traffic flow capacity.

Truck platooning is one of the first examples of swarms applied to a convoy of typically two to three semi-autonomous trucks, wirelessly-connected and all closely following one another. Acceleration, braking and steering across all trucks in the platoon is controlled by the lead vehicle. Each lorry is manned by a driver whose role is to manage the system and retake control in case of emergency or to drive the freight to its delivery destination, once the truck has split from the platoon. At present the practical emphasis is hold on semi-autonomous trucks for platooning including a driver although the media is discussing future driverless, autonomous trucks.

Figure 8 shows how a platoon of vehicles could be modelled according to (Deng, 2016). According to this figure, the platoon may have three main properties: platoon ID, platoon speed and a list of platoon members. The platoon ID and the platoon speed are the ID of the platoon leader. The list of platoon members includes information and vehicle status of each vehicle operating in the platoon. In addition to basic platoon acceleration and deceleration, inter-vehicle distance adjustment is defined for different traffic scenarios and road facilities. For example, large inter-vehicle distances would be required when a platoon approaches ramp area to enhance safety for other vehicles. After passing the ramp area, the inter-vehicle distances in platoon can be reduced to enhance air-drag reduction and fuel saving.

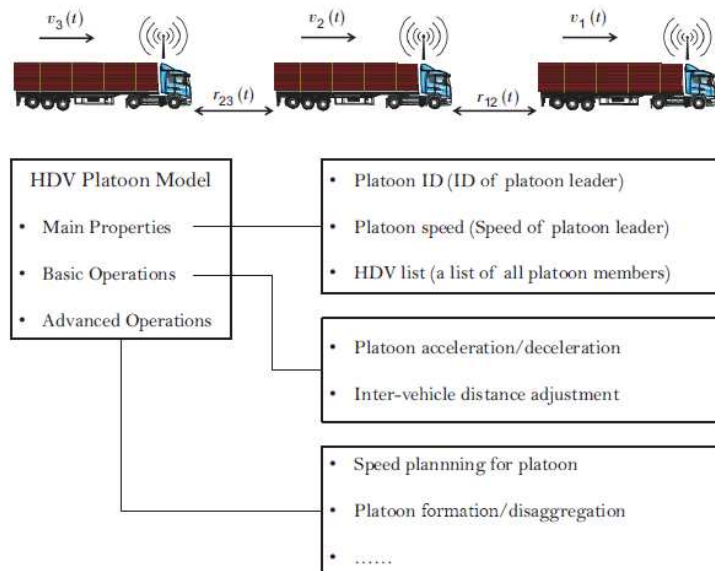


Figure 8. Model of a platoon of vehicles with its properties and operations

Advanced operations are speed planning, platoon aggregation and disaggregation, etc. All platoon operations are initiated and controlled by the platoon leader.

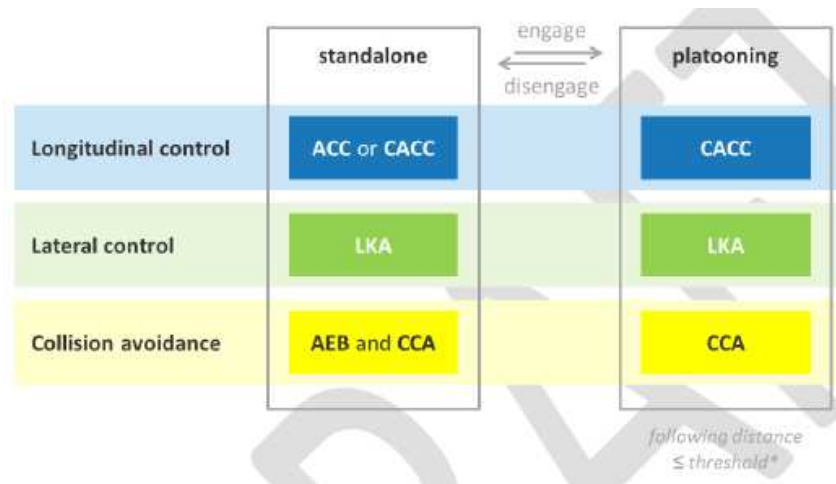


Figure 9. Scope of platooning (Trucks, 2018)

In Figure 9, the concept of platooning versus standalone vehicle is presented. When the vehicle is driven in a standalone mode, the longitudinal control may be commanded by ACC or CACC systems while when a vehicle is engaged in a platoon only the CACC systems can be used.

From the driver perspective, there will be only one longitudinal control functionality for both the standalone and the platooning modes. To achieve this, the longitudinal platooning functionality will be integrated with the today existing longitudinal control functionality ACC.

The platooning concept defines different roles and positions within the platoon as shown in Table 2:

Role	Position	Description
<b>Candidate</b>	<i>n/a</i>	<i>Any vehicle equipped with a compatible platooning function, driving in front of the ego vehicle and sharing the same route.</i>
<b>Leading vehicle</b>	<i>1 of n</i>	<i>The first vehicle in the platoon.</i>
<b>Following vehicle</b>	<i>(&gt;1) of n</i>	<i>Any vehicle in the platoon that is not the leading vehicle.</i>
<b>Trailing vehicle</b>	<i>n of n</i>	<i>The last vehicle in the platoon.</i>

Table 2: Platoon roles and positions (Trucks, 2018)

Figure 10 shows the above roles and position:



Figure 10. Platooning roles and positions (Trucks, 2018)

On an existing platoon of vehicles, one vehicle could decide to engage the platoon or disengage from it. Conditions for these actions shall be programmed so that the behaviour of the vehicle and the platoon are accommodated to the new situation.

One of these special situations is a vehicle cut-in an existing platoon as illustrated in Figure 11:

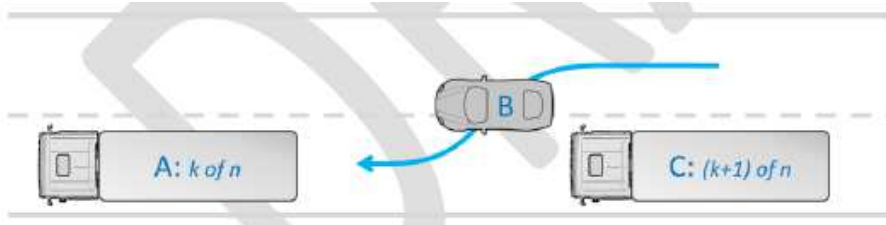


Figure 11. *Platooning cut-in scenario (Trucks, 2018)*

The benefits of platooning include, as mentioned in (Prakash, 2014) and (Williams D., 2015):

- a) Significant fuel savings and a consequent reduction in CO<sub>2</sub> emissions

An important benefit derived from the improvement of the inter-vehicle distance is the reduction in fuel consumption (Naus, 2010) due to the corresponding reduction of drag forces as show in Figure 12:

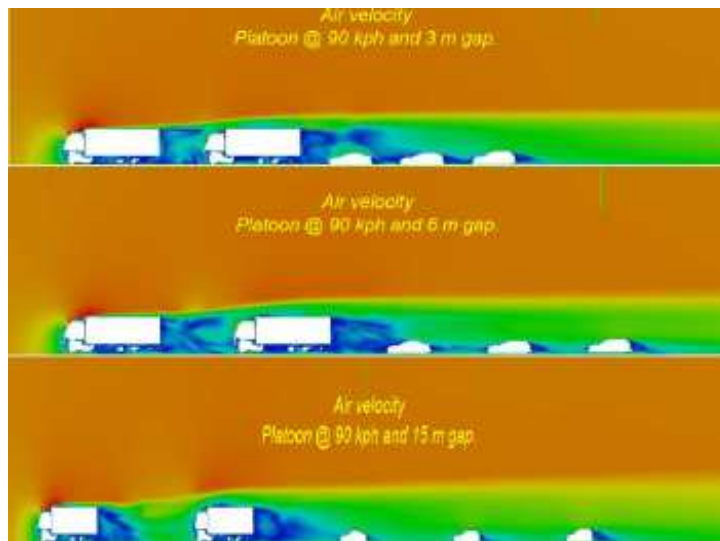


Figure 12. *Aerodynamic air force reduction for different inter-vehicle distances (Happee, 2016)*

In 2014, DOE's National Renewable Energy Laboratory (NREL) conducted tests of platooning systems implemented by Peloton Technology. The SAE J1321 Type II Fuel Consumption Test Procedure was managed by NREL, using vehicles loaded at 65,000 lbs running at up to 70 mph. 20-75-foot inter-vehicle gaps were evaluated. The testing documented up to 5.3% fuel savings for the lead truck and up to 9.7% fuel savings for the trailing truck.

- b) Road safety. Braking reaction along the platoon is immediate
- c) Improved traffic flow. Platooning boosts traffic flow and reduces tailbacks
- d) The creation of new jobs and opportunities for further improvement in the logistics supply chain.

There are also potential disadvantages that must be considered as well such as:

- a) System could be hacked by remote computers creating a hazardous situation.
- b) Drivers would feel less in control of their own driving, being at the hands of computer software or the leading driver.
- c) Drivers may be less attentive than usual, and they may not be able to react as quickly to adverse situations if the software or hardware were to fail.

During the last years, there have been several international initiatives driven by the car/truck manufactures and governments:

- Daimler (Williams D., 2015): In 2015, a licence was given by the State of Nevada, USA, to test its Freightliner Inspiration semi-autonomous trucks for platooning in the state (Figure 13)  
In 2016, Daimler unveiled the Highway Pilot Connect, a truck platooning system that was approved for use in a limited area in Germany. It claimed that its platooning system offers up to 7% lower fuel consumption and correspondingly lower CO2 emissions, plus only half of the previously required traffic space.



Figure 13. *Freightliner inspiration semi-autonomous truck*

- In 2016, the Dutch EU Presidency developed the European Truck Platooning Challenge which aimed to address platooning issues at a European member state level (European Truck Platooning, 2016). Among the highlights, there was a Challenge in which truck platoons from all the major European truck manufacturers drove successfully to Rotterdam from various cities across Europe. This was step 1 of 4 in the European platooning project road map described in Figure 14:

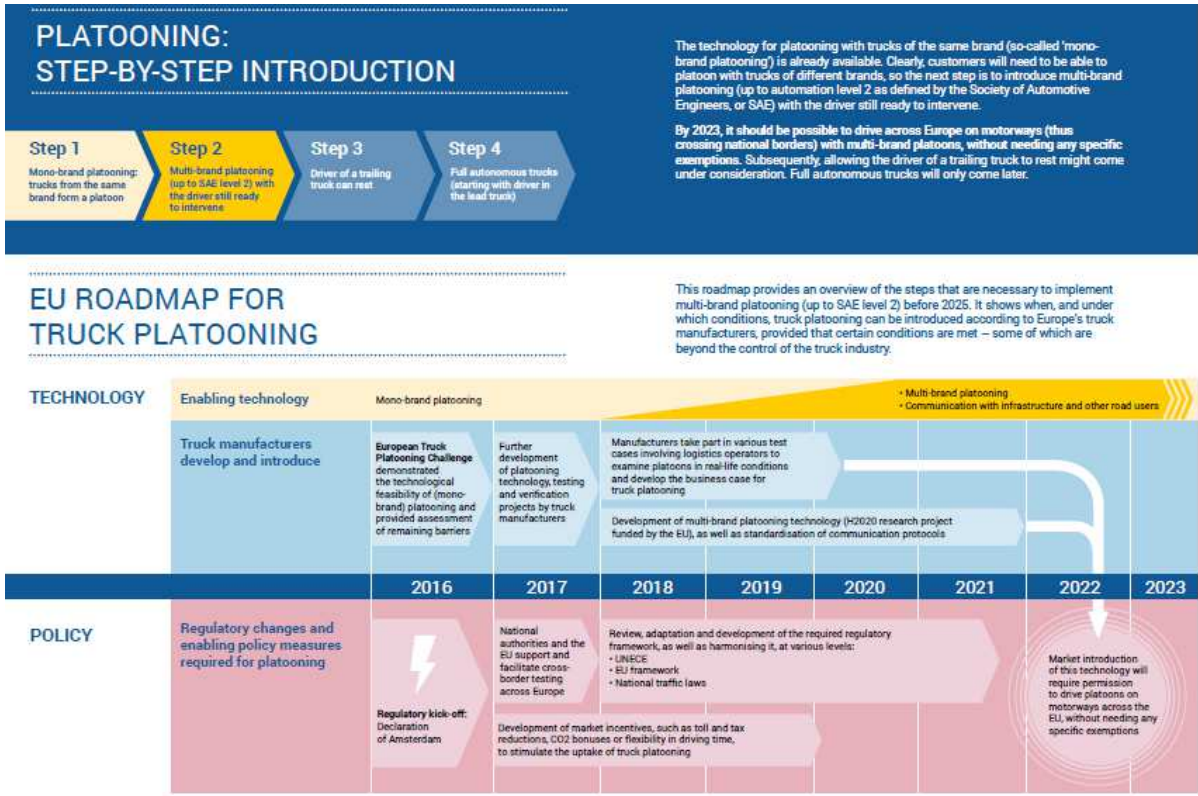


Figure 14. European truck platooning road map (Manufacturer, 2017)

This roadmap provides an overview of the steps that are necessary to implement multi-brand platooning (up to SAE level 2 of Figure 2) before 2025. It shows when, and under which conditions, truck platooning can be introduced according to Europe's truck manufacturers, provided that certain conditions are met –some of which are beyond the control of the truck industry.



Figure 15. Scania truck platooning challenge

Figure 15 shows the Scania truck platooning concept introduced in the European Truck Platooning Challenge project.

Some other projects that will be accomplished in the next years are:

- Nine states in the USA have already regulations that allow platooning and many more are expected to follow. Earlier in the year, Scania and Toyota announced that they will be trialling platooning on the public highways of Singapore (SCANIA, 2017).
- In August 2017, the UK government announced that it will test a three semi-autonomous truck platoon on public roads in 2018 (Government, 2017).

Whether or not the world is ready for platoons of semi-autonomous or autonomous trucks, there will always be demand for transporters to carry large volumes of products in their trailers. Having flexible trailer capacity with trailers that are equipped with the latest technology are the keys to playing a successful part in the intelligent transport industry.

### 2.4.3 Automation of Vehicles

Another example of swarm intelligence application to commercial vehicles in urban scenarios is the management of the traffic light phases that could be set flexibly according to the traffic volume (Garcia-Nieto, 2012). This *Traffic Jam Assist* system could make the traffic flow again in places where there was congestion. This could be introduced not only for individual vehicles, but also for whole swarms, which would bring about a further increase in efficiency.

As shown in Figure 16, using a mobile connection to the central traffic management computer, the vehicle is informed about how long the next phase of the lights will last and at what speed it needs to travel in order to pass through those traffic lights in green. If all vehicles had access to the traffic-light data, there would be less hustling and fewer overtaking manoeuvres.

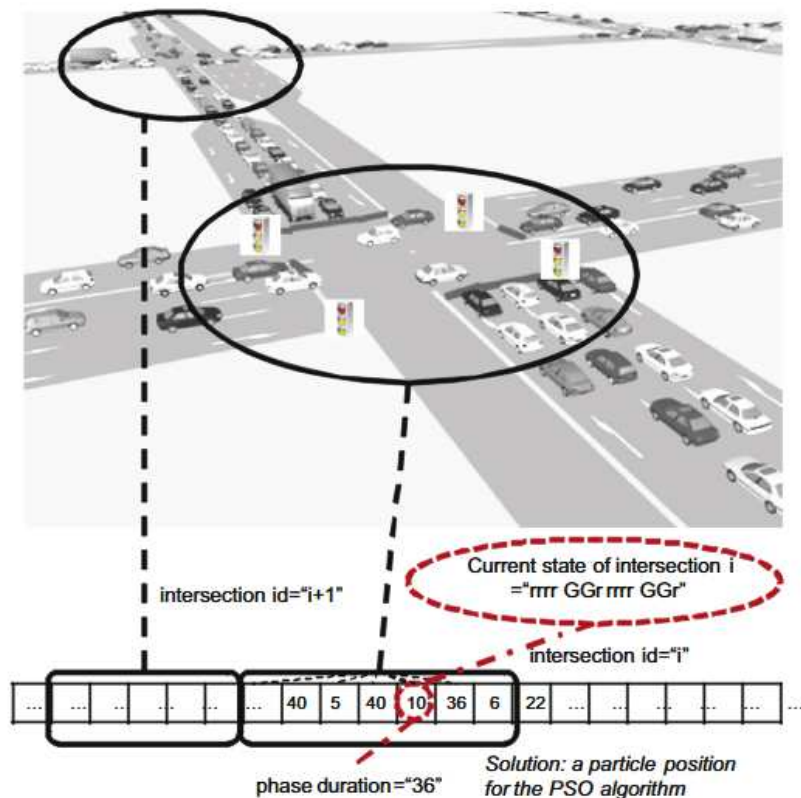


Figure 16. *Traffic Jam Assist Example*

In the urban scenario, the complex and varied situations of the street driving make the automation difficult to achieve and is postponed for later in the timeline. Some of the future proposals are the following.

- **Automation on Valet Parking**

The concept behind this idea is that the driver steps out of the car at a parking entrance and sends some commands to the vehicle via a smartphone to park it in the desired location. The vehicle would return to the entrance when called by the driver.

- **Automated Taxi Services**

The automation of the taxi services is a natural convergence of autonomous driving technology and car sharing programs. The taxi owner company would bring a car where it is needed to pick up a passenger, and when the passenger has got off, it would drive away on its own to pick up someone else. Several companies like Uber and Cabify are developing their own systems that would provide this service in the near future.

There are some functionalities that are already available for vehicles in high ways such as:

- **Co-Pilot:** it is a combination of Adaptive Cruise Control (ACC) with lane centring operating at high speeds on well-structure highways. These systems became available in 2013. The road curvature that the steering system can handle is normally limited. These systems are not intended as “hands-off” systems.
- **Traffic Jam Assist:** a system which provides automated highway driving in traffic jams. It is disabled above a speed threshold in the range of 45 Km/h. The driver is expected to keep their hands on the wheel; if the system detects the driver hands are off the wheel for a set period of time, it automatically disables the system. These systems became available in 2013.
- **Highway Pilot:** the capability of Co-Pilot for highway use across the full speed range.

## **2.5 Vehicle Control Systems**

To foster the application of swarm intelligence to autonomous vehicles, the industry of vehicles needs to develop intelligent automatic control systems to adjust vehicles speed based on the preceding vehicles velocity, modifying the dynamics of the traffic response. A control action in the longitudinal controllers is performed by the actuation of either the throttle or the brake (Ra, 2014). These control systems should be part of the Advance Driver Assistance Systems (ADAS) that more and more often are nowadays included in the vehicles.

Vehicles connected in a swarm configuration would eventually need such systems to maintain the group structure and prevent traffic issues that may appear.

Several systems have been developed to perform the longitudinal control so far such as CC and ACC and, most recently, CACC which are here briefly explained.

### 2.5.1 Cruise Control (CC)

The first commercial systems that actively control vehicle speeds independently of driver actions were the Conventional Cruise Control (CCC) systems, based on regulating the throttle action (Jarrah, 1997). Its goal is to maintain the speed pre-set by the driver by adjusting the throttle and the brake pedals positions.

The system does not require any ranging sensors; hence it does not react to the dangerous approaching to the preceding vehicle. In such a risky situation, the driver is obliged to disengage the system by taking manual control over the brake pedal.

### 2.5.2 Adaptive Cruise Control (ACC)

The next step in the development of longitudinal control systems was the Adaptive Cruise Control (ACC) (Serafin, 1996). Like CCC systems, a set speed can be chosen using the driver HMI interface. But when a preceding vehicle is detected by a radar sensor, the vehicle speed is adapted to the preceding one based on a pre-selected time gap. The most important advantage of this technology is that the driver's tasks are considerably reduced under regular traffic circumstances as the control of the distance to the preceding vehicle, via both brake and throttle action, is done automatically (Weinberger, 2001).

Adaptive Cruise Control systems can be divided into two major groups: (i) standard ACC and (ii) FSRA, also called Stop&Go system.

- The standard ACC is not able to operate at a very low speed, namely, below speed  $V_{low} \leq 5$  m/s the control is handed over to the driver.
- Full-Speed-Range ACC is able to operate in the entire speed range up to 0 m/s

### 2.5.3 Cooperative Adaptive Cruise Control (CACC)

The next generation of longitudinal control systems is focused on adding vehicle-to-vehicle (V2V) communications to take advantage of more extensive preceding vehicle information, from multiple preceding vehicles, and with reduced delays (Milanés, 2014). Using this additional information, control system performance can be tightened significantly, enabling significant reductions in inter-vehicle distance and improvements in string stability and noises (Shladover, Cooperative Adaptive Cruise Control: Driver Selection of Car-following Gaps, 2010). Such an improvement allows to decrease a headway distance between two consecutive vehicles to a few meters (Piao, 2008), which allows to improve traffic throughput and safety of the roads network. Figure 17 shows the CACC principles for two trucks in platoon configuration:

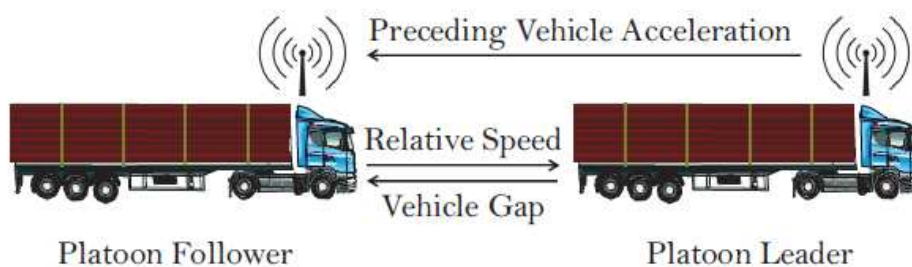


Figure 17. Example of two vehicles in platoon using CACC system

The relative speed and the vehicle gap distance can be measured by an on-board radar and sensors while the acceleration and deceleration are obtained by the vehicle to vehicle wireless communication.

A simple model for CACC and ACC vehicles is presented in (Shladover, Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow, 2012) where results show that the increase in the number of ACC vehicles is unlikely to produce any significant change in the highway capacity. The experiment also confirms that ACC systems are merely comfort systems which do not increase highway capacity. However, with CACC systems, the experiments do show an increasing highway capacity when market penetration is over 50% as show in Figure 18:

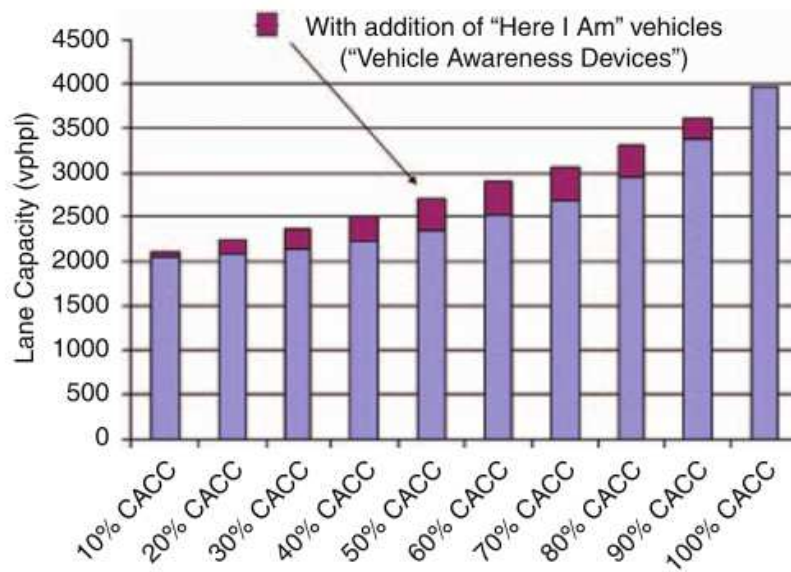


Figure 18. Highway increase capacity with CACC market penetration

According to this Figure 18, the trend in highway lane capacity increases quadratically with the increase of market penetration of CACC systems. The increase of the lane capacity in the first half of the bar plot is not significant, since a vehicle with CACC which follows a manually-driven vehicle must revert to conventional ACC system. The rapid growth of the lane capacity starts at 60 % of market penetration with vehicles equipped with CACC technology. In a situation of about 100 % the market penetration, the improvement will rise from around 2100 vehicles per hour per lane (vphpl) for ACC system to 3970 vphpl.

The string stability is proved in (Milanés, 2014) where 10 consecutive CACC equipped vehicles were simulated in a platoon configuration. The result shows that all the vehicles follow the leading vehicle speed changes without amplifying its oscillations downstream as shown in Figure 19. In this figure, up to ten vehicles are considered. In the top of the figure, the speed of all vehicles is represented in the y-axis. As it is possible to see, all vehicles maintain its desired speed without significant changes. At the same time, as shown in the figure of the middle, the distance between vehicles is maintained constant during the experiment which results in almost a constant time gap as represented at the bottom of the figure.

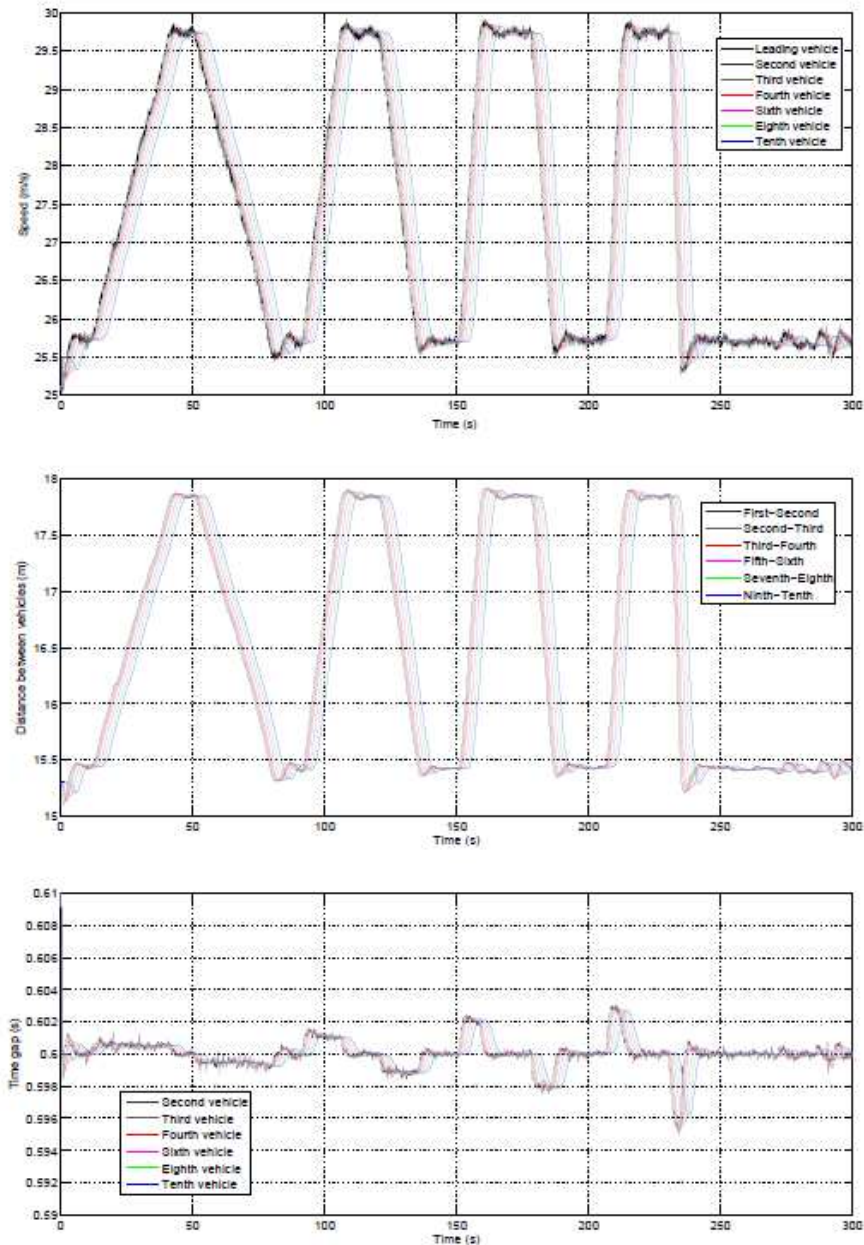


Figure 19. Simulation of 10 CACC equipped vehicles (Milanés, 2014)

This behaviour is, however, not achieved when platoon concept is applied to ACC equipped vehicles. In this case, the delay introduced by each vehicle provokes the vehicle to get out of phase with each other, and therefore, generates system instabilities. The more vehicles in the platoon, the worse result is obtained.

Several initiatives have proved the benefits of vehicle platooning technology in the last years such as SARTRE (Europe), PATH (California), Energy ITS (Japan), and the Grand Cooperative Driving Challenge held in Helmond, The Netherlands in 2011 (Nunen, 2012), where nine vehicles from different European research institutions drove in a two-lane platoon using different control techniques.

The automotive industry has been pushing forward the Advance Driving Assist Systems (ADAS) since the 90's. New technologies such as Adaptive Cruise Control (ACC), Lane

Keeping Assist (LKA), Collision Mitigation Braking, Speed Sign Recognition, Blind Spot Warning and Parking Assist have been or are being implemented. This technology could potentially support the use of swarm intelligence in traffic management.



From the different models shown, the Intelligent Driver Model (IDM) is a very well-known microscopic model that can be used to examine traffic flow behaviour at an individual level with emphasis on the relation to the following vehicle. This model holds several convenient properties, like easy tuning parameters, which could at some level mimic individual decisions. That is why this is the one selected to be implemented in our work.

### 3.2 Optimal Velocity Model (OVM)

The Optimal Velocity Model (OVM) was proposed by Bando (Bando, 1995), being one of the simplest and more realistic traffic models so far. This model considers the dynamics of the traffic congestion.

The model can be expressed with the following formula:

$$\dot{x}_n(t) = k\{V(\Delta x_n(t)) - \dot{x}_n(t)\} \quad (1)$$

$$\Delta x_n(t) = x_{n-1}(t) - x_n(t) \quad (2)$$

$$V(\Delta x_n) = V_1 + V_2 \cdot \tanh[C_1(\Delta x_n - l_c) - C_2] \quad (3)$$

Where  $n$  is the number of the vehicle and:

$k$  = driver's sensitivity, which is assumed to be independent of  $n$

$x_n(t)$  = position of the  $n$ -th vehicle at time  $t$

$\dot{x}_n(t)$  = velocity of the  $n$ -th vehicle at time  $t$

$\Delta x_n(t)$  = space headway, that is, between consecutive vehicles

$l_c$  = length of the vehicle

$V(\Delta x_n)$  = optimal velocity function of the  $n$ -th vehicle

Figure 21 represents the OVM model with its variables:

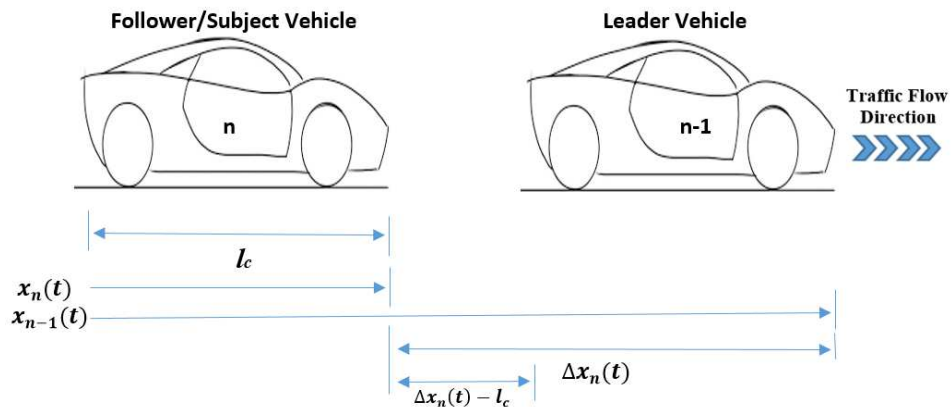


Figure 21. Representation of the Optimal Velocity Model (OVM)

The optimal velocity function depends on the gap distance of the preceding car ( $n-1$ ). When the headway between the subject and the preceding vehicle becomes smaller than a threshold the velocity must be reduced to prevent crashing into the previous car (Ra, 2014).

### 3.3 Gipp's Model

Gipps' model is a safety distance car-following model developed by Peter G. Gipps in 1981. It is based directly on the driver behaviour and the expectancy for vehicles in a stream of traffic. Limitations on driver and vehicle parameters for safety purposes mimic the traits of vehicles following vehicles in the front of the traffic stream. Gipps' model differs from other models in that Gipp's uses a time step so that to reduce the computation time required for the numerical analysis (Wikipedia, Gipps' model - Wikipedia, 2018).

According to (Kesting, 2013), accidents are prevented in the Gipp's model by introducing a "safe speed", which depends on the distance and on the speed of the leading vehicle. It is based on the following assumptions:

1. Vehicle will not exceed the driver's desired speed.
2. The acceleration of a vehicle should first increase with speed, and then decrease to zero as the desired speed is approached.
3. If the downstream vehicle starts braking, the observed vehicle should be able to make a complete stop without collision.

The first two constraints are disabled when the vehicle drives freely and is able to choose its own speed, whereas the third constraint limits the speed when the driver needs to adopt the behaviour of the downstream vehicle into account. This applies to congested traffic flow and also to uncongested flow when the distance to the downstream vehicle is lower than a certain limit. The model can be formulated as:

$$u_n^a(t + \tau) = u_n(t) + 2.5a_n\tau \left(1 - \frac{u_n(t)}{u_n}\right) \sqrt{0.025 + \frac{u_n(t)}{u_n}} \quad (5)$$

$$u_n^b(t + \tau) = b_n\tau + \sqrt{b_n^2\tau^2 - b_n \left[2[x_{n-1}(t) - s_{n-1} - x_n(t)] - u_n(t)\tau - \frac{u_{n-1}(t)^2}{\hat{b}}\right]} \quad (6)$$

$$u_n(t + \tau) = \min\{u_n^a(t + \tau), u_n^b(t + \tau)\} \quad (7)$$

Where:

$a_n$ : is the maximum acceleration which the driver of vehicle  $n$  is willing to undertake.

$b_n$ : is the most severe deceleration that the driver of vehicle  $n$  wishes to undertake.

$\hat{b}$ : is the most severe deceleration of vehicle  $n-1$  as estimated by the driver of vehicle  $n$ .

$s_{n-1}$ : is the effective size of vehicle  $n-1$ . This includes the physical length of vehicle  $n-1$  and a safety margin, into which the driver of vehicle  $n$  is not willing to intrude even at rest.

$u_n$ : is the desired speed of vehicle  $n$ .

$x_n(t)$ : is the location of the front of vehicle  $n$  at time  $t$ .

$u_n(t)$ : is the speed of vehicle  $n$  at time  $t$ .

$\tau$ : is the reaction time, which is constant for all vehicles and equal to the simulation step

### 3.4 Intelligent Traffic Model (IDM)

The Intelligent Driver Model (IDM) is a deterministic car-following (time-continuous and autonomous) model of the OV family with descriptive parameters to make it accident-free (Kesting, 2013). The fundamental idea behind this system is to combine the ability to reach the desired speed limit in a free traffic situation with the ability to identify how much braking is necessary to steer clear of any collision. Figure 22 shows the graphical representation of the IDM model:

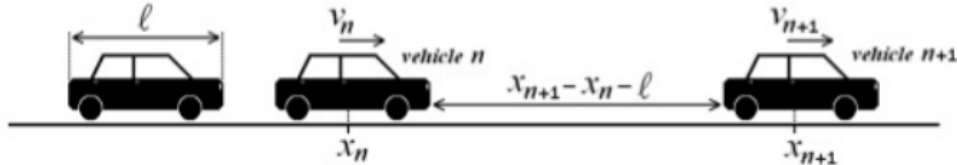


Figure 22. Graphical representation of the IDM model

The IDM acceleration  $\dot{v}$  of each vehicle  $\alpha$  is a continuous function of the velocity  $v_n$ , the distance gap  $s_n$ , and of the velocity difference  $\Delta v_n$  to the leading vehicle. The following formula describes the acceleration in the case of homogeneous vehicles:

$$\dot{v}_n(s_n, v_n, \Delta v_n) = a_\alpha \left[ 1 - \left( \frac{v_n}{v_{0,n}} \right)^\delta - \left( \frac{S^*(v_n, \Delta v_n)}{s_n} \right)^2 \right] \quad (8)$$

Where the desired gap  $s^*$  is formulated as follows:

$$S^*(v_n, \Delta v_n) = s_{0,n} + s_{1,n} \sqrt{\frac{v_n}{v_{0,n}}} + T_n v_n + \frac{v_n \Delta v_n}{2\sqrt{a_n b_n}} \quad (9)$$

The IDM parameters can be described as follows:

$s_{0,n}$ : is the minimum bumper-to-bumper distance to the front vehicle

$s_{1,n} \sqrt{\frac{v_n}{v_{0,n}}}$ : is the comfortable distance

$T_n v_n$ : is the desired safety time headway when following other vehicles

$\frac{v_n \Delta v_n}{2\sqrt{a_n b_n}}$ : is the anticipation

$v_{0,n}$ : is the desired speed when driving on a free road

$a$ : is the acceleration in everyday traffic

$b$ : is the comfortable braking deceleration in everyday traffic

$\delta$ : is the acceleration exponent

In (9), the first term is aiming to maintain the desired distance  $s_{0,n}$ , in meters. This term has the most influence when standing still. The second term is dependent on the speed of the vehicle in a way that it adds some comfort to the driving. By adding some extra distance to the desired distance, the driver has more time to react to changes in the speed of the following vehicle, and therefore, the driver can react more cautiously and thus more comfortably. The jam distance parameter,  $s_{1,n}$ , together with the ratio of the actual speed and the desired speed determines how much extra distance is added.

As opposed to the comfortable distance term, the safe time headway is the absolute minimal distance necessary to come to a standstill if the predecessor vehicle suddenly breaks. This distance becomes larger for higher speeds by multiplying the speed with  $T$ , which is referred to as the safe time headway parameter.

The simulator tool was initially tested using equation (8) but this produced an unrealistic behaviour. According to the IDM new model, it was needed to update the limit of the last term in the equation to prevent it from taking negative values. Equation (8) was then re-designed as follows:

$$S^*(v_n, \Delta v_n) = s_{0,n} + \max\left(0, s_{1,n} \sqrt{\frac{v_n}{v_{0,n}}} + T_n v_n + \frac{v_n \Delta v_n}{2\sqrt{a_n b_n}}\right) \quad (10)$$

In the IDM model a driver only looks to the first vehicle ahead. If this predecessor is coming closer to the current driver, he will respond by releasing the gas pedal or braking. In the IDM model this is modelled by setting a higher desired distance. The approach rate will be positive in this case, since it is calculated as the speed of vehicle  $\alpha$  minus the speed of the leading vehicle:

$$\Delta v_n = v_{n+1} - v_n \quad (11)$$

The anticipation term also contains the deceleration parameter,  $b$ , which is used to control the vehicle's deceleration. Note however, that the deceleration is theoretically not limited as opposed to the acceleration. For each vehicle, the acceleration is integrated over time to get the velocity and the velocity is again integrated over time to get the current position  $x$ .

$$\dot{x}_n = v_n \quad (12)$$

The actual distance to the predecessor is calculated by taking the position of the leading vehicle  $x_{n+1}$  and subtracting the position of vehicle  $x_n$  and subtracting the length of a vehicle  $l$ , which is a parameter of the model (13):

$$s_n = x_{n+1} - x_n - l_n \quad (13)$$

According to the information gathered from different researches (Horst, 2011), (Treiber, 2000), a normal driving behaviour of a vehicle can be simulated with the following parameters values described in Table 3:

Parameters	Variable	Realistic Value
Maximum Acceleration	$a_n \left(\frac{m}{s^2}\right)$	0.73
Desired Speed	$V_0 \left(\frac{m}{s}\right)$	33.3
Linear Jam Distance	$s_n^0 (m)$	2
Non-Linear Yam Distance	$s_n^1 (m)$	3

Safe Time Headway	$\tau_n(s)$	1.3
Comfortable Deceleration	$b_n \left(\frac{m}{s^2}\right)$	1.67
Acceleration Exponent	$\delta_n$	4

Table 3: IDM parameters in the homogeneous implementation

The IDM model parameters can be interpreted by considering the following three standard situations:

- When accelerating on a free road from a standstill, the vehicle starts with the maximum acceleration  $a$ . The acceleration decreases with increasing speed and goes to zero as the speed approaches the desired speed  $v_0$ . The exponent  $\delta$  controls this reduction: the higher its value, the later the reduction of the acceleration when approaching the desired speed. The limit  $\delta \rightarrow \infty$  corresponds to the acceleration profile of Gipps' model while  $\delta = 1$  reproduces the overly smooth acceleration behaviour of the Optimal Velocity Model.
- When following a leading vehicle, the distance gap is approximatively given by the safety distance  $s_0 + v_n T_n$ . The safety distance is determined by the time gap  $\tau_n$  plus the minimum distance gap  $s_0$ .
- When approaching slower or stopped vehicles, the deceleration usually does not exceed the comfortable deceleration  $b_n$ . The acceleration function is smooth during transitions between these situations.

### 3.5.1 Intelligent Traffic Model (IDM) – Heterogeneous Form

The IDM model developed by Treiber (Treiber, 2000) considered homogeneous traffic flow condition in which all the vehicles have similar parameters. Based on Jin, Ran, Pu and Yand studies (Transportation Research Board, 2013), IDM model from Treiber's has been upgraded for heterogeneous traffic flow. The new model considers the impact of different combinations of cars and trucks parameters and implement them into the original IDM model as shown below:

$$\begin{cases} \frac{d^2 x_n(t)}{dt^2} = a \left[ 1 - \left( \frac{v_n(t)}{V} \right)^\delta - \left( \frac{S(v_n(t), \Delta v_n(t))}{\Delta x_n(t) - l} \right)^2 \right] \\ S(v_n(t), \Delta v_n(t)) = s^0 + s^1 \sqrt{\frac{v_n(t)}{V}} + \tau v_n(t) - \frac{v_n(t) \cdot \Delta v_n(t)}{2\sqrt{ab}} \end{cases} \quad (14)$$

$$\begin{cases} \frac{d^2 x_n(t)}{dt^2} = a_n \left[ 1 - \left( \frac{v_n(t)}{V_n} \right)^{\delta_n} - \left( \frac{S_n(v_n(t), \Delta v_n(t))}{\Delta x_n(t) - l_n} \right)^2 \right] \\ S_n(v_n(t), \Delta v_n(t)) = s_n^0 + s_n^1 \sqrt{\frac{v_n(t)}{V_n}} + \tau_n v_n(t) - \frac{v_n(t) \cdot \Delta v_n(t)}{2\sqrt{a_n b_n}} \end{cases} \quad (15)$$

Where all the parameters  $a_n, \delta_n, V_n, s_n^0, s_n^1, \tau_n$  and  $b_n$  have four alternatives considering the possible combinations of cars (subindex C) and trucks (subindex T). The leader vehicle length  $l_n$  has two possible values,  $l_c$  and  $l_t$ . From some calibration studies of this model, the following reference values (Table 4) has been used in this work:

Parameters	Variable	Car to Car	Car to Truck	Truck to Car	Truck to Truck
Maximum Acceleration	$a_n \left( \frac{m}{s^2} \right)$	1.01	1.03	0.78	0.74
Desired Speed	$V_n \left( \frac{m}{s} \right)$	27	19.3	20.6	17.7
Linear Jam Distance	$s_n^0 (m)$	0.85	1.35	1.11	1.53
Non-Linear Jam Distance	$s_n^1 (m)$	0.19	0.27	0.12	0.36
Safe Time Headway	$\tau_n (s)$	1.2	1.4	1.8	2
Comfortable Deceleration	$b_n \left( \frac{m}{s^2} \right)$	2.26	2.12	1.7	1.61
Acceleration Exponent	$\delta_n$	4	4	4	4

Table 4: IDM parameters for the heterogeneous implementation

In the homogeneous traffic flow, all vehicles at the equilibrium state have zero acceleration, the same distance headway and the same velocity; at the equilibrium state, all vehicles in the heterogeneous traffic flow still have zero acceleration and the same velocity, but their distance headways vary for different vehicles.

### 3.6 Lane Changing Model – MOBIL

In the past, single lane car following models have been developed to describe traffic dynamics (Ra, 2014). These models are helpful to understand the dynamics of congested traffic on single lanes. But in real life traffic there are different types of vehicles such as cars and trucks. Therefore, a more realistic description of heterogeneous traffic is only possible with a multi lane model that allows faster vehicles to pass slower vehicles.

The lane change model MOBIL (“Minimizing Overall Braking Induced by Lane Changes”) derives lane-changing rules for a wide class of car-following models as described in (Kesting, A., Treiber, M., Helbing, D., 2006). Both the utility of a given lane and the risk associated with lane changes are determined in terms of longitudinal accelerations calculated with microscopic traffic models as OVM and IDM.

The formulation of the MOBIL algorithm is expressed by general safety and incentive criteria both for symmetric (US lanes) and asymmetric (EU lanes) passing rules. While the safety criterion prevents critical lane changes and collisions, the incentive criterion takes into account not only the own advantage but also the disadvantages of other drivers associated with a lane change via a “politeness factor”. This parameter allows to vary the motivation for lane-changing from purely egoistic to a more cooperative driving behaviour (Kesting, A., Treiber, M., Helbing, D., 2006).

Figure 23 summarises the type of driver that can be found on our roads and the behaviour when the driver considers making a lane change decision. The type of driver will define the politeness factor and the safe deceleration in the MOBIL model.

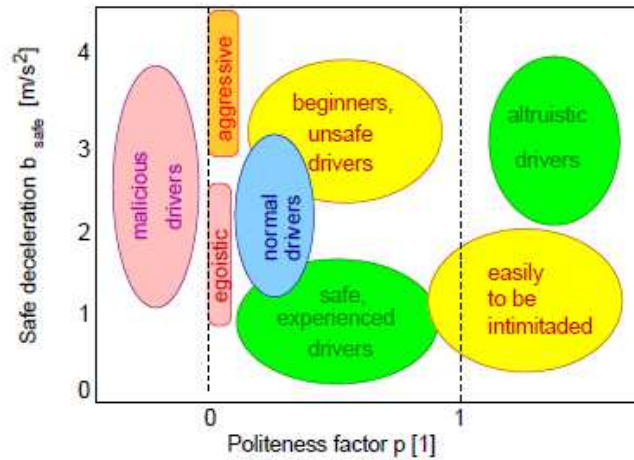


Figure 23. *Politeness factor vs safe deceleration (Kesting, A., Treiber, M., Helbing, D., 2006)*

For a given vehicle “c”, that is considering a lane change, e.g., from the centre lane to the median lane (Figure 24), this overtake depends generally on the two follower vehicles named “o” and “n” that are behind on the present and the target lane, respectively.

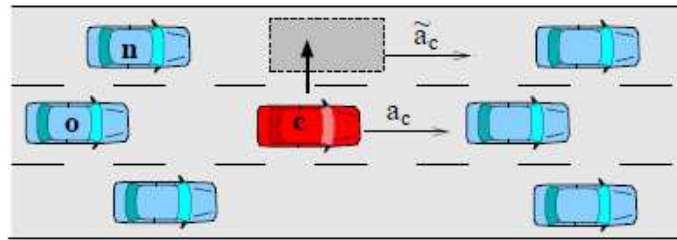


Figure 24. *Example of lane change (Kesting, A., Treiber, M., Helbing, D., 2006)*

The acceleration  $a_c$  represents the acceleration of vehicle “c” in the current lane, while  $\tilde{a}_c$  refers to the potential acceleration that it should achieve in the target lane. Likewise,  $a_o$  and  $a_n$  denote the acceleration of the previous and new followers after the lane change of vehicle c, respectively, according to Figure 24.

The MOBIL lane change algorithm distinguishes between an *incentive* to change lanes and *safety* constraints to determine whether a lane change is allowed:

- The **safety criterion** checks the possibility of executing a lane change (gap acceptance) by considering the effect on the new follower vehicle in the target lane. Therefore, the safety criterion guarantees that, after the lane change, the deceleration of the follower car  $a_n$  in the target lane does not exceed a given safe limit  $b_{safe}$ . The following formula describes this criterion:

$$a_n \geq -b_{safe} \quad (16)$$

Based on it, larger gaps between the following vehicle in the target lane and the own position are required to satisfy the safety constraint if the following vehicle is faster

than the own's speed. In contrast, lower values for the gap are allowed if the following vehicle is slower.

- The **incentive criterion** determines if a lane change improves the individual local traffic situation of a driver. In terms of acceleration values from longitudinal traffic models, this criterion evaluates whether a lane change improves the own acceleration considering the affected neighbors. The politeness factor  $p$  determines to which degree these vehicles influence the lane-changing decision.

The incentive criterion is expressed differently depending whether it is applied to a symmetric or asymmetric lane change (Kesting, A., Treiber, M., Helbing, D., 2006). The formulation of these situations is described below:

- Symmetric lane changes: no differences between the lanes, e.g., US lanes

$$\underbrace{\tilde{a}_c - a_c}_{\text{driver}} + p \left( \underbrace{\tilde{a}_n - a_n}_{\text{new follower}} + \underbrace{\tilde{a}_o - a_o}_{\text{old follower}} \right) > \Delta a_{th} \quad (17)$$

- Asymmetric lane changes: differences between the lanes, e.g., EU lanes

$$L \rightarrow R: \tilde{a}_c^{eur} - a_c + p(\tilde{a}_o - a_o) > \Delta a_{th} - \Delta a_{bias} \quad (18)$$

$$R \rightarrow L: \tilde{a}_c - a_c^{eur} + p(\tilde{a}_n - a_n) > \Delta a_{th} + \Delta a_{bias} \quad (19)$$

where  $a_c^{eur}$  is defined as follows:

$$a_c^{eur} = \begin{cases} \min(a_c, \tilde{a}_c) & \text{if } v_c > \tilde{v}_{lead} > v_{crit}, \\ a_c & \text{otherwise,} \end{cases} \quad (20)$$

Where  $\Delta a_{th}$  is the threshold to determine that a lane change is “desired”;  $\Delta a_{bias}$  is included on the formulation to satisfy the “keep right” criterion typically imposed by the EU traffic laws.

In this work, we have adopted and modified this MOBIL model to implement lane changes on the IDM traffic model.



# CHAPTER 4: Swarm Traffic Simulation Tool

## 4.1 Introduction

Today traffic can be simulated by using existing traffic models that mimic real cars behaviour, but these models are very often very simple, and there are many factors that are not taken into account. Thus, in this work we have developed a simulation tool where different traffic scenarios have been implemented, in order to test if swarm intelligence can help to manage the traffic. Besides, this simulation tool allows us to change some parameters and analyse the influence of the tuning on the traffic flow.

As it has been said in Chapter 3, the two main categories of traffic flow models are macroscopic and microscopic. Microscopic models use knowledge about each individual vehicle that enters the stretch of the freeway under consideration. This is the opposite of macroscopic models which more commonly operate with an average flow and density for a stretch of the freeway. Both models have their own advantages and disadvantages, and therefore other models have been developed to overcome certain shortcomings such as mesoscopic models, which do not have exact knowledge about individual vehicles but model the probability that a vehicle has a certain velocity or that a road segment has certain density.

In this project, the Intelligent Driver Model (IDM), a microscopic model, has been used as a basis to introduce swarm intelligence into the traffic simulation. This model is developed keeping in mind that a model should be as simple as possible but without missing important features. Furthermore, the parameters of this model are intuitive and relevant. Another important aspect is that this model provides a good characterization of individual cars based on driving properties such as comfort acceleration/deceleration, desired speed, length, safety bumper to bumper distance, etc ... These parameters are of interests in the definition of a swarm and its interaction with other vehicles or swarms as intrinsically was developed to operate as the ACC systems.

In addition, both homogeneous and heterogeneous traffic flows have been implemented in the proposed swarm traffic simulator.

## 4.2 Traffic Flow Simulation Tool

A new simulation tool has been developed using Matlab software to simulate vehicles interaction for different road configurations and driving conditions. In particular, the platooning concept is applied to trucks and cars. The target, thus, is to use this tool to study whether a swarm configuration can be applied to improve road safety and traffic flow efficiency.

The architecture framework of the simulation tool considers the following requirements:

1. A car-following model must simulate different vehicles in stand-alone and swarm configurations.
2. The car-following model must be parametrizable in such a way that the individual's vehicle parameters can be changed
3. It must allow to implement different types of roads with several number of lanes

4. It must measure the most important and standard traffic metrics.

According to the above premises, Figure 25 shows the simulation implemented:

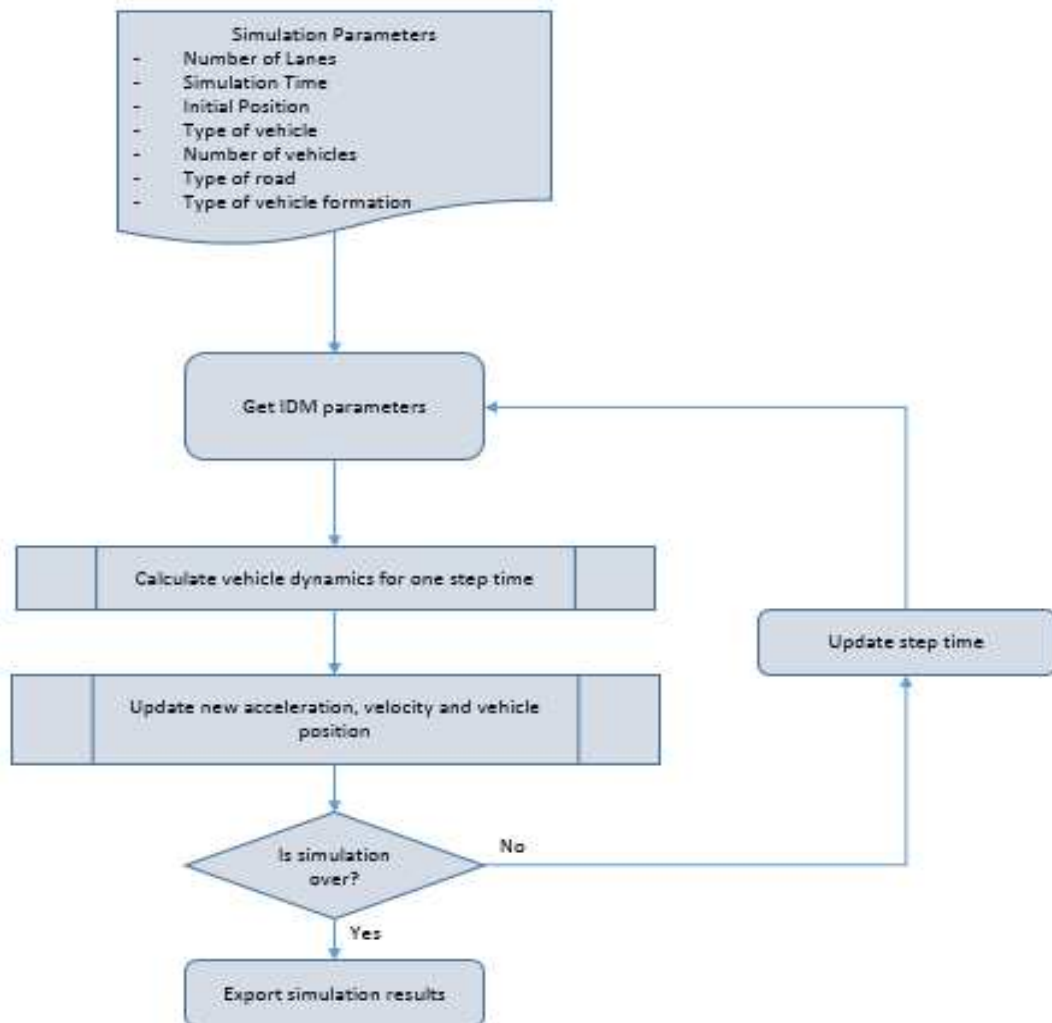


Figure 25. *Simulation workflow*

Before starting the simulation, the user defines the key parameters of the car-following model and the conditions for the simulation. The data set with these values is then loaded to run the developed MATLAB GUI. Results are then processed and presented for analysis.

Figure 26 shows the GUI of the simulation tool developed, called "Traffic Simulator". On the left top, there is a window where the vehicles are placed in a virtual road created from the user inputs. The different type of vehicles is represented by a square with different colours and sizes depending on the length of the vehicles; e.g., car length is 4m, truck length is 12m approximately, and so on. Blue square represents the different type of cars while a red square represents a long vehicle such as trucks or coaches.

On the right, top, the "Simulation Settings" are defined by the user; the initial values are set by default. That is, depending on the type of vehicle, some values are assigned to the acceleration, deceleration, car length, different distances, etc.

Simulation time, number of lanes, road length, etc, are also configured in this menu. Besides, there is a button menu where the user can switch on/off the MOBIL model (to consider lane change) and the Metrics.

In the middle (“Simulation case”), there is a window to configure the simulation in terms of number of vehicles, their position (in which lane they are placed), the distribution (platoon or random), etc ... These simulation tool inputs are requested to the user before starting the simulation, otherwise the start simulation button will not be enabled.

On the bottom part of the simulation tool, the GUI presents the most relevant information from the simulation such as the vehicle position, velocity, acceleration, neighbours, headway, etc ... This window will be only refreshed at the beginning and at the end of the simulation to save computational time. Some of the columns shown in this window can be configured by the user such as the initial position and velocity in case the default values provided by the program does not match with the desired simulation.

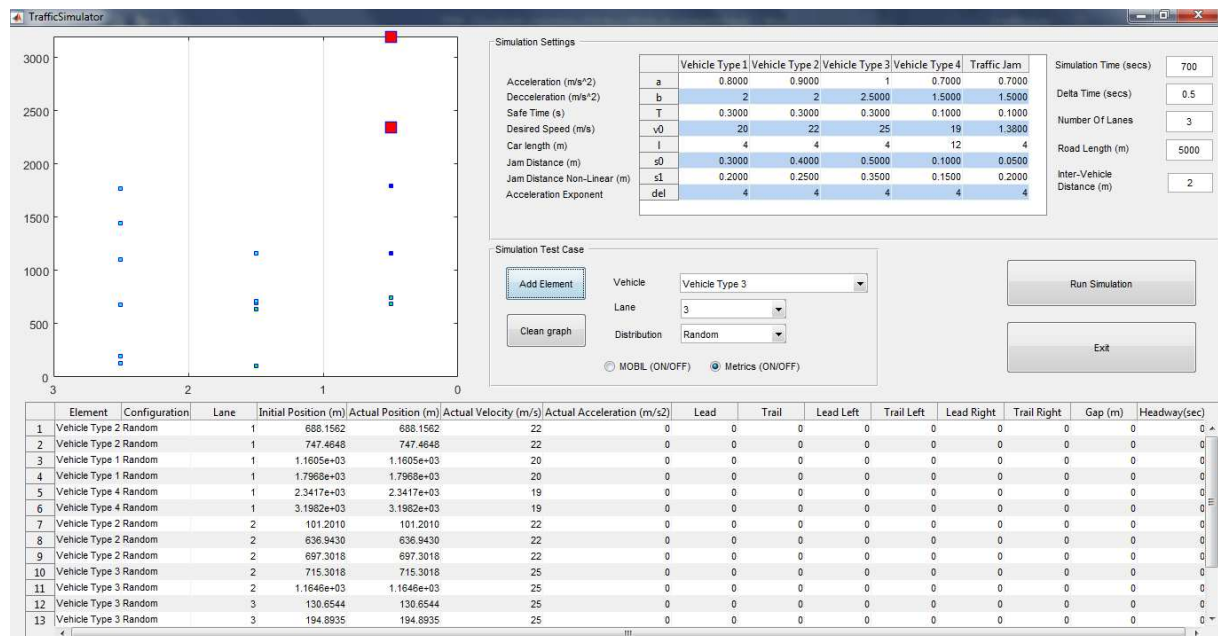


Figure 26. GUI Simulation tool

The simulation kernel relies on the car following model implemented in the code that is executed every time step per individual vehicle. The results of the internal calculations are the vehicle new position, velocity and acceleration according to its relative position regarding its neighbours.

The car following model implemented in the simulation tool is based on the well-known Intelligent Driver Model (IDM) both for homogeneous and heterogeneous traffic conditions (Yang, 2012). The algorithm internally decides whether one or the other must be applied depending on the combination of the leader and the follower vehicles. The IDM model, as explained in previous chapters, does consider the individual vehicle characteristics such as desired speed, vehicle length, maximum acceleration and deceleration, and safety distance as parameters that define the individual behaviour of the vehicle (see Figure 27, settings). These characteristics make it ideal for swarm traffic application investigation as vehicles could potentially be organized by similar parameters. The time-continuous Intelligent Driver Model (IDM) is probably the simplest complete and accident-free model producing realistic acceleration profiles and a plausible behaviour in essentially all single-lane traffic situations.

In addition to the car following model, a lane change model has been implemented in the simulator to consider the possibility of a vehicle overcoming a slower vehicle that is in the same lane due to different vehicle settings. The selected model is the General Lane Changing Model for Car-Following Models (MOBIL) as described by (Kesting, A., Treiber, M., Helbing, D., 2006). In this work, we have proved that this model works correctly in combination with the IDM car-following model. This is one of the main contributions of this Master Final Project.

Additional contributions that are proposed are listed below:

- Adaptation of the IDM model to work in a swarm configuration. It is proposed that when vehicles are considered part of a swarm, they will all have the same model settings, i.e. acceleration, deceleration and safety distance are assumed to be the same in all vehicles. With this proposal, the string stability of the swarm is kept during the simulation time. This is a simple implementation of how a CACC system would perform in reality.
- Vehicle heterogeneity with short vehicle inter-distance typically produces artefacts in the simulation due to different model settings in the vehicles. This problem can be solved by adapting some of the model parameters when vehicles are close enough. In this case, it is proposed to change the desired vehicle speed  $v_0$  follower vehicle according to the current velocity of the preceding vehicle. This solution avoids potential collisions in case of a faster vehicle is approaching a slower vehicle. In reality, this solution will perform similar to a vehicle equipped with ACC device. In this case, faster vehicle will not overtake the preceding vehicle but just approaching it until the defined safety gap distance.

The following parameters can be configured in the Swarm Simulator to address a specific test case (Figure 27).

	Vehicle Type 1	Vehicle Type 2	Vehicle Type 3	Vehicle Type 4	Traffic Jam
Acceleration (m/s <sup>2</sup> )	0.8000	0.9000	1	0.7000	0.7000
Deceleration (m/s <sup>2</sup> )	2	2	2.5000	1.5000	1.5000
Safe Time (s)	0.3000	0.3000	0.3000	0.1000	0.1000
Desired Speed (m/s)	20	22	25	19	1.3800
Car length (m)	4	4	4	12	4
Jam Distance (m)	0.3000	0.4000	0.5000	0.1000	0.0500
Jam Distance Non-Linear (m)	0.2000	0.2500	0.3500	0.1500	0.2000
Acceleration Exponent	4	4	4	4	4

Simulation Time (secs)	700
Delta Time (secs)	0.5
Number Of Lanes	1
Road Length (m)	5000
Inter-Vehicle Distance (m)	10

Figure 27. Simulation Settings Panel

1. **Road Length (m):** the maximum road length considered in the simulation.
2. **Vehicle Type:** different types of vehicle dynamics can be selected from the tool menu for the IDM car-following model depending on the purpose of the study. This way homogeneous and heterogeneous traffic flow can be simulated. The values presented below are based on the studies carried out in (Kesting, 2013) and they cannot be changed by the user as it is not within the scope of this project to tune them.

For the simulation of the vehicle heterogeneity, four types of vehicles are considered:

- **Vehicle Type 1:** Vehicle with max 20 Meters per Second (m/s) desired speed and 4 m length. This configuration simulates a slow car with low acceleration and deceleration requirements which could match an urban transportation vehicle for carrying goods.
- **Vehicle Type 2:** Standard car with maximum 22 m/s desired speed and 4 m length. It represents a standard vehicle with standard acceleration and deceleration profiles. The comfort driving is therefore the main requirement.
- **Vehicle Type 3:** Emergency or sport car with maximum 25 m/s desired speed and 4 m length. This vehicle simulates special vehicles that could be found on a road under some circumstances. Main requirement for these vehicles is the high speed with less importance to the comfort.
- **Vehicle Type 4:** Standard truck with max 19 m/s desired speed and 12 m length. This vehicle simulates a standard truck with low acceleration and braking requirements.
- **Traffic Jam:** Beside of the vehicle type, it has been considered a special case when the vehicles are driven under traffic jam conditions. In this case, all the vehicles within the simulation will have the same IDM parameters independently of its type so that they can be managed as unique swarm of vehicles. For simulation purposes, a desired vehicle speed of 1.38 m/s is considered.
- **Traffic Light:** As an additional feature, a congestion situation or virtual traffic light can be simulated by setting all IDM parameters to 0. This option can be selected at the same time than the vehicles.

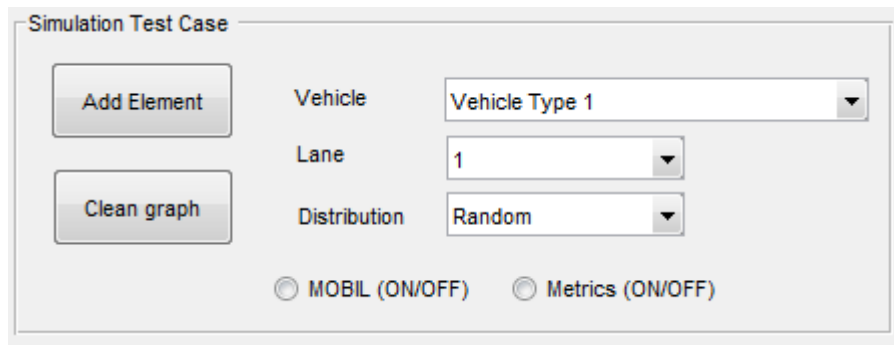
In homogeneous driving, these parameters can be used in the internal calculations as defined; however, when simulating different types of vehicle on the road, different parameters must be considered for the IDM heterogeneous implementation as presented in (Transportation Research Board, 2013). The different combinations of vehicles and trucks result in different IDM model parameters than the ones used in homogeneous conditions. The values implemented by default are based on previous researches and cannot be configured by the user.

Additionally, it has been proposed to include a condition in the IDM model that when the distance between the vehicles is below a certain value, the follower vehicle will adapt its desired speed to the its leader vehicle. In the original IDM model implementation, the deceleration term  $b$ , is intentionally limited typically to 9m/s to simulate a real vehicle behaviour. However, as heterogeneity of vehicles

3. **Number of lanes:** Number of road lanes to be simulated.
4. **Lane in Lane:** Lane on which the defined vehicle has to be placed.
5. **Simulation Time (secs):** Time of simulation.
6. **Delta Time (secs):** Simulation step.

7. **Inter-Vehicle Distance:** the user can select which is the inter-vehicle distance in case a vehicle platoon distribution is selected.

Once the simulation settings are configured, the user is requested to add vehicles in the simulation. A graphic panel shows all the available options so that the user can put the vehicles in different simulation conditions (Figure 28).



The image shows a software interface titled "Simulation Test Case". It contains two buttons on the left: "Add Element" and "Clean graph". To the right of these buttons are three dropdown menus: "Vehicle" (set to "Vehicle Type 1"), "Lane" (set to "1"), and "Distribution" (set to "Random"). At the bottom, there are two radio buttons: "MOBIL (ON/OFF)" and "Metrics (ON/OFF)".

Figure 28. *Simulation Test Case Panel*

The following parameters can be then selected by the user:

1. **Vehicle Type:** The user can select from a list of vehicles already defined in the simulation settings panel.
2. **Lane:** The user selects the lane on which the vehicle will be placed at the beginning of the simulation.
3. **Vehicle Road Distribution:** The user can select if the vehicles are initially placed in random or platoon configuration at the beginning of the simulation. In case of the platoon option, the program will set the vehicles according the defined inter-vehicle distance. The vehicles in a platoon configuration will have the same model settings so that overall swarm performance is maintained during the simulation time. Besides, the user can select in which lane the vehicle will be placed.
4. **Metrics (ON/OFF):** The user can select whether the tool reports main traffic flow metrics such as flow vs density, average speed, average acceleration, distance and headway vs time after the simulation is finished, etc.
5. **Lane changing (ON/OFF):** Activate/Deactivate MOBIL lane changing

These parameters must be set for each vehicle that is added. That is, when adding a new "element", the type of vehicle, in which lane it must be placed and with which inter-vehicle distance pattern will be initially implemented (random or platoon) have to be configured. The vehicles then are graphically represented in a window with the most relevant information. Different vehicle colours and sizes identify the type of vehicles (Figure 29). Note that vehicle position is only updated at the end of the simulation to save computing time.

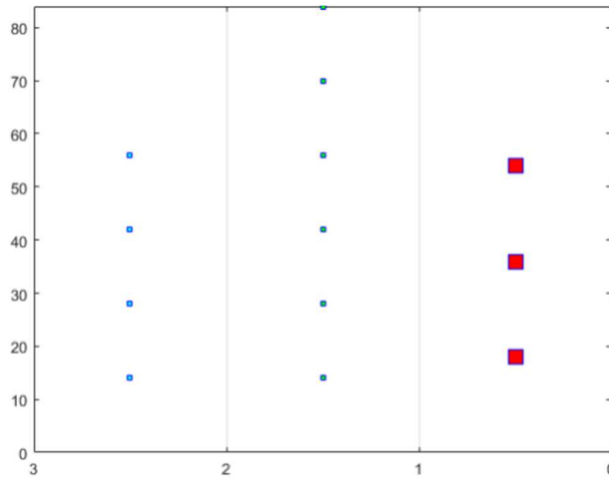


Figure 29. Example of vehicle distribution panel

Once the test vehicles are placed in the selected lanes, the user can start the simulation.

The simulator tool has also the possibility to log and report the simulation data both in a .mat file or in the simulator panel as shown below (Figure 30). Current position, vehicle velocity, acceleration, neighbours and headway time are some of the variables visible to the user at the beginning and at the end of the simulation. Additionally, it is possible to modify predefined settings of initial positions, velocity and acceleration so that the simulation starts with different parameters than the ones defined by default.

	Element	Configuration	Lane	Initial Position (m)	Actual Position (m)	Actual Velocity (m/s)	Actual Acceleration (m/s <sup>2</sup> )	Lead	Trail	Lead Left	Trail Left	Leac
1	Vehicle Type 1 Random		1	206.2300	206.2300	10	0	0	0	0	0	0
2	Vehicle Type 1 Random		1	232.2300	232.2300	10	0	0	0	0	0	0
3	Vehicle Type 1 Random		1	353.1441	353.1441	10	0	0	0	0	0	0
4	Vehicle Type 1 Random		1	529.1406	529.1406	10	0	0	0	0	0	0
5	Vehicle Type 4 Random		1	723.9609	723.9609	9.5000	0	0	0	0	0	0
6	Vehicle Type 4 Random		1	781.0169	781.0169	9.5000	0	0	0	0	0	0
7	Vehicle Type 4 Random		1	985.0712	985.0712	9.5000	0	0	0	0	0	0
8	Vehicle Type 2 Random		2	196.6115	196.6115	11	0	0	0	0	0	0
9	Vehicle Type 2 Random		2	231.9778	231.9778	11	0	0	0	0	0	0
10	Vehicle Type 2 Random		2	313.8651	313.8651	11	0	0	0	0	0	0
11	Vehicle Type 2 Random		2	442.2324	442.2324	11	0	0	0	0	0	0
12	Vehicle Type 3 Random		3	102.0998	102.0998	16.6500	0	0	0	0	0	0
13	Vehicle Type 3 Random		3	230.7732	230.7732	16.6500	0	0	0	0	0	0

Figure 30. Simulation Results Panel

Once the simulations have been run, the results are processed and analysed.

### 4.3 Traffic Simulation Metrics

There are several metrics that can be considered when evaluating traffic flow in roads. The following subsections describe the most commonly used that have been implemented in the developed simulation tool.

#### 5.3.1 Speed

Speed ( $V$ ) is defined as the travel distance per unit time in traffic flow. The accurate speed of each car is difficult to measure. In practice, the average speed of the sample vehicles is calculated. In a time-space diagram, time is measured along the horizontal axis and distance is represented in the vertical axis. The velocity of the traffic stream is computed as the slope of the traffic trajectory ( $v=dx/dt$ ). Figure 31 shows the non-linear traffic stream.

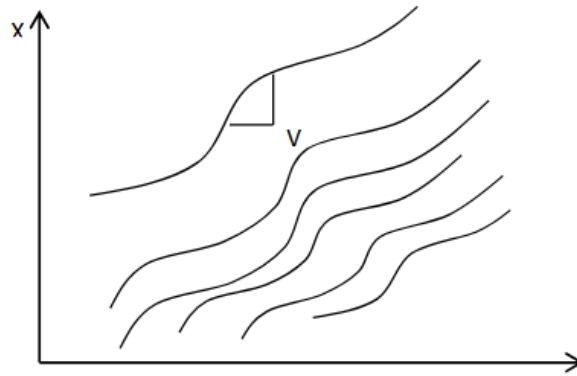


Figure 31. Time Space Chart

As the speed is given by the average speed, the time mean speed is measured by the average speed of a traffic stream passing a fixed point along a roadway over a fixed period of time. Time mean speed can be sampled by loop detectors and other fixed-location speed detection equipment.

The time-mean speed can be calculated as:

$$v_t = \frac{1}{m} \sum_{i=1}^m v_i, \tag{21}$$

Where  $m$  is the number of vehicles passing the fix point, and  $v_i$  is the speed of the passing vehicles.

### 5.3.2 Average Density

Density ( $k$ ) is defined as the number of vehicles per unit length of the roadway. The density in a stretch of the roadway of length ( $L$ ) during the simulation is used for the calculation of the average density. Besides, the inverse of the density is spacing ( $s$ ), that is, the center-to-center distance between two vehicles.

Figure 32 shows the relation between velocity and density:

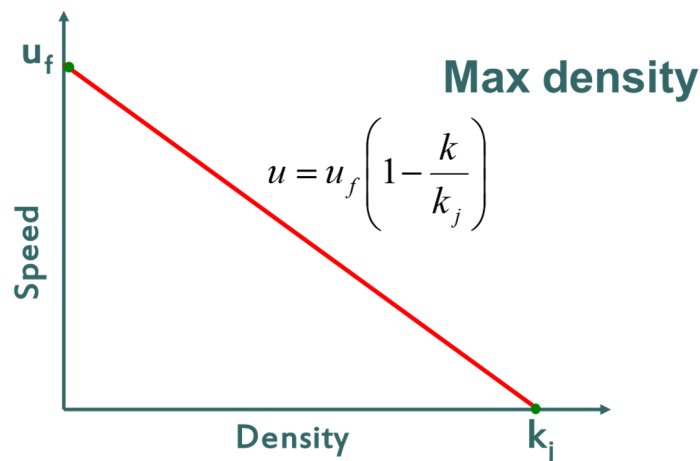


Figure 32. Traffic density vs average speed relation (Engineering)

From Figure 32, it can be concluded that:

- When vehicle speed is close to the maximum desired speed  $u_f$ , the traffic density is minimum
- When traffic density is maximum  $k_j$ , the vehicle speed is reduced to a minimum

### 5.3.3 Flow

Flow ( $q$ ) is the number of vehicles passing a reference point per unit of time, i.e., vehicles per hour. The inverse of the flow is the headway ( $h$ ), which is the time that elapses between the  $i$ -th vehicle passing a reference point in space and the  $(i+1)$ -th vehicle. In congestion,  $h$  remains constant. When there is a traffic jam,  $h$  approaches to infinity. Figure 33 defines the traffic flow rate based on different parameters.

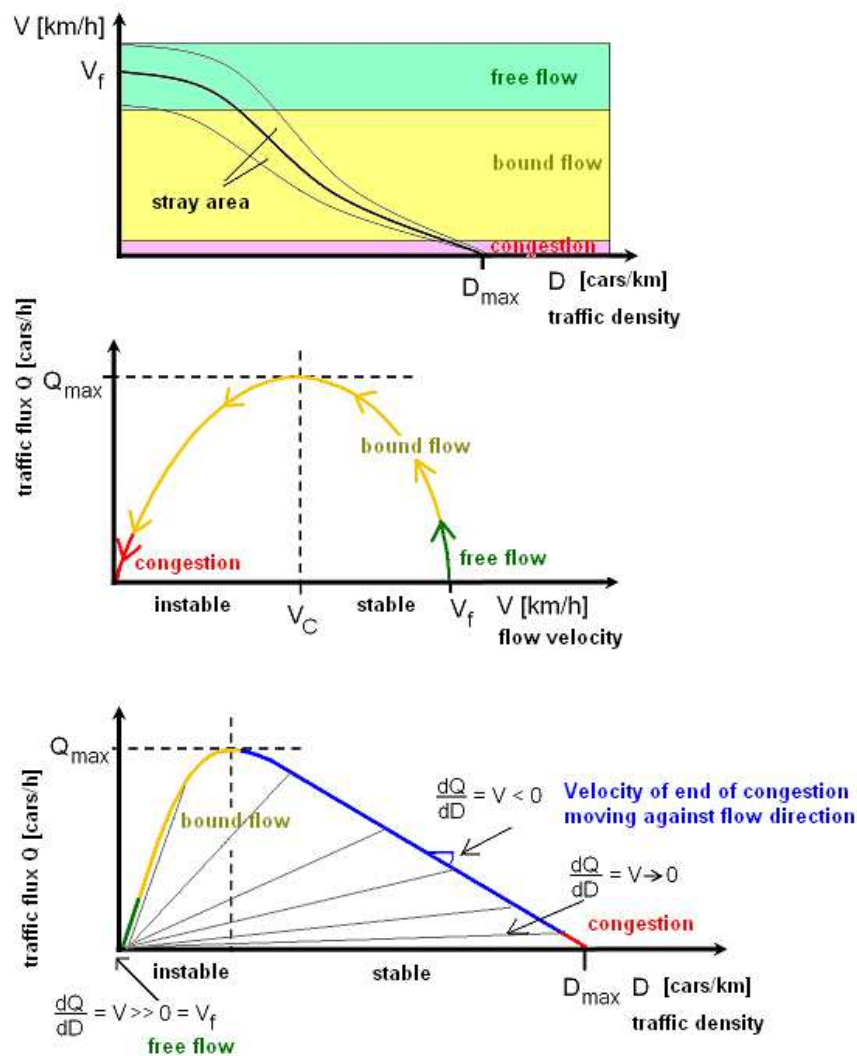


Figure 33. *Fundamental diagrams of traffic flow (Sigua, 2008)*

As shown in Figure 33, the upper graph that traffic density increases when average speed decreases. Different areas of flow are calculated based on the velocity of the vehicles from free up to congestion flow. In the middle graph, the traffic flow can also be represented

as a parabolic function of the speed. This graph defines the optimal lane speed which maximizes the traffic flow. In the lower graph, the traffic flow is represented as a function of the traffic density. This function is initially starting parabolic but as soon as traffic density increases, it changes into a linear type ending in zero which represents a traffic congestion situation.

### 5.3.4 Mimicking Detectors

Mimicking detectors are mostly based on the functioning of loop detectors currently installed on the roads. This device detects how many vehicles driver over a loop and this information is used for the calculation of the flow and other traffic measures such as average speed and density around the loop detector position (Horst, 2011).

The following formulation is used for the calculation of the flow:

$$\bar{q}_d = \frac{N_{cross,d-1}}{\sum_{c=1}^{N_{cross,d-1}} \hat{h}_c} \quad (22)$$

where

- $N_{cross}$  is the number of vehicles that crossed the detector
- $\hat{h}_c$  is the time between two adjacent vehicles crossing the detector

The above formula (22) calculates the flow if vehicles cross the detector every predefined time step in seconds. This is show in Figure 34 (Horst, 2011) for two different detectors, d1 and d2, placed at distances 180 m and 750 m, respectively.

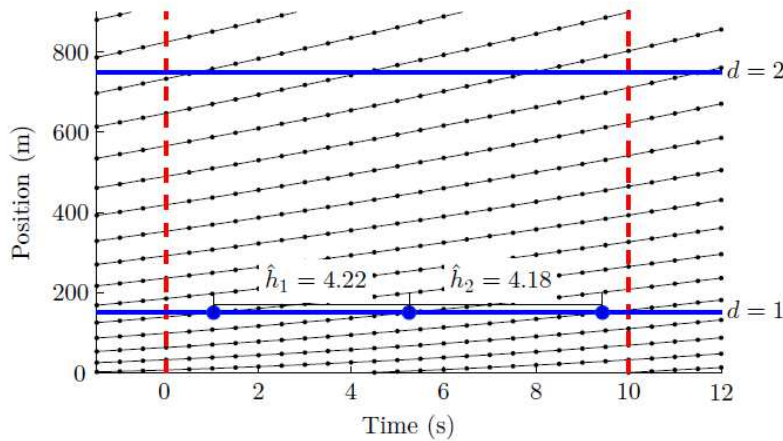


Figure 34. *Mimicking detectors working principle (Horst, 2011)*

A detector starts counting vehicles for a period of 10 sec (dash red lines) whenever they are activated.

The speed of each vehicle can be also measured by the loop detectors using the formula (23) (Horst, 2011), with the help of two loops that are placed with a known distance between them. When simulating the IDM model, the speed of all vehicles is already known and can easily be averaged over the macroscopic time step:

$$\bar{v}_d = \frac{1}{N_{cross,d-1}} \sum_{c=1}^{N_{cross,d-1}} v_c \quad (23)$$

where  $v_c$  is the speed of each individual vehicle that crosses the location of the detector.



# CHAPTER 5: Simulations and Results

The simulation tool developed in this work has been used to run several simulations under different sets of conditions to evaluate the impact of platoons on the traffic flow in terms of space mean speed and average traffic flow rate, among other traffic flow metrics. The following traffic scenarios have been considered in this evaluation:

1. Freeway traffic with heterogeneous and non-heterogeneous vehicles
2. Freeway traffic with homogeneous vehicles in swarm configuration
3. Freeway traffic with heterogeneous vehicles in swarm configuration

The aim of studying the above scenarios is to derive some conclusions whether the platoon formation improves traffic flow and improve the road safety.

Finally, in addition to the high road capacity study (freeway), the traffic jam assistant functionality has been also implemented and simulated to test the results.

Once the simulation is finished, a post-processing algorithm is executed to compare the results and to determine when a swarm approximation may benefit overall traffic flow and which parameters are required for the swarm definition.

## 5.1 Highway Capacity Study

A simulation is performed considering different scenarios of vehicles running on single and multiple lanes in a freeway type of road. The goal is to understand vehicles behaviour on today roads and extract information about traffic flow patterns. Main relevant traffic flow metrics are measured.

All the simulations that are compared have been performed considering the same conditions and parameters such as simulation time, number of vehicles, time step and type of road. The simulation time is around 700 secs as it provides enough system stability.

Heterogeneous and non-heterogeneous vehicles have been taken into account to study the traffic flow.

### 5.1.1 Single Lane with Homogeneous Vehicles

First, we have started with the simplest case in order to better understand the information given by the metrics and the behaviour of the vehicles. A scenario on which the same type of vehicles is located in a freeway single lane is simulated. The organization of vehicles within the road is considered random so that no cooperation among the vehicles is imposed. The following table lists the simulations parameters (Table 5).

<b>Number of vehicles</b>	20
<b>Type of vehicles</b>	Car type1
<b>Simulation Time</b>	700 sec
<b>Time step</b>	0.5sec
<b>Type of lane</b>	Freeway

<b>Number of lanes</b>	1
<b>Initial position</b>	Random
<b>Initial speed</b>	v0

Table 5: Simulation parameters for a single lane with homogeneous vehicles

The simulated vehicles are placed in the virtual freeway road randomly (Figure 35):

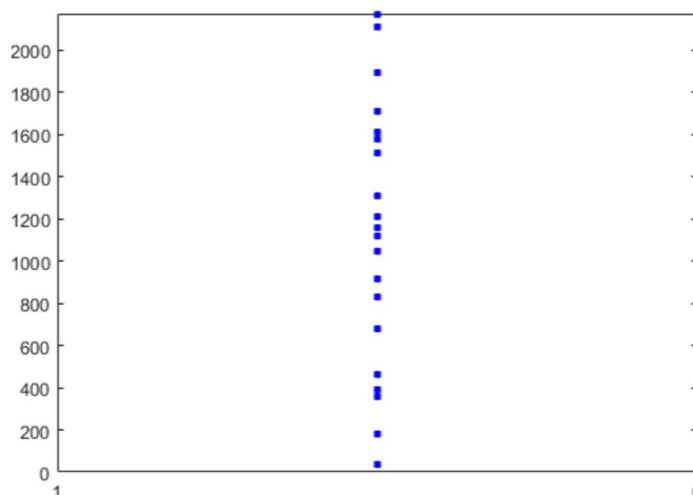


Figure 35. Homogeneous vehicles in a freeway road – random initial position

When the simulation finishes, the following results are obtained:

1. Vehicle speeds are almost constant and close to the desired speed all over the simulation time. Small acceleration of some vehicles happens at the beginning of the simulation until system reaches stability.

Figure 36, left, shows the vehicle distance. As it is possible to see, as the vehicles speed is constant (Figure 36, right), the travel distance is the same for all of them, as expected.

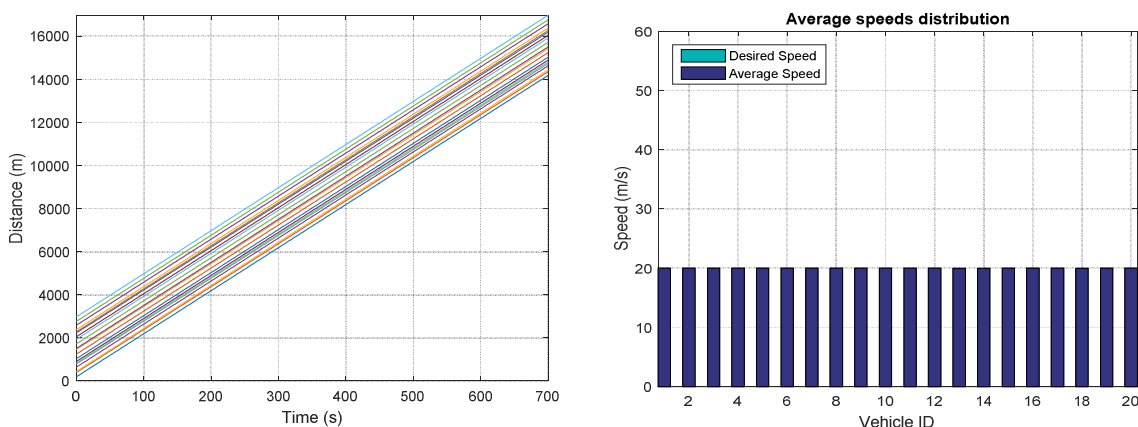


Figure 36. Vehicle distance (left); average speed distribution (right)

2. Road density is kept constant during the simulation as average vehicle speed remains constant as well (Figure 37, left). As density is constant, traffic flow also remains constant (Figure 37, right).

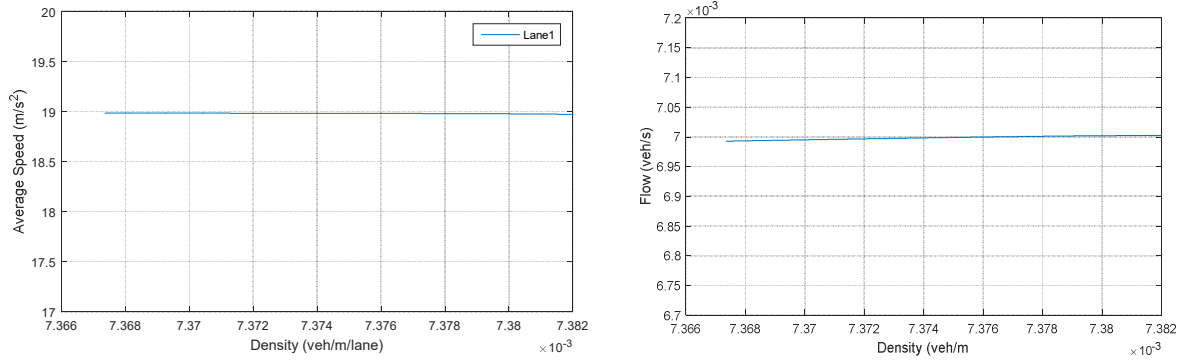


Figure 37. Average speed vs road density (left); Road density vs flow rate (right)

That is, having homogeneous vehicles in the same road is unrealistic. That is why it was decided to evaluate the same performance with heterogeneous vehicles in order to get some useful insights.

### 5.1.2 Single Lane with Heterogeneous Vehicles

A scenario in which different types of vehicles are located in a freeway single lane is simulated. The organization of the vehicles in the road is random so there is not any cooperation among the vehicles. Table 6 shows the simulations parameters (Table 6).

<b>Number of vehicles</b>	20
<b>Type of vehicles</b>	Car type1, Car type2, Car type3 and Truck
<b>Simulation Time</b>	700 sec
<b>Time step</b>	0.5sec
<b>Type of lane</b>	Freeway
<b>Number of lanes</b>	1
<b>Initial position</b>	Random
<b>Initial speed</b>	$v_0$

Table 6: Simulation parameters for a single lane with homogeneous vehicles

Vehicles are placed into the lane randomly with initial vehicle speeds equal to their initial desired vehicle speed  $v_0$  (Figure 38). There is not any specific requirement on the number of vehicles of each type (red squares, trucks; blue squares, cars).

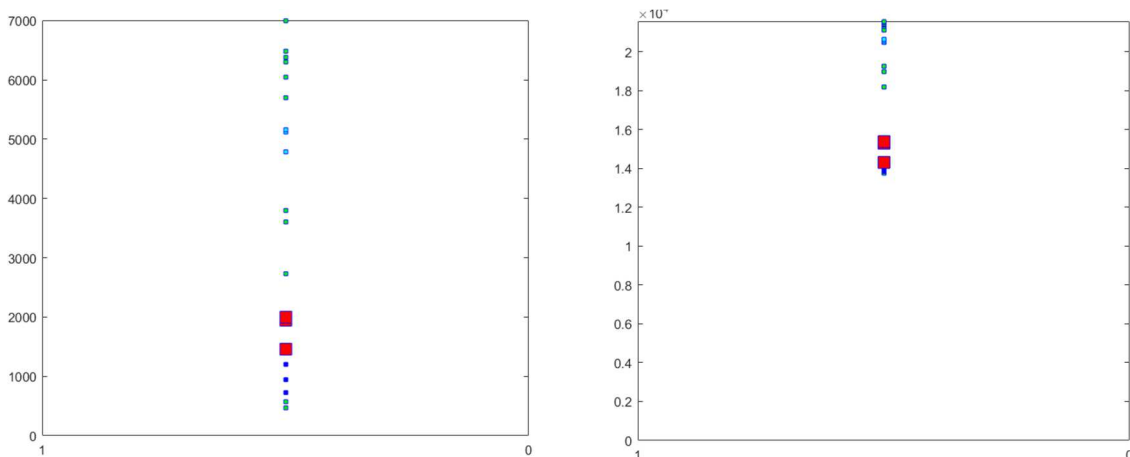


Figure 38. Heterogeneous vehicle initial (left) and final (right) distributions

As desired vehicle speeds for the different types of vehicles are not the same, vehicles with higher desired speed adapt their speed to the slower ones. In this case, the truck desired speed is the limiting value. In Figure 39, left, it can be seen that different “artificial platoons” of vehicles are formed by the slower vehicles as there is not any possibility to undertake (single lane). This fact makes that the vehicles have different travel distances and some of the vehicles cannot reach their desired speed at the end of the simulation (Figure 39, right). Those vehicles that are not “stopped” by the slower vehicles will achieve its desired speed at some point.

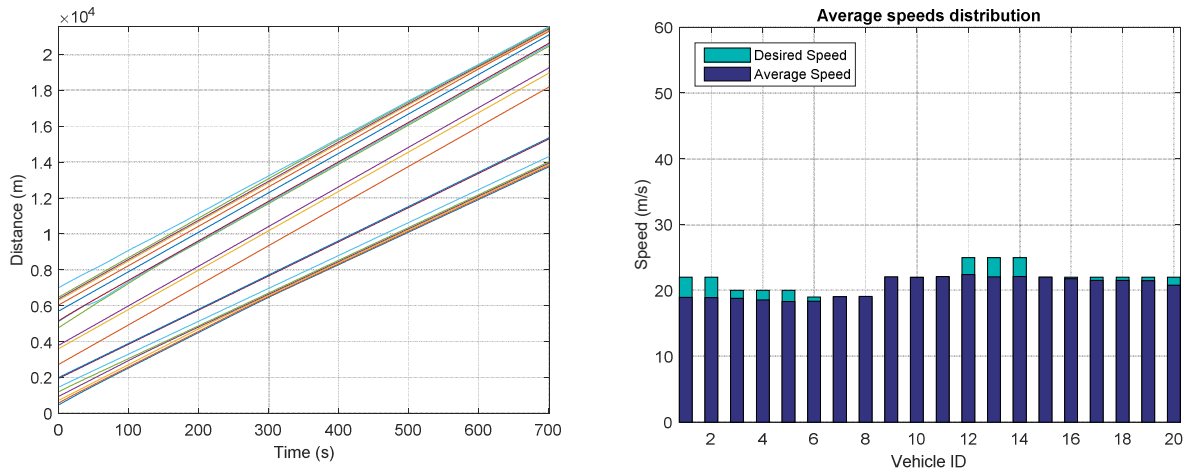


Figure 39. Vehicle distance (left); Average speed distribution (right)

The speed and acceleration performance during the simulation time is presented in Figure 40 where it can be noticed that some of the vehicles continuously adapt their acceleration in order to maintain the safety distance with the vehicle in front according the type of vehicle being simulated. This behaviour produces a constant speed and therefore, the creation of artificial swarms that can be seen in Figure 40. Acceleration oscillations on these vehicles (blue lines) confirm this behaviour.

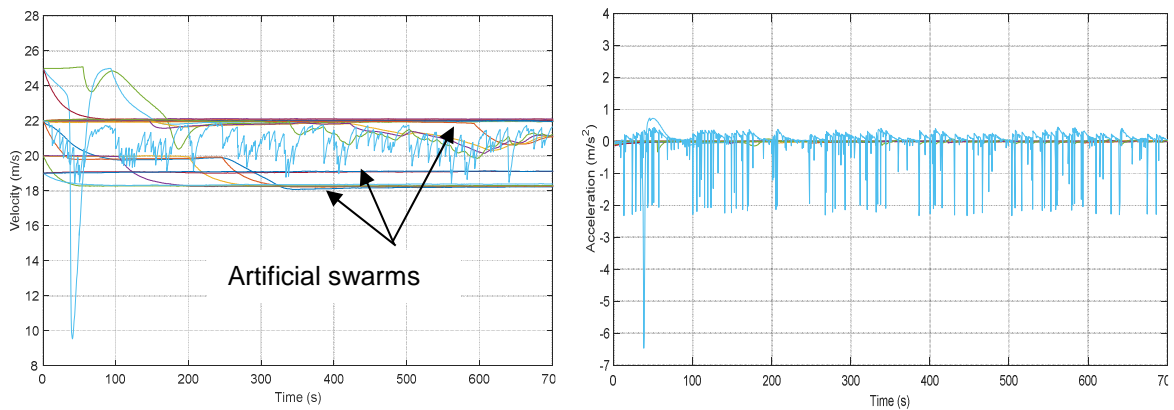


Figure 40. Vehicle speed (left) and acceleration (right)

Road density increases as average speed also increases (Figure 41, left). In the same way, flow rate increases as density increases (Figure 41, right). This is the consequence of the vehicle heterogeneity and confirms that traffic flow, under these conditions, is in the free flow instable area according the Figure 33.

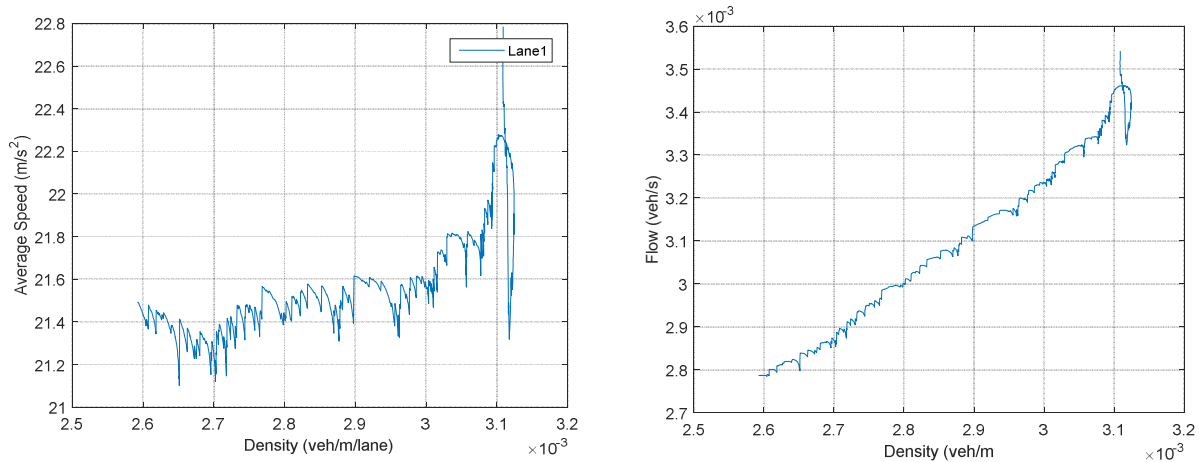


Figure 41. Average speed vs road density (left); Road density vs flow rate (right)

The artificial swarms formed by vehicles with different targets on one hand provokes an indirect increase in the traffic flow and road capacity but on the other hand, the traffic management is more complex because of the traffic instability. That is the expected result when there is heterogeneity of vehicles in the same lane and the lane changing option is not enabled.

### 5.1.3 Multiple Lanes with Heterogeneous Vehicles

Based on the results from the previous simulations, it was decided to simulate the behaviour of heterogeneous vehicles in multiple lanes to confirm whether the same results as shown before are applicable under these conditions.

The simulation conditions that are considered for this simulation are presented in Table 7; In this case 3 lanes are used.

<b>Number of vehicles</b>	20
<b>Type of vehicles</b>	Car type1, Car type2, Car type3 and Truck
<b>Simulation Time</b>	700 sec
<b>Time step</b>	0.5sec
<b>Type of lane</b>	Freeway
<b>Number of lanes</b>	3
<b>Initial position</b>	Random
<b>Initial speed</b>	$v_0$

Table 7: Simulation parameters for multiple lanes with heterogeneous vehicles

Vehicles are placed into the lane randomly with initial vehicle speeds equal to their initial desired vehicle speed  $v_0$ . There is not any specific requirement on the number of vehicles of each type for the simulation. The only premise adopted is that the slower vehicles must be placed on the right lanes while the faster ones must be in the left ones as in nowadays normal driving in Europe (Figure 42).

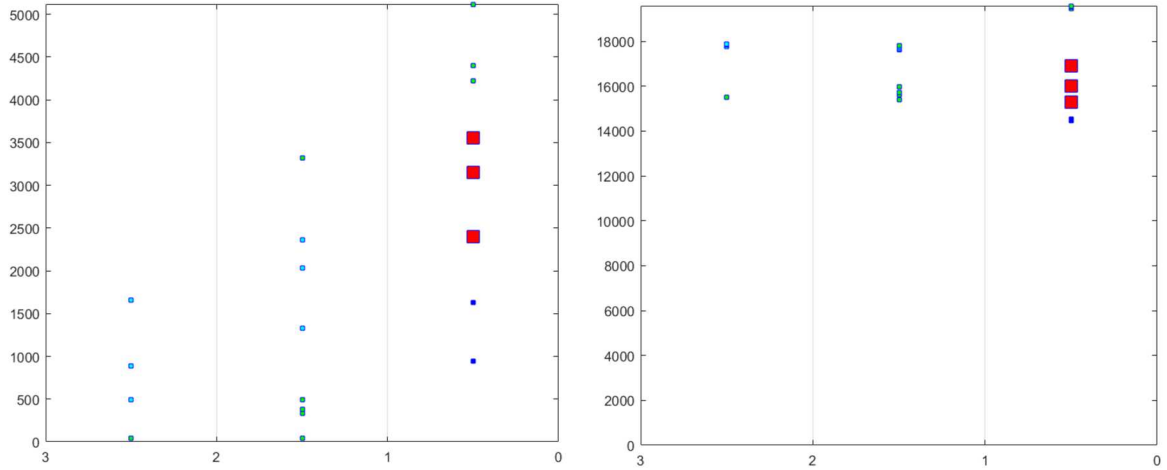


Figure 42. *Heterogeneous traffic simulation on 3 lanes initial (left) and final (right) distributions*

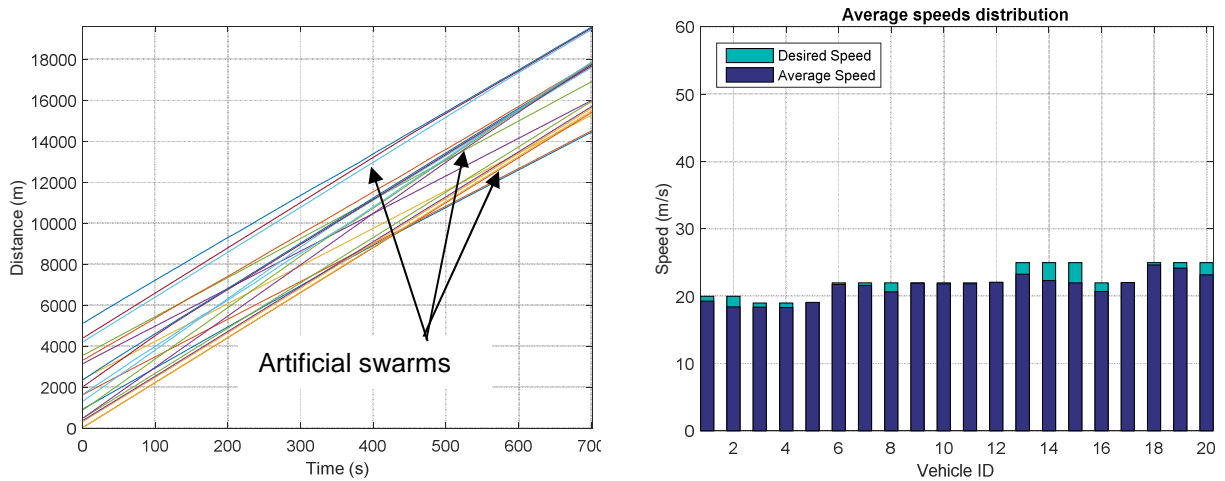


Figure 43. *Vehicle distance (left); Average speed distribution (right)*

According to the simulation results, the vehicles in the left lanes circulate at higher speed than ones driving in the right lanes (Figure 43, left). The average speed of the vehicles is close to the desired speed for most of the vehicles but there are some of them that cannot reach it because some slower vehicles were located in the same lane (Figure 43, right). As overtaken manoeuvres are not considered in this simulation, the slower vehicles produced un-intended “artificial swarms” (see Figure 43 left). The slower vehicles define, therefore, the swarms.

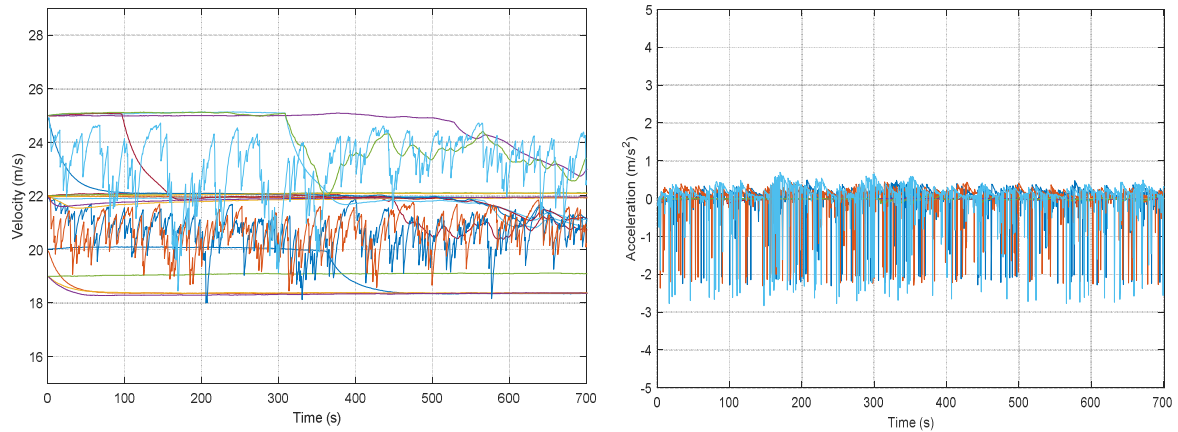


Figure 44. *Velocity and acceleration performance*

As shown in Figure 44, faster vehicles adapt continuously its velocity when they find a slower vehicle in front of them. Vehicles with faster vehicles in front achieve their desired speed and therefore, their velocity performance does not show oscillations.

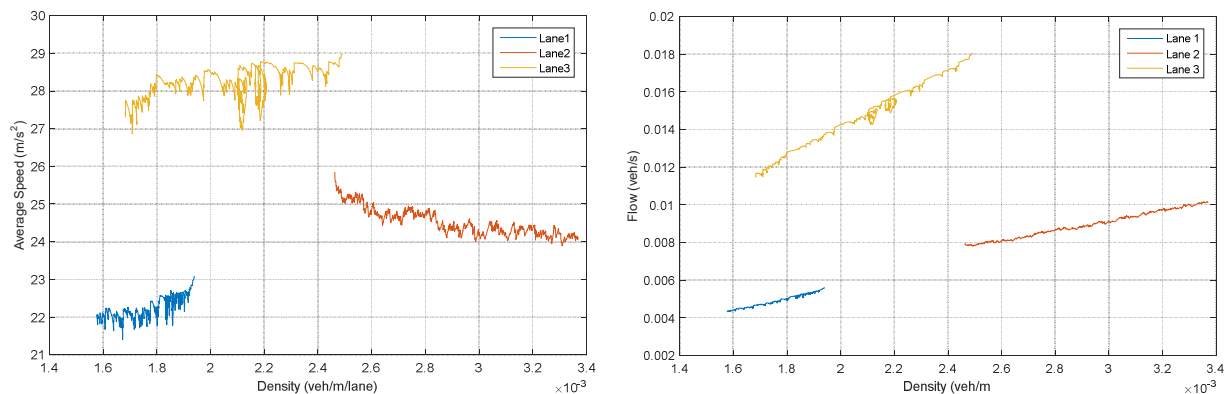


Figure 45. *Average speed vs road density (left); Road density vs flow rate (right)*

Interestingly, when the stabilization is reached, average speed is constant for all the lanes. However, density lane slightly increases as consequence of the artificial swarms formation (Figure 45, left). Consequently, flow rate slightly increases accordingly (Figure 45, right). This is the consequence of the vehicle heterogeneity.

### 5.1.4 Homogeneous Vehicles in Swarm Configuration

Now we are going to show how the traffic flows behaves when the vehicles form swarm configuration both for homogeneous and heterogeneous vehicles. Based on the previous simulations we will check if driving in a swarm configuration could potentially benefit the overall traffic flow.

First, only one lane in freeway traffic is considered and the same type of vehicles, in this case trucks. The tests parameters are the following (Table 8):

<b>Number of Vehicles</b>	20
<b>Type of Vehicles</b>	Truck
<b>Simulation Time</b>	700 sec
<b>Time Step</b>	0.5sec
<b>Type of Lane</b>	Freeway

<b>Number of Lanes</b>	1
<b>Initial Position</b>	Random
<b>Initial Speed</b>	v0
<b>Swarm Size</b>	4
<b>Inter-vehicle Swarm Distance</b>	10m

Table 8: Traffic flow parameters with homogeneous vehicles in swarm configuration

That is, there is only one lane but swarms of up to 4 vehicles are allowed. Figure 46 shows the initial vehicle distribution in a platoon configuration. Five swarms of trucks (4 units per swarm) were randomly placed in the road lane with a predefined inter-vehicle distance between vehicles within the swarm.

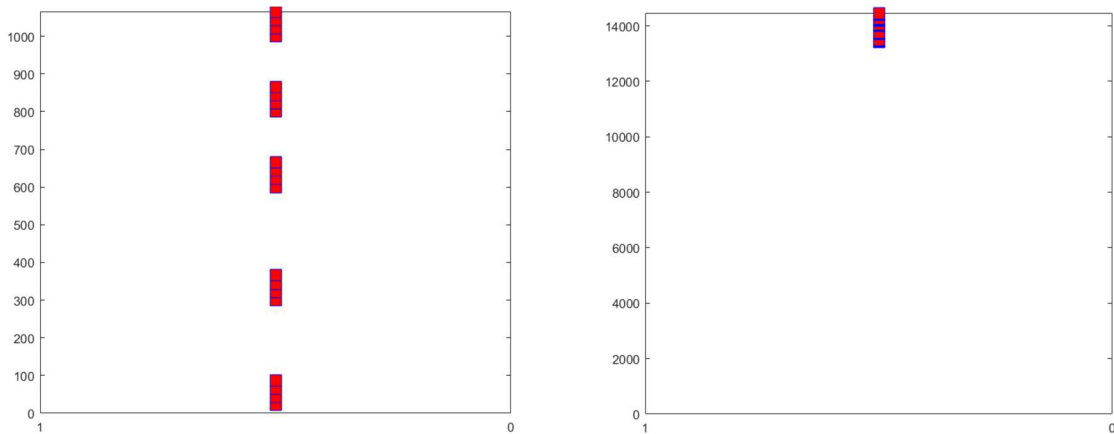


Figure 46. Homogeneous traffic simulation initial (left) and final (right) distribution

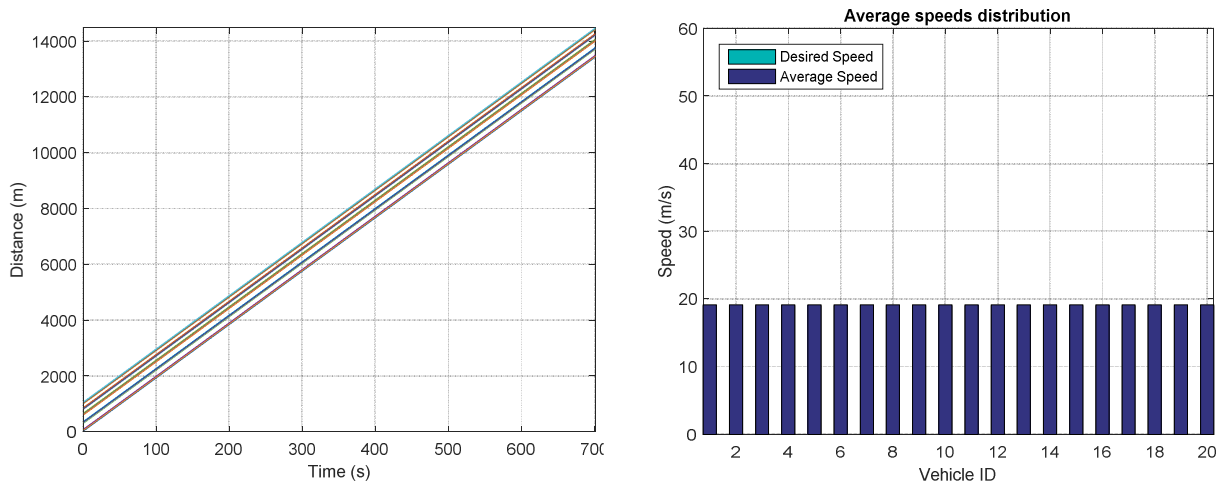


Figure 47. Vehicle distance over simulation time (left); Average speed distribution (right)

According to the results shown in Figure 47 left, the five swarms drive together during the simulation time without oscillations. Apart from that, as the vehicles stay within the platoon, the desired speed of the vehicles is achieved and only small variations on acceleration/deceleration are measured in all the vehicles (Figure 48). The swarm behaviour therefore, maximizes the individual vehicle efficiency.

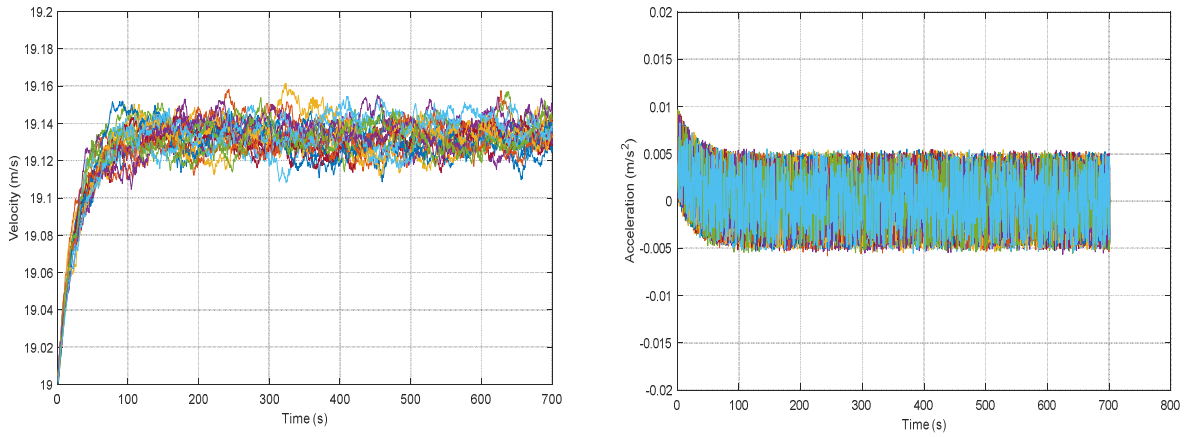


Figure 48. *Swarm velocity (left) and acceleration (right) performance*

As shown in Figure 49, it is measured a slightly variation in the inter-vehicle distance around the programmed value of 10m. This may be the consequence of the current IDM implementation and parameter settings, which it is not under the scope of this project.

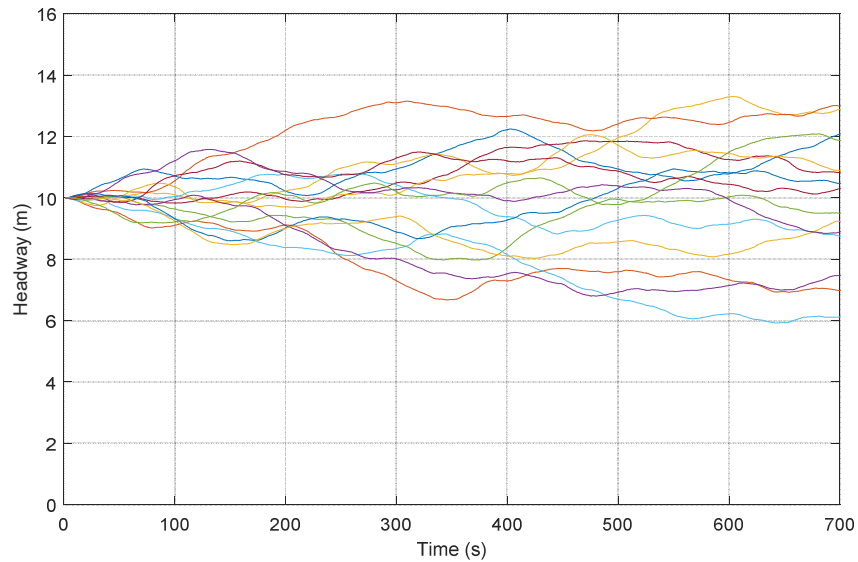


Figure 49. *Inter-vehicle distance distribution*

Given that all the vehicles in the road are driven at the same desired speed (same type of vehicles are placed in the lane), there is an opportunity to increase the number of vehicles per swarm which would positively impact the road flow.

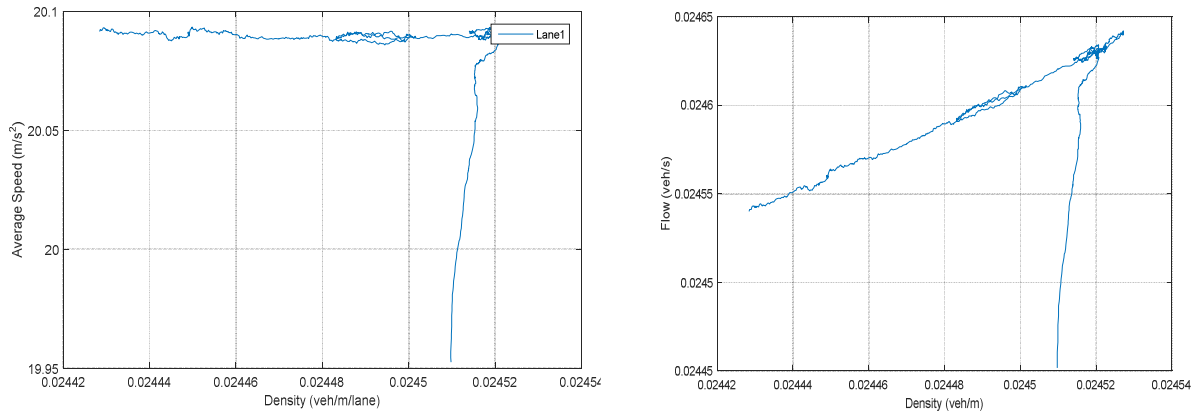


Figure 50. Average speed vs road density (left); Road density vs flow rate (right)

According to Figure 50, left, average vehicle speed is kept constant as expected during the simulation time which is traduced in a slight increase in traffic density and thus, flow rate (Figure 50 right).

Although this simulation has been run for a single lane, the same results are expected to be obtained with multiple lanes if the same conditions are applied. In the case of different types of swarms with different settings (e.g. different desired speeds), the proposal is to place them in different and dedicated lanes so that the likelihood of conflicts among them is minimized.

### 5.1.5 Heterogeneous Vehicles in Swarm Configuration

Several simulations have been carried out to find and select the best configuration of a swarm in terms of number of members, desired speed, position in the lane, swarm activation/deactivation, etc, ...

#### 5.1.5.1 Number of swarm elements

The number of members of the swarm will not, in principle, represent any limitation. The traffic road is not supposed to be disturbed by the size of it. Having said that, it is clear that the maximum size of a swarm should not exceed a number of vehicles that could potentially block the exit ramp when a vehicle in a different lane than the swarm wants to exit the highway. One potential solution to this problem is to anticipate the exit of this car by V2V communication between the car and the swarm so that a cut-in manoeuvre could be planned by the swarm and then this vehicle can be integrated in the swarm before its exit.

It will be investigated in depth the impact of a large number of vehicles in a swarm when an emergency situation arises, and a coordinated manoeuvre is commanded, for example, simultaneous braking. As vehicles in a swarm are supposed to be communicated by a V2V and V2X protocols, it is under study if the lag in the communication could represent a safety relevant issue.

Vehicles in the swarm do not have the same performance (even if they are the same type of vehicles). So, it is expected that vehicles share the status of their most important systems such as engine, braking capability, position, etc ... This information must be coordinated by a control center, typically a leader vehicle, which will adapt swarm conditions to the traffic situation accordingly.

Figure 51 compares the average headway space for different sizes of swarms with the same type of vehicles in the same route:

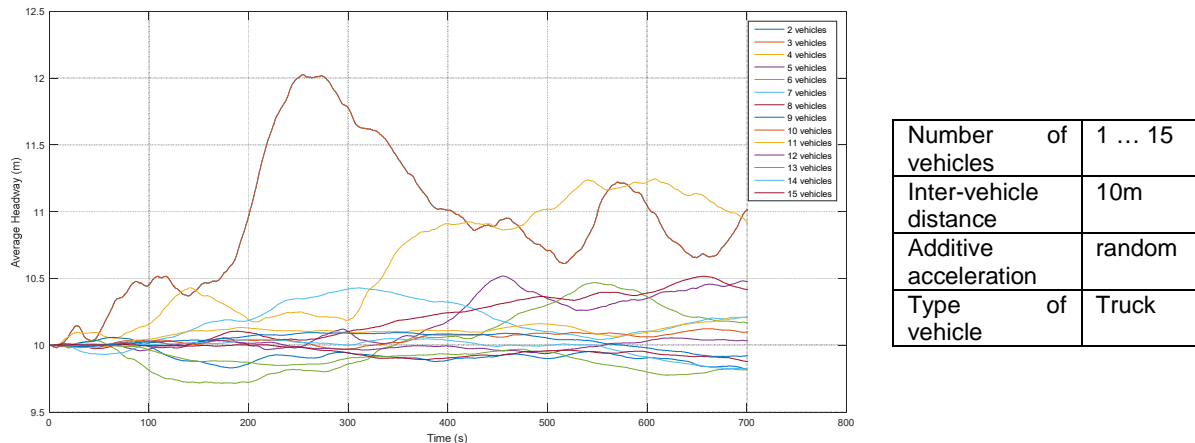


Figure 51. Swarm headway comparison on different swarm sizes

As it is shown in Figure 51, as swarm size increases, the predefined inter-space distance of 10 m between the members of the swarm is somehow maintained within some limits on most of the simulations that have been carried out. A white noise has been added on the acceleration term of the IDM model to create a more realistic behaviour which, in some of the cases (3 and 4 vehicles) contributes to a higher inter-space variance.

### 5.1.5.2 Inter-vehicle Distance

The inter-vehicle distance is an important parameter that have a great impact on road safety, efficiency and CO2 reduction, especially for big vehicles such as trucks and coaches.

The swarm simulation tool integrates a parameter which can be tuned so that the inter-vehicle distance is modified for each simulation. Considering a standard swarm of 10 vehicles, different inter-vehicle distances are simulated, and the swarm headway is checked (Figure 52).

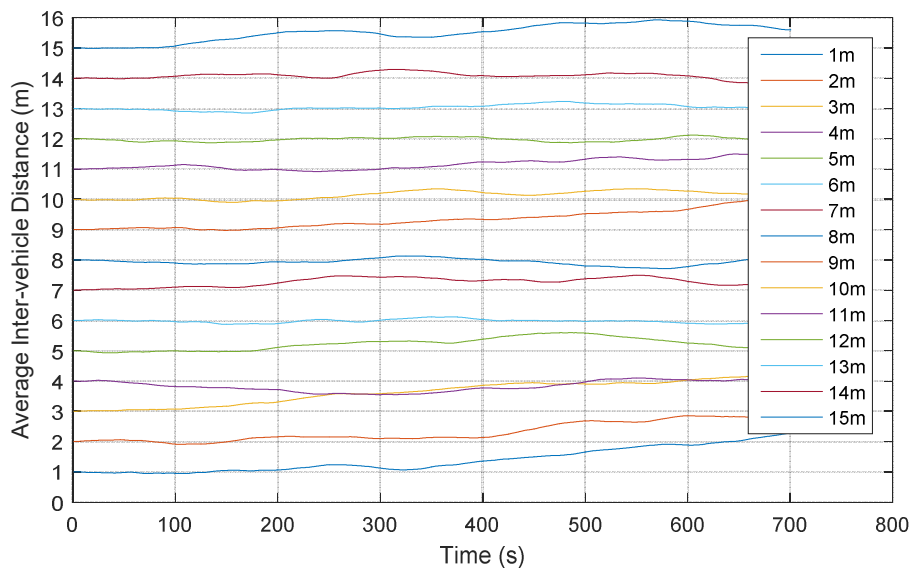


Figure 52. Swarm headway comparison on different inter-vehicle distance

According to Figure 52, it is confirmed that as inter-vehicle distance increases the vehicles keep the swarm formation. In the case of trucks and coaches, having a high inter-vehicle distance does have a negative impact on the fuel reduction as air drag forces between vehicles increases with this distance (Figure 17).

In terms of road safety, having high inter-vehicle distance would make the swarm less sensible to changes in the vehicle acceleration/deceleration. This is due to the fact that traffic changes such as accidents, road inclination, vehicles cut-in actions, ..., could be anticipated without compromising the other vehicles in the swarm.

### 5.1.5.3 Desired Speed

The desired speed is the parameter that mainly affects the swarm. The simulation tool allows swarms by vehicles with the same desired speed. The following vehicles can be grouped together as a good representation of the population of vehicles in nowadays roads:

Trucks/Coaches: Vehicle speed low

Standard vehicle: Vehicle speed medium

Emergency and Sport vehicles: Vehicle speed high

### 5.1.5.4 Position in Lane

The swarm position in the road is also one of the key aspects. It would be desirable that swarms with high differences regarding desired speeds do not share the same lane in order not to penalise the slower ones. Therefore, it is here proposed that swarms are located in the lanes depending on the desired speed so that the slow swarms are placed on the right lanes and as swarm speed increases, they are located in the left lanes. Considering the proposed type of swarms in a 3-lane road, they should be placed as follows (Figure 53):

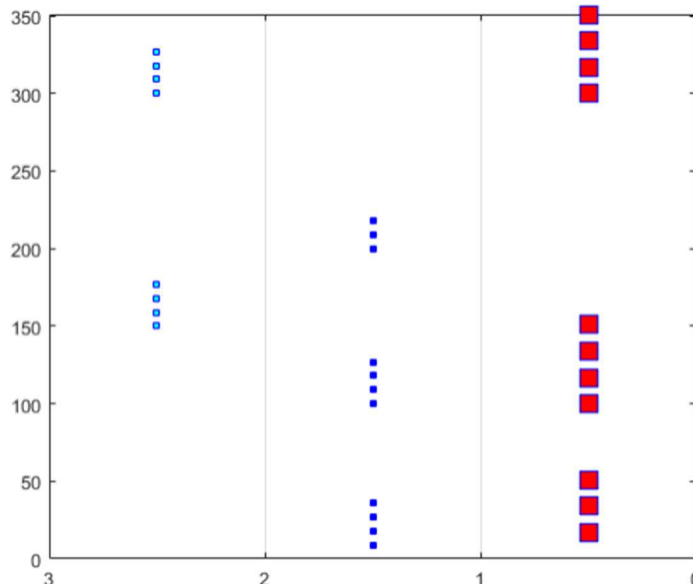


Figure 53. Example of swarm position in a 3-lane road

A swarm, initially, would not be able to overtake another swarm in the same lane. Only individual members of a swarm could make this action if its speed target differs from the

swarm it is engaged to (e.g., ramp exit, vehicle damage, etc ...). In this case, a programmed dis-engaged action must be taken by this member.

#### 5.1.5.5 Swarm Permeability

One of the functions that the swarms must have to be efficient in real traffic is the capacity to accept new vehicles and to create a safe distance between vehicles for cut-in manoeuvres. This function, therefore, can only be achieved if a V2V communication is available for the swarm and other nearby vehicles that do not belong to it; then, a programmed action can be coordinated. In case of this work, it has been proposed that as long as the distance between a swarm and the new approaching vehicle is less than a predefined value, the new vehicle will adapt its IDM model parameters to the ones defined by the swarm. This would make that the swarm string stability is kept.

#### 5.1.5.6 String Stability

The stability of the platoon has been evaluated by injecting a perturbation into the platoon leader. This chapter analyses how the perturbation affects the platoon members and their performance during the simulation time.

The simulation considers a platoon of 10 vehicles on which the leader vehicle varies its vehicle speed randomly as shown below in Figure 54:

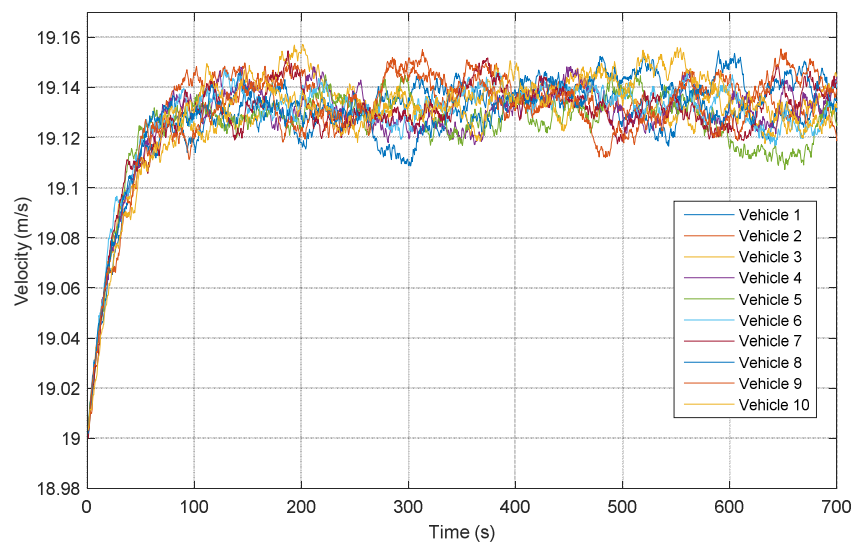


Figure 54. Platoon string velocity performance

According with Figure 54, independently of the magnitude of the oscillation in the leader vehicle of the platoon, the rest of the members will adapt its vehicle speed to follow the leader (Vehicle ID 10) and try to meet the programmed inter-vehicle distance of 10 meters (Figure 55). This behavior was confirmed by the use of same IDM parameters in all the vehicles in the swarm. Further tuning on the IDM model will assure more stability and less inter-vehicle distance oscillations but this task is not considered within the scope of this work.

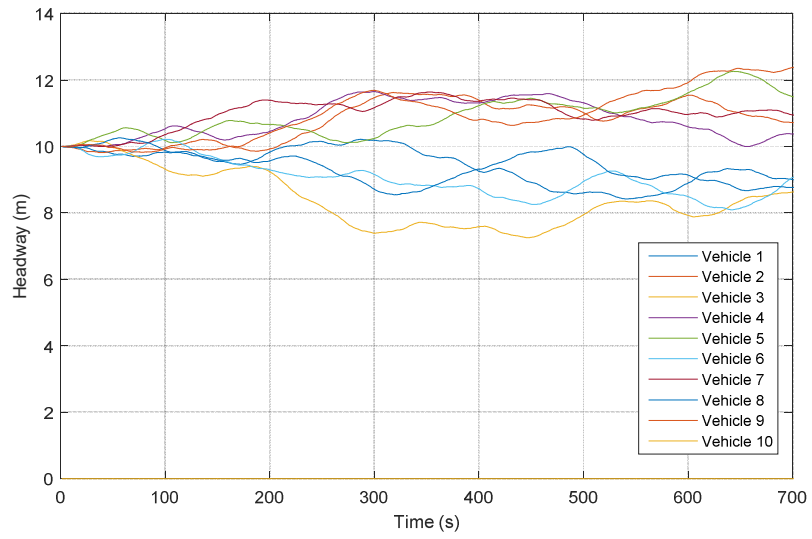


Figure 55. *Inter-vehicle distance performance on a platoon of vehicles*

## 5.2 Traffic Jam Assist

With the use of the swarm traffic simulator, the traffic jam assistance function was simulated to evaluate the advantages of this function and understand how it can be implemented. For the testing purposes, the IDM model implemented within the simulator tool has been modified so that all vehicles that are driving in a traffic jam assistance have the same IDM model parameters. This proposal considers therefore, that all vehicles behave similarly under a traffic jam situation. The modifications into this model are presented in Table 9 below:

Parameters	Variable	Vehicle Type 1	Vehicle Type 2	Vehicle Type 3	Vehicle Type 4	Traffic Jam
Maximum Acceleration	$a_n(\frac{m}{s^2})$	0.8	0.9	1	0.7	0.7
Desired Speed	$V_0(\frac{m}{s})$	20	22	25	19	1.38
Linear Jam Distance	$s_n^0(m)$	0.3	0.4	0.5	0.1	0.05
Non-Linear Jam Distance	$s_n^1(m)$	0.2	0.25	0.35	0.15	0.2
Safe Time Headway	$\tau_n(s)$	0.3	0.3	0.3	0.1	0.1
Comfortable Deceleration	$b_n(\frac{m}{s^2})$	2	2	2.5	1.5	1.5
Acceleration Exponent	$\delta_n$	4	4	4	4	4
Car Length	$l$	4	4	4	12	4

Table 9: Original IDM vs traffic jam settings

The simulation considers different scenarios of vehicles being driven in a traffic jam with relative low vehicle speeds of less than 10kph and inter-vehicle distance of two meters.

### 5.2.1 Single Lane with heterogeneous vehicles

A number of twenty different vehicles were simulated being driven in a single lane under low speed conditions and with inter-vehicle distance of two meters as shown in Figure 56 below:

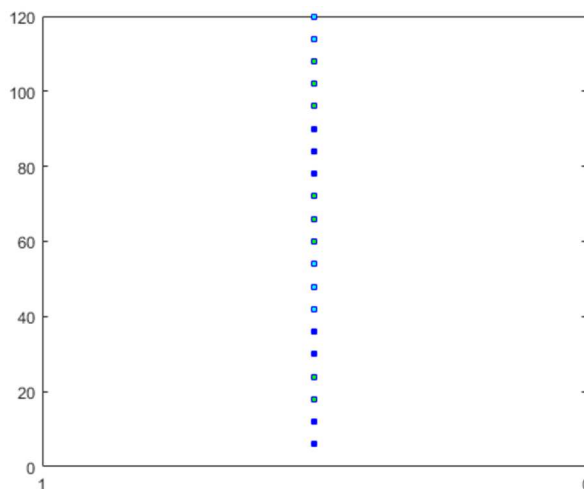


Figure 56. Single lane traffic jam simulation

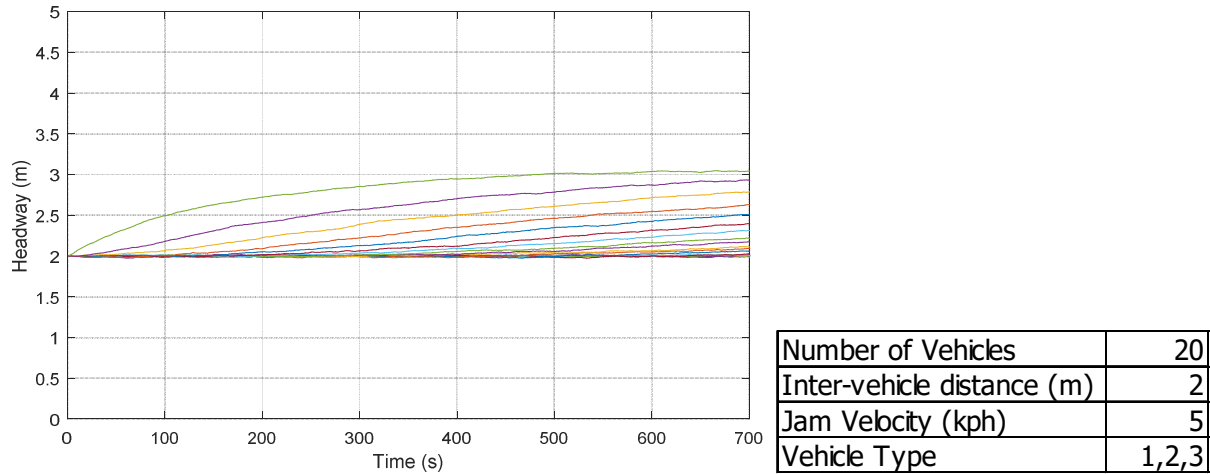


Figure 57. Single lane traffic jam simulation result

According to Figure 57, the inter-vehicle distance increases as long as simulation time increases. The reason for this behavior is found in the implementation of the IDM model for the leader vehicle (green upper line) which considers a fixed space distance with its “virtual” leader. The rest of the vehicles in the row will follow this vehicle and thus, they will adapt their velocity according to it as shown in Figure 58. At second 500 of the simulation, the leader vehicle headway space reaches the stability distance of 3 meters although for the rest of the vehicles, it is still increasing.

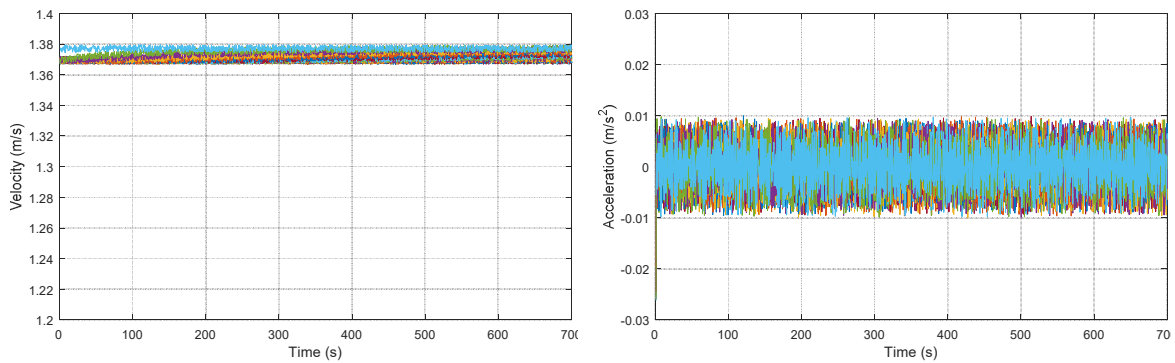


Figure 58. Traffic jam vehicle velocity and acceleration performance

The velocity and acceleration performance appear to be quite smooth and with almost no high oscillations in magnitude which is desirable under traffic jam conditions to avoid unintended crashes. As a consequence, flow rate is kept almost constant during the simulation time (Figure 59). The reason for not achieving a fully constant flow rate is due to again the IDM model implementation as explained before.

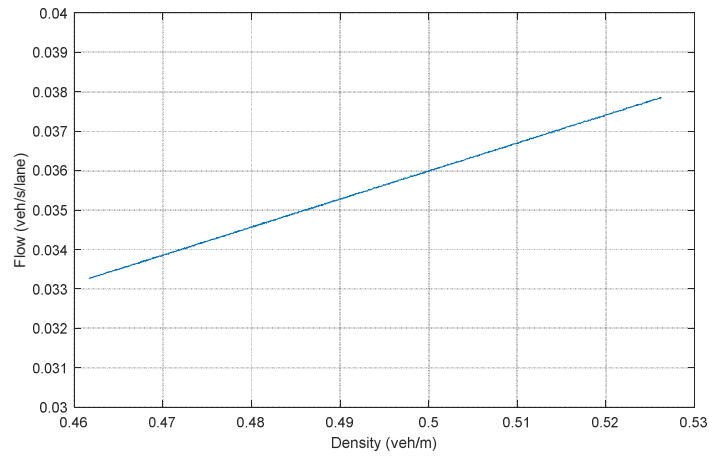


Figure 59. Flow rate in traffic jam assistance

### 5.2.2 Multiple Lanes with Heterogeneous Vehicles

A number of twenty different vehicles were simulated being driven on a 3-lane road under low speed conditions with inter-vehicle distance of two meter as shown in Figure 60 below:

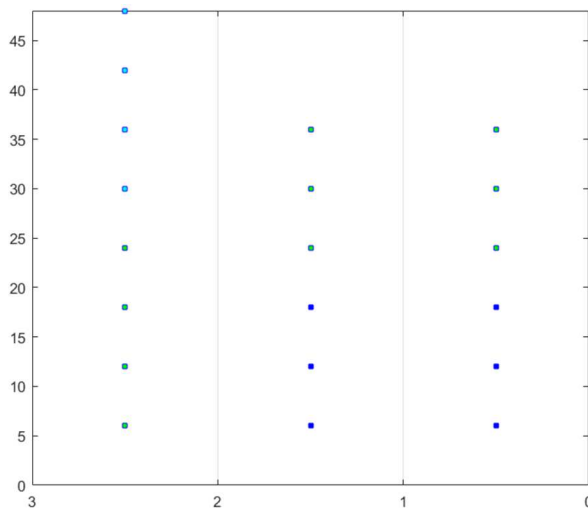
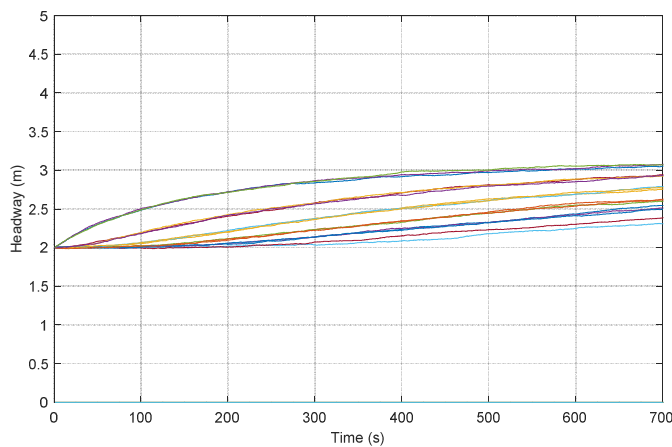


Figure 60. Multiple lanes traffic jam simulation



Number of Vehicles	20
Inter-vehicle distance (m)	2
Jam Velocity (kph)	5
Vehicle Type	1,2,3

Figure 61. Multiple lane traffic jam simulation result

According to Figure 61, the inter-vehicle distance increases as long as simulation time increases. The reason for this behavior is found in the implementation of the IDM model for the leader vehicles on the lanes (green, blue and pink upper lines) which considers a fixed space distance with its “virtual” leader. The rest of the vehicles in the row will follow this vehicle and thus, they will adapt their velocity according to it. As shown in figure 62, the velocity and acceleration performance of the vehicles is kept smooth with no high oscillations which is translated in almost constant flow rate as shown in Figure 63:

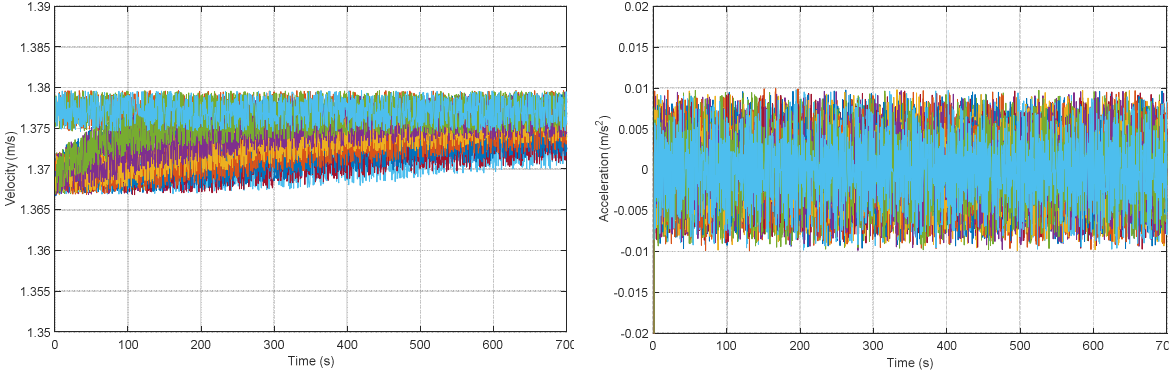


Figure 62. Traffic jam velocity and acceleration performance

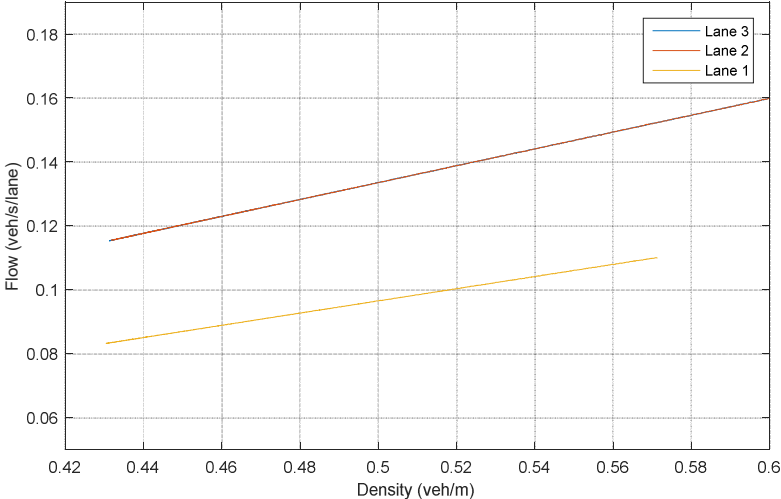


Figure 63. Flow rate in traffic jam assistance

The reason for not achieving a fully constant flow rate is due to again the IDM model implementation as explained before.

# CHAPTER 6: Conclusions and Future Work

## 6.1 Conclusions

This work has analysed the platooning of vehicles as one of the applications of the swarm intelligence in the automotive industry. Different platoon of vehicles has been proposed and have been evaluated within a simulation environment specifically designed for this purpose. The result confirms the following results:

- Depending on the platooning definition e.g. desired speed, comfort premises, fuel efficiency, etc., the platoon must be placed on a specified road lane to be defined by traffic authorities. By doing this, traffic flow efficiency will be increased and indirectly, road safety too as long as the vehicles exchange information among them.
- If the platoon is not placed according conclusion 1), the traffic flow will be reduced due to the fact that vehicles with higher speed than the intended platoon will be limited unless a proper and safe lane changing function is implemented
- Vehicles within the platoon must share similar targets/premises such as desired speed, acceleration and deceleration patterns. If vehicles with different profiles belong to a platoon, they must adapt their vehicle profiles to the “defined” platoon profile
- The application of the vehicles in a platoon must be restricted to free road driving conditions with more or equal to two lanes so that the platoon can always be driven on the right lanes and the rest are kept free for non-platoon members
- The size of a platoon it is not a determinant factor and ideally any size could be implemented. However, it is a must that a proper V2V and V2I communications are developed so that safe headway between vehicles is constantly monitored. Functions such as cut-in and engaged/disengaged must be implemented on the platooning controller so that the interactions with non-platoon members are correctly addressed. This fact will help the introduction of this technology in current traffic conditions

## 6.2 Future Work

- Develop proper swarm traffic models considering heterogeneity of vehicles
- Develop proper lane changing models to allow a complete swarm to overtake the slower vehicles
- Develop models for cut-in platoon and engaged/disengaged functions to simulate real traffic scenarios
- Implement a model that simulate a traffic issues such as accidents, road work, etc, ... to evaluate the swarm detection and reaction when this event is detected by a member of the swarm. Thanks to V2V or V2I communication protocols, a controlled reaction of the whole swarm could theoretically be programmed so that the best fail-safe strategy can be applied (e.g., stop the vehicles, reduce swarm speed to a safe value, etc ...)

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