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ENabling **S**af**E** **M**ulti-**B**rand p**L**atooning for **E**urope

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Revision history

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1. EXECUTIVE SUMMARY

1.1. Context

Platooning technology has made significant advances in the last decade, but to achieve the next step towards deployment of truck platooning, an integral multi-brand approach is required. Aiming for Europe-wide deployment of platooning, ‘multi-brand’ solutions are paramount. It is the ambition of ENSEMBLE to realise pre-standards for interoperability between trucks, platoons and logistics solution providers, to speed up actual market pick-up of (sub)system development and implementation and to enable harmonisation of legal frameworks in the member states.

1.2. Project scope

The main goal of the ENSEMBLE project is to pave the way for the adoption of multi-brand truck platooning in Europe to improve fuel economy, traffic safety and throughput. This has been demonstrated by driving up to seven differently branded trucks in one (or more) platoon(s) under real world traffic conditions across national borders. During the years, the project goals were:

- Year 1: setting the specifications and developing a reference design;
- Year 2 and 3: implementing this reference design on the OEM own trucks, as well as performing impact assessments with several criteria;
- Year 4: focus on testing the multi-brand platoons on test tracks and public road.

The technical results have been evaluated against the initial requirements. Also, the impact on fuel consumption, drivers and other road users has been established. In the end, all activities within the project aim to accelerate the deployment of multi-brand truck platooning in Europe.

1.3. Abstract of this Deliverable

Deliverable 4.3 analyses the impacts of multi-brand platooning on transport costs and logistics chains and identifies the business models that will maximise the deployment of multi-brand platooning. Furthermore, the environmental impacts of platooning are assessed

The business models of platooning were analysed qualitatively and quantitatively through various approaches. The core of the value of platooning comes from the formation of platoons. **When two vehicles form a platoon, a cost reduction may follow**, for example through reduced fuel consumption. The benefit of this reduced fuel consumption is proportional to the distance covered by the platoon before it is dissolved. These savings are not the same for the leader vehicle and for the following ones, which benefit most from the formation of the platoon. **Platoon formation also comes at a cost**: first, the vehicles must be able to platoon, which implies an **investment cost**. Second, they must meet, which means that one vehicle must wait for the other to join, and/or both must make detours: there is a **coordination cost.** This causes a delay, implying increased workforce

costs, capital opportunity costs, and reduced level of service for shippers, i.e. downwards supply chain costs. **This coordination cost is lower on average when there are more platooning opportunities**, which means several things: first, there must be enough truck traffic; second, a significant share of these trucks should be platoon-enabled; third, a significant share of these trucks should have similar trip patterns. In other words, traffic on one road cannot be a sufficient indicator of the relevance of platooning: the whole **economic life cycle** of the vehicles should be considered, that is to say the totality of the origins, destinations and routes they are expected to be used over in the years after the moment they are acquired by a carrier.

Carriers are at the core of the value chain of platooning. Platooning is costly, because vehicles need to be equipped; it is costly to use, because vehicle routes need coordination; and it is risky, because the benefit one carrier will get off their investment decision depends on the investment decisions of other carriers. Other stakeholders, such as public institutions, infrastructure managers, or insurance companies may influence a bit the business case of platooning, but they will not be substitute to the absence of a core business case, would it be lacking. **Without legal obligation, there cannot be a business case of platooning without net benefits to carriers**.

Simulations based on micro-economic models show that **with the specification of the Platooning Support Function in ENSEMBLE, the business case of platooning is very weak**. Cost savings are very probably too low to be able to at least compensate the cost of platooning for carriers. However, **with the more favourable assumptions in terms of fuel savings associated with the Platooning Autonomous Function in ENSEMBLE, or other reductions in trucking costs, the business case of platooning can be brighter**, provided the cost of the platooning technology doesn't increase too much. In particular, the business case of platooning improves if one assumes that fuel prices are going to increase steadily over the coming years. Also, **market uptake can benefit spectacularly from a sizable injection of platoon-enabled trucks in the fleet** at the beginning. Then, in favourable cases, market uptake goes to the same rhythm as fleet renewal, for trucks with an adequate economic life-cycle (qualitatively, those trucks who cover long distances over regular routes with a lot of truck traffic, but not so much that there is congestion)

Eventually, regarding the business case of platooning, the more opportunities to form platoons, the lower the expected coordination cost when forming platoons. Simulations based on dynamic programming make explicit **the importance of interoperability for the business case of platooning**. In particular, they show that the business case of platooning is much higher when platooning is allowed between vehicles of all carriers than when each carrier can only form platoons between vehicles of its own fleet.

The environmental impacts of platooning depend on how platooning is actually implemented. From road track tests and open road tests, it is concluded that **at support level, platooning will not yield substantial fuel savings**, especially given the fact that adaptative cruise control (ACC) already allows for some of those benefits, albeit at a lower safety level. For the emissions of local pollutants (NOx and PM) no significant effects were found. Still, there may be **the benefit of a fuel saving if**

the inter-vehicle gap within the platoon gets short enough. The life-cycle analysis provides consistent conclusions.

2. INTRODUCTION

2.1. Background

Multi brand platooning is the process through which partially automated trucks can form convoys of trucks of different brands. The benefits platooning can bring to the society, in a wide sense (i.e. improvements in terms of productivity, environmental impacts, social impacts) have been the topic of many projects in the past. A lot of those works focused, in particular, on the benefits of platooning in terms of fuel efficiency: if two trucks or more can drive with a close intervehicle distance, the reduction in aerodynamic drag should improve the energy efficiency of the following vehicles, with a positive impact in terms of fuel consumption. This should turn into both positive environmental and financial impacts.

However, past literature, research, and projects, have left a number of questions unanswered. The first one is the question of the business model of platooning. Indeed, business models and socio-economic analyses should not be confused, despite the close proximity between both exercises. Socio-economic analysis mostly focuses on the monetary and non-monetary benefits of platooning, once assumed platooning is widely used. Business case analysis (or, to use a micro-economic wording, private equilibrium determination) is solely focused on the question of the spontaneous adoption of platooning by the market, without direct regulatory action from governments or other public institutions[1].

The second question is that of the fuel savings actually made possible with platooning. The literature provides some consistent figures, but the direction was taken, in the ENSEMBLE project, to proceed to tests in real conditions, on open road, to obtain the most up to date and relevant figures to the particular specification of platooning at the heart of the ENSEMBLE project. This implies that the assessment of the environmental benefits of platooning should be updated, both in terms of fuel consumption – and, as a direct consequence, of greenhouse gas emissions – and in terms of life-cycle analysis.

2.2. Aim and report structure

The objective of Deliverable 4.3 is to provide answers to the two questions raised in the introduction above: that of the business case of platooning, and that of the environmental impact of platooning.

2.2.1. The business case of platooning

Regarding the business case of platooning, a three-directional approach is chosen, combining a range of methodologies. First, a qualitative analysis identified the stakeholders of the platooning

[1] The distinction should be nuanced: an entirely consistent socio-economic analysis should either assume regulatory obligation to use one technology, or proceed to a business case analysis as *a necessary step* to the approach. This is not always done with a great amount of detail.

market. Each category is analysed in terms of their objectives, constraints, and interactions with other parties, with a perspective specifically oriented to understand the position of each stakeholder regarding platooning. In particular, for each stakeholder, several questions are addressed: do they benefit from platooning? Do they bear costs if platooning is implemented? What are their decisions? What are their payoff functions? Can they, and would they, play a role in amplifying or dampening the benefits of platooning in one way or another? Several stakeholder categories are analysed; the value of chain of platooning is identified; the core benefits and potential benefit amplifiers of platooning are identified; risks of platooning as an investment for the parties involved are discussed. This is the object of Chapter 3.

The second approach is a quantitative, analytical one. Its objective is to model the market uptake of platooning as a result of economic decisions (including investment decisions) made by private stakeholders aiming at maximizing their profits. A bilevel model of platooning is elaborated, modelling both the decision of carriers to form a platoon or not based on a micro-economic trade-off; and the decision – also of carriers – to equip their vehicles with the platooning technology. Based on the qualitative analysis, the model's main characteristic is the interdependency of the strategic decisions of carriers, the dynamics of market uptake, and the monetary benefits and fuel savings which can be expected from platooning under a range of distinct sets of assumptions. The model and numerical results are presented in Chapter 4.

The third approach is operations research: its objective is to provide evidence of the value of platooning when more vehicles can form platoons than when platoon formation is limited to subsets of vehicles. An algorithm optimizes platooning formation over a complex highway network, and a large set of carriers with fleets of very heterogenous size. Two sets of assumptions are compared: one where platooning can only take place between vehicles owned by the same carrier, and one where platoons can be formed between vehicles of all carriers. The approach is detailed in Chapter 5.

2.3. The environmental impacts of platooning

Chapter **Error! Reference source not found.** is focused on the benefits of platooning in terms of f uel consumption and environmental pollution. It is based on a literature review, test tracks measurements, and open road tests. In particular, impacts of platooning in terms of fuel consumption, CO_2 emissions, NOx and PM emissions are measured, analysed, and compared to the literature.

Chapter 7 presents a life-cycle analysis of platooning. The analysis accounts for the production, usage and treatment of a truck over its life cycle. The impacts are computed and discussed, primarily in terms of contribution to climate change.

Chapter 8 concludes the deliverable.

3. BUSINESS MODEL ANALYSIS

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The economic benefits of platooning are potentially significant for shippers, for the economy as a whole, and for the environment. However, turning this potential into actual benefits is not trivial: some benefits are not directly monetary, some of them involve public stakeholders, some of them depend on the overall market uptake of the technology, etc. The objectives of this chapter of the deliverable is first, to analyse the actual economic interdependencies of the technology and the associated risks, uncertainties and opportunities; second, to identify ways to maximise the success and impact of platooning. A by-product of this analysis is to anticipate policy interrogations, such as how platooning interacts with other freight transport policy instruments; whether specific infrastructure investments are required; and whether funding or regulation are required.

This chapter proceeds in two parts. First, stakeholders are identified and analysed. Second, the overall stakeholder system is described and discussed with respect to platooning.

3.1. Analysis of stakeholders and their relationships

We distinguish eight categories of agents, or stakeholders, directly involved in the decision to implement platooning or directly impacted by its implementation. These categories are:

- Shippers (**S**): any firm, institution or individual managing a commodity flow and interested in how these commodities are made available to their receivers.
- Infrastructure managers (**IM**): any firm or institution involved in the planning, provision, exploitation and maintenance of transport infrastructures. Those can be linear (such as roads) or nodal infrastructures (such as ports).
- Insurance companies (**I**): firms managing and mitigating risks for other firms, individuals, or households, mainly by pooling and incentives.
- Original Equipment Manufacturers (**OEM**): firms manufacturing vehicles. Only they can produce platooning enabled vehicles.

- Platooning Service Providers (**PSP**): firms providing the digital infrastructure and protocols required for platooning to work. They can provide a variety of services, including matching vehicles applying to be part of a platoon.

- Drivers (**U**): they are required for road freight transportation; they can be implied in a variety of ways by platooning.

- Regulator (**R**): they make and enforce rules, determine taxes and subsidies, and implement multi-aspect policies.

- Carriers (**C**): they produce transport operations, on the basis of four types of inputs: vehicles, drivers, energy, and infrastructure.

Let us now examine each of these stakeholders, so as to identify their objectives, constraints and interactions with the other stakeholders.

3.1.1. Shippers

Shippers are the customers of carriers. Shippers can be firms, persons or institutions, who want commodities to be moved from one place to another place, under given conditions. They can organize themselves their transport operations (this situation is referred to as own-account transport: in that case shippers are also carriers) or bind contracts with carriers to do so.

Platooning is a transport technology. As a consequence, the question of whether it has value or not should primarily be examined from the standpoint of carriers. However, it is of critical importance to consider shippers in the analysis: one reason why carriers may adopt a new technology or process is that it allows them to produce services that are a better fit to shippers' preferences. The second reason is that it would allow carriers to produce existing services with a better cost efficiency. Let us discuss here the first reason. In order to determine whether shippers benefit from better services, it is important to understand shippers' objectives and constraints, and their preferences regarding freight transport.

A brief introduction to supply chain management

Shippers manage supply chains. According to the Council of Supply Chain Management Professionals: "*logistics management is that part of supply chain management that plans, implements and controls the efficient, effective forward and reverse flow and storage of goods, services and related information between the point of origin and the point of consumption in order to meet customer's requirements*" (CSCMP, 2013). This definition calls for a number of comments. First, logistics is not just about transport. As a matter of fact, freight transport is but one of the categories of operations that a supply chain manager must plan and manage as a part of their job. Second, while the notion of cost efficiency is not made explicit in the definition, it is of critical importance, as part of the customer requirements, which include cost-efficiency through competitive prices. Third, customer requirements are not reduced to prices. They actually include a host of other criteria, or dimensions, that are regrouped in the concept of level of service (Rushton et al., 2014).

In order to understand where customer requirements come from, the following premise is fundamental: *products only have value to their users when they are in their hands*. It is the job of the firm, public service, or any agent acting as a commodity provider, to define and implement how said commodity will be made available to customers. Will it require a lot of effort from those customers (e.g. they are required to transport the goods themselves, wait for it a long time, have no guarantee as to when the product will be available, etc.) or will the good be made readily available to them (e.g. the goods are delivered at any address given by the customer, very quickly, with a guarantee that there will be no damaged, a forgiving return policy, etc.)? These dimensions of logistics level of service are as important to customers as the intrinsic characteristics of the product[2]. Is should be noted that this representation applies to firms and consumers alike. Firms will base their requirements – and their willingness to pay for those – on how those contribute to their strategic objectives, how they contribute to satisfy their own customers' requirements better, or how they can reduce their own costs; consumers will base their requirements on similar bases, in addition to their own tastes and preferences[3].

Dimensions of level of service include everything related to the way goods are made available to customers, including:

- Shipment size and conditioning: specific equipment is required to load and unload bulk, pallets, parcels, barrels, oversized packages. Some carriers are specialized in specific shipment sizes. Quite often, the transport process is very dependent on shipment size (FTL – full truckload – is direct from origin to destination, while parcel transport relies on a network and mixed fleet process.)

[2] As a matter of fact, this is a particular case of the service-dominant logic, put forward by Vargo and Lusch (2008). According to them, any economic transaction is based on one party providing their skills to another party, whether the deal implies commodities, or not. In fact, those commodities are support of services that they will help to provide (e.g. buying a refrigerator is acquiring the possibility to store fresh products; buying a car is acquiring a capability to move with a certain speed, and/or to display a certain level of wealth, and certain preferences). Within this framework, the consumer is co-creator of value. This says with the vocabulary of marketing exactly the same thing as transport economists say when they say that consumers bear user costs.

[3] This is particularly well explained by the following quote from Jeff Bezos, president of the company Amazon: "I very frequently get the question: '*What's going to change in the next 10 years?' And that is a very interesting question; it's a very common one. I almost never get the question: 'What's not going to change in the next 10 years?' And I submit to you that that second question is actually the more important of the two – because you can build a business strategy around the things that are stable in time. ... [I]n our retail business, we know that customers want low prices, and I know that's going to be true 10 years from now. They want fast delivery; they want vast selection. It's impossible to imagine a future 10 years from now where a customer comes up and says, 'Jeff I love Amazon; I just wish the prices were a little higher,' [or] 'I love Amazon ; I just wish you'd deliver a little more slowly.*'" (https ://techcrunch.com/2017/05/14/why-amazonis-eating-the-world/, accessed May the 30th, 2017.)

- Loading and unloading conditions: some vehicles require specific loading bays, others can be loaded and unloaded from the ground. Some commodities require dedicated handling technologies.
- Transport lead time: this is the transport time as perceived by the shipper. It covers all the stages of the transport operation, including break-bulk operations, transhipments, and temporary storage if any.
- Transport lead time reliability: this is related to how certain the shipper is that the shipment will be picked up and/or delivered at the time agreed upon;
- Commodity safety (against pilfering and damage);
- Tracking: this category relates to all services providing information to the sender or receiver about the current location and/or current state of the shipment, as well as additional information such as estimated delivery time.
- Flexibility: this is related to how early a shipper has to order a transport operation which should happen at a given time. Some freight transport markets can provide a very high flexibility (orders can be placed up to the last moment) while others require a lot of visibility from the shipper (transport has to be planned months before it is actually executed.)
- Loading and unloading time window precision: the shipper may have some flexibility, or some very precise request, with exactly when the shipments are picked up and delivered.

The choice of a logistic strategy dimensions is a complex process. Shippers consider their own constraints (including the geographical, technical, and legal ones); their understanding of the competition's strategy; their understanding of their own customers' requirements and willingness to pay for those; and their own business strategy. As a result, they plan their supply chain strategy, including (but not limited to):

- the number, characteristics, and location of their warehouses;
- the production, distribution and procurement process;
- the marketing strategy;
- the planning, monitoring and forecasting process;
- the nature and characteristics of transport operations.

A micro-economic representation of shippers

From a micro-economic perspective, shippers are producers, providing goods to customers with given intrinsic characteristics and given extrinsic characteristics (including a given logistic level of service). We opt for the theoretical framework of Lancaster (1966): in this paper, Lancaster submits that goods are characterized by a vector of dimensions, on which are based the preferences of consumers. This framework has several qualities, including the fact that it is the theoretical basis for hedonic prices analysis.

Shippers combine resources, including transport operations with given characteristics, in order to provide goods to their customers. The characteristics of these goods are produced in order to match the preferences of customers in a cost-efficient way[4]. Shippers' preferences regarding transport operations are related to the intrinsic characteristics of goods (conditioning and vehicles depend on the nature, weight and volume of goods) as well as on their extrinsic characteristics. This is the case, in particular, of transport lead time, and of course of its price (Tavasszy, de Jong, 2013.) This is illustrated by Figure 1 below.

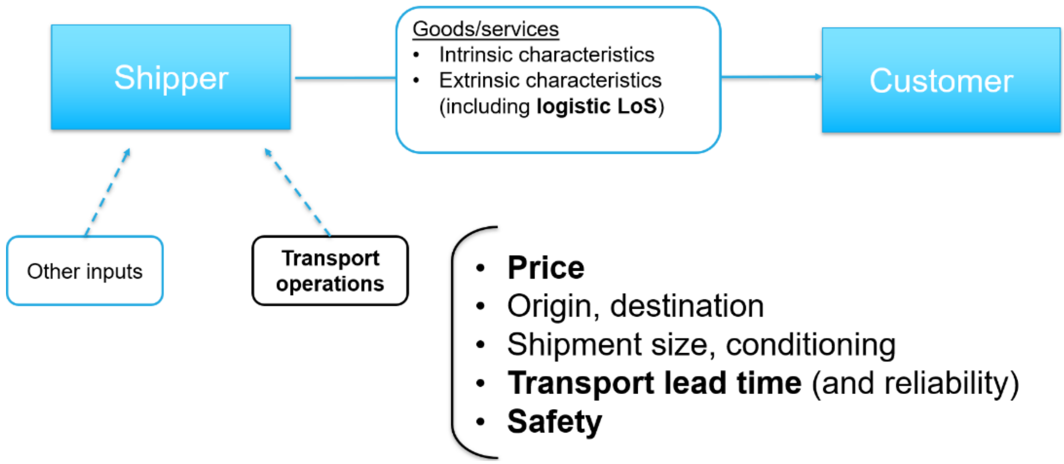

Figure 1: Inputs and outputs of shippers

Shippers and platooning

On the basis of this discussion, how does platooning fit into supply chain management? As stated above, platooning is a transport technology. The following ways it can have an impact for shippers are:

- platooning modifies the price (and the price structure) of transport operations;
- platooning modifies some characteristics of transport operations (e.g. transport lead time, or safety)
- platooning interferes with supply chain management (some decisions of shippers, such as shipment dispatch scheduling, need modification if platooning is used)

[4] The standard microeconomic theory of the producer is presented in all standard micro-economic textbooks, such as Varian (2014).

These items are now reviewed in detailed.

Changes in transport price

A modification of price of platooning can come from a reduction of fuel consumption, or any other cost reduction that platooning would allow (such as, for example, labour cost reduction.) This cost decrease would directly affect the operating costs of carriers, once factored in all the cost modifications and operating modifications. Cost modifications are then transferred to prices. In general, the impact of a modification of costs on prices can be quite complex in the transport industry, as in any network industry. In any case, a decrease of prices will be beneficial to shippers, all other things equal.

Impact on the level of service of transport operations

A change in the level of service of transport operations will also have a direct impact on shippers. One of the important characteristics of freight transport level of service is lead time (and together with lead time: lead time predictability and reliability.) All other things equal, lower lead times are generally a good thing for shippers, which are ready to pay for faster transport.

The shippers' willingness to pay for faster transport, commonly referred to as the 'shipper value of time'[5], is a key parameter for demand forecasting, and financial and socio-economic appraisal of projects or policies. There is a substantial literature on the value, dispersion, and explanatory variables of the value of time for freight transport. The empirical literature is reviewed in Feo-Valero et al. (2011); it displays considerable variability and some level of ambiguity regarding whether the studies account for the shipper value of time alone, or the carrier value of time as well. The review concludes that the type of commodity and shipment characteristics can have a large influence on the value of time, and that this value of time ranges from zero, or a few cents per ton per hour, to several euros per ton per hour. Value of time for palettized goods carried by semi-trailers on highways over long distances (presumably the core market of platooning) would pertain to the higher side of the literature value range. Assuming a value of time of 2€/ton/hour and a shipment of 8 tons, a 10 minutes delay would cost about 2,7€ for the shipper. This is often less than a percent of the standard price for such an operation, but it is a substantial amount when compared to the typical margin of a freight carrier.

Lead time reliability is another important characteristic of level of service for shippers. It is not the same to have a shipment delivered at 10am sharp than to have it delivered somewhere between 9am and 11am. It is consensually accepted that shippers are ready to pay for improved reliability; low reliability is often raised as one of the main reasons why shift from road to non-road modes is

[5] In the frame of freight transport, it is necessary to distinguish the shipper value of time, the carrier value of time, and the total value of time. It is also required to distinguish whether the value is computed over a shipment, or a vehicle movement. The relevant approach depends on the question. When examining how much a shipper would be ready to pay for a decrease in transport lead time, the carrier value of time should not be factored in. When proceeding to the financial or socio-economic appraisal of a public policy or infrastructure project, both the shipper and the carrier values of time should be accounted for.

difficult. Moreover, it is also considered intuitive that the value of reliability is higher for shorter transport lead times. However, empirical research did not yield a robust value or value range of the value of reliability of freight transport. As reviewed in Dullaert and Zamparini (2013), several papers are available, but their methodologies are vastly heterogenous. Also, Dullaert and Zamparini point out that the way reliability is defined and measured seems to have a strong impact on the estimation of the value of reliability. Whatsoever, lead time reliability is important for shippers. As a consequence, it is important to assess whether platooning improves or downgrades lead time reliability. This complex issue is discussed in more detail in the next section.

Changes in the safety of transport operations is also of interest for carriers, and for shippers: less accidents means that the probability that the freight is destroyed, damaged or lost is lowered; also, the lower risk of accident is beneficial for carriers, because their costs decrease; and for drivers, whose exposition to the risk of death or wound is also diminished. Of course, this item depends entirely on the actual safety benefits of the platooning technology, compared to the baseline scenario.

Impact on supply chain management decisions

Freight transport operations are but a small part of the decisions a supply chain manager has to make. Moreover, some decisions pertaining to freight transport have direct interdependencies with other important logistics variables. For example, choices regarding freight transport have direct impacts on inventories: more frequent shipments dispatched from a given warehouse or plant will often allow to reduce average inventory levels, which is generally a good thing for shippers. In practice, decisions regarding freight transportation cannot be examined without considering these interdependencies. On that topic, see Baumol and Vinod (1970), or Combes and Tavasszy (2016).

Regarding platooning, two cases should be distinguished. In one case, shippers do not contribute to the organization of platoons: platooning is transparent for them; it is a technical choice of carriers. However, it is also possible that shippers contribute directly to the organization of platoons.

Consider, for example, the case of a shipper sending one full truckload to one receiver every day. That shipper could decide to dispatch platoons of two trucks once every other day instead. There would be positive impacts on transport costs, but a need to reorganize inventories at the origin and destination, with probable additional logistics costs. In that case, the platoon is essentially a new type of vehicle: instead of one truck with a given capacity, a new vehicle can be used; it consists of two trucks or more, with a higher capacity, and a lower operation cost. There is some literature on the problem of the choice of shipment size and vehicle type (e.g. Abate and de Jong, 2014) however it is not stabilized and still raises fundamental methodological difficulties. That situation is, in practice, quite rare, and has not been examined in detail in the frame of this project.

Conclusion

For shippers, platooning is only a visible issue if they are actively involved in the platoon formation process. In all other cases (which will typically be the case with spontaneous platooning), then platooning is, in essence, a technological change for carriers, with indirect implications such as price and/or level of service modifications. In particular, there are no significant interactions with the supply chain process of shippers, other than the usual ones between transport and other logistics decisions.

As a consequence, it should be considered that platooning can only bring value to shippers if one of two conditions is met: either it improves the productivity of freight transport for a given level of service (in a way which results in a market price decrease), or level of service is improved so as to more than compensated with the change in market price.

The specific case where shippers are actively involved in the planning of platoons warrants a dedicated discussion. There is an important distinction between this case and the previous one: it is theoretically possible that platooning can bring some added value to the shipper and that freight transport costs increase for that same shipper, if this cost increase is more than compensated by the decrease in other logistics costs.

In any event, a general conclusion emerges: platooning will be used by carriers in one of two cases only:

- It brings value to some or all shippers, in the way described above; or,
- it is made partially or fully compulsory.

3.1.2. Carriers

Carriers are economic agents combining resources in order to produce freight transport operations. As explained above, freight transport operations are characterized by a number of parameters collectively defined as the level of service. Shippers are their customers. The preferences of shippers regarding freight transport operations have been discussed at length in the previous section.

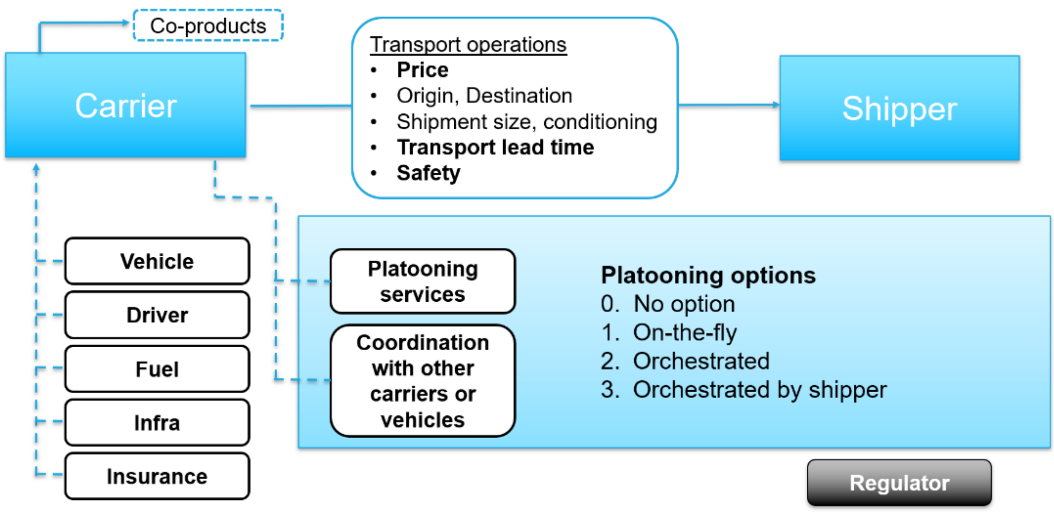

Figure 2: Inputs and outputs of carriers

Figure 2 details the inputs and outputs of carriers, their relationship with a number of other agents, and their specific position with regard platooning. Indeed, while platooning is only a distant issue for shippers, it is a very concrete issue for carriers, as it involves the acquisition of specific equipment and technologies, and the modification of their production processes.

This section first examines the resources consumed by carriers, then the relationships of carriers with other stakeholders, and, eventually, the decisions carriers need to make with regard to platooning. A specific issue with platooning is that the decision of one carrier will have an impact on the preferences of other carriers: this internal interdependency will be the object of a specific focus (see e.g. 3.1.2).

The cost components of carriers, and their dependencies with other stakeholders

The main resources for a carrier are given in Figure 2: they are the vehicle, the driver, the fuel, the infrastructure, and insurances. However, in order to clearly distinguish all the impacts of platooning on carriers, a more detailed cost breakdown has been specifically designed. The cost components are discussed below; at the same time, the impact of platooning on each cost component is examined. The discussion remains qualitative and general. Other parts of the report will provide numerical assumptions, when those are required for quantitative simulations (Chapter 4).

Fuel consumption

Fuel is one of the main components of freight transportation costs, whatever the mode and technology. This is particularly true of road freight transport, and even more of inter-urban road freight transport, which is most often produced with semitrailers. A semi-trailer typically consumes between 30 and 35 litres of gasoil for a 100 km, depending on its load, and many other factors. Fuel consumption easily accounts for about a third of the cost of moving a semi-trailer[6].

As a result, anything able to improve fuel efficiency is a major driver of cost reduction, and will easily find a market. It so happens that this is one of the expected impacts of platooning: by reducing the distance between two vehicles or more in a platoon, the platooning technology would allow for a reduction of the aerodynamic drag of all vehicles in the platoon, although the effect would be stronger for follower vehicles than for the leader vehicle. The actual fuel reduction depends on how much time the vehicles spend inside platoons over their full economic life, and how often they are leaders and followers when inside platoons.

Driver productivity

A second major cost component of all transport techniques is the workforce. For road freight

[6] Transport prices can move quite far from the costs of moving a given vehicle, for several reasons. The first reason is that many transport operations involve a combination of movements of different vehicles and transshipments (this is the case of LTL – less than truckload, or parcel transport). The second reason is that prices can get quite far from costs as a result of the supply-demand equilibrium (Felton, 1981)

transport, there is one driver per vehicle, sometimes more[7]. One manner platooning could generate added value for carriers is if the drivers of the following vehicles in a platoon could do something else than driving, and that this substituted activity generates revenue (the by-products in Figure 2). An additional condition would be that this additional revenue isn't entirely captured by the drivers.

The case for improved driver productivity as a source of added value of platooning is rather weak. In any case, the involved stakeholders are the drivers themselves, and the regulator, which has a say about whether such configurations are allowed or not. Other carriers are also directly relevant, through the formation of platoons.

Operating constraints

There is another theoretical possibility for platooning to bring added value: drivers would rest when they aren't leaders in a platoon. In that case, they may be payed less, or the transport operations could be organized in such a way that the vehicles can move almost continuously while driving time regulations are respected. In other words, the operating constraints on road freight transport would be relaxed. This would yield a direct reduction of transport costs, and the opportunity to lower transport lead times, to the direct benefit of shippers.

These scenarios raise a number of critical concerns, regarding their feasibility, safety and acceptability. For example, a scenario where drivers can get some actual rest while being in a follower vehicle (notwithstanding their own comfort and safety), the question is raised to know why a driver is still needed in those vehicles in the first place. Whether drivers would be ready to proceed to other tasks and to be only partially paid for that, is a second question without a robust answer at the time this report is written.

As above, the involved stakeholders are the drivers, the regulator, and the other carriers.

Reliability

As in many industrial processes, random events happen, and cause processes to deviate from their nominal state. This can result in unreliability in the output production, which comes with a large number of costs, as it makes it difficult for customers to rely on deliveries, and it makes it difficult for firms to adapt tightly their resources to their needs.

Unreliability can be addressed by adapting processes in a number of ways. One way is to reduce the epistemic uncertainty of events by getting more information and improving prediction. Another

[7] Inter-urban road freight transport is typically organized in three different ways in terms of workforce. The first and dominant one is when there is one driver per vehicle. Then, the driver is limited by driving time regulation, and so is the vehicle. In some cases, there can be two drivers per vehicle; drivers can rest alternatively while the truck moves on. This make it possible to vastly decrease transport lead times over long distances (more than 700km, i.e. more than 8h at 90km/h). Another way to circumvent the driving time regulation is to setup relays, where drivers board vehicles, drive 4 or 8 hours, then alight; with a suitable organization, it is possible to have the trucks operate continuously with only one driver on board (Combes and Leurent, 2013.)

way is to adapt the process to make it more robust to those random events, in other words to reduce the severity of the consequences of the realization of those events. For the case of transport, travel time is often unreliable: a series of largely unpredictable events can cause a truck to deviate from its planned temporal trajectory: mechanical trouble, traffic jams, accidents of other vehicles, late departure time, etc., will interfere with the nominal travel time and often cause the truck to arrive late. The consequences can be mitigated by introducing buffers: instead than announcing that the truck arrives at the nominal time h_n, which will be missed with probability π_n, the carrier can announce that the truck arrives at time $h_n + b$, which will only be missed with probability $\pi_b < \pi_n$. Increasing b increases the expected transport costs

Regarding platooning, the question is: how is the travel time distribution of a given vehicle modified (in shape *and* position) when it gets into a platoon? Platooning introduces a necessary synchronization between the movements of distinct vehicles: the trucks which are supposed to get together to form a platoon. This comes at a double cost in terms of reliability:

- first, the interaction increases the severity of the consequences of a random event. Consider a platooning process, where trucks have to meet, move together and then separate. Compare that process to the baseline process where all trucks are moving independently. Assume that a random event impacts any of these trucks: delay, mechanical incident, etc. In the baseline process, chances are that the other trucks will not be impacted. In the platooning process, all trucks can be impacted. If the platoon is planned to be formed but isn't formed yet, the formation plan has to be delayed or modified; if the platoon is already formed then it has to be rearranged.

- Second, the interaction is also a random event in itself: in particular, platoons which are formed on the fly require at least one vehicle to slow down until the other vehicles catch up. This introduces a random delay in transport operations for that vehicle, given that on-the-fly platooning is, by definition, unscheduled.

All in all, introducing the platooning process inside transport operations is both the introduction of a new source of variability, and an increase in the system vulnerability to variabilities. This does not lead to the automatic conclusion that platooning should not be implemented, but it is a clear disadvantage of the technology, liable to increase costs and to decrease level of service. Carriers will have to account for that in the decision to use platooning or not, and protect themselves against it if needed to.

The intensity of the impact of platooning in terms of reliability depends on the number of carriers adopting the platooning technology.

Probability and severity of road accidents

Road freight transport causes accidents. The less severe cause damage, to the infrastructure, the vehicle and the freight, and possibly to other vehicles. The more severe accidents also cause wounds and casualties. The probability of accidents, and their severity, is directly relevant to carriers, as they bear a substantial share of the implied costs, even when they are insured. More frequent accidents cause also a loss in terms of level of service for shippers; in other words, more safety means more added value for carriers.

Platooning may generate additional safety, either by reducing the probability of accidents, or by reducing their consequences when they happen. This issue is not analysed in detail in this report. However, it is considered, qualitatively, with regard to carrier costs. Note that with respect to this issue, as well as others, it is extremely important to keep in mind that the benefits of platooning should be assessed in comparison with a relevant baseline scenario. That baseline scenario should include the arrival on the market of trucks equipped with new technologies improving safety too.

The intensity of the impact of platooning in terms of safety would also depend on the number of carriers adopting the platooning technology.

Insurance

If platooning has a substantial impact on safety, carriers and shippers will perceive this indirectly through a change in their insurance costs. Indeed, the core service of insurance companies is to provide covering for risks through pooling: while the consequences of one accident can be unbearable for a given individual, family or firm, they are manageable if a large group of agents pool financial resources together. Also, insurance companies set up incentives for agents to behave so as to decrease their exposition to risks, through the conditions of the insurance policies they provide and financial incentives.

As a consequence, if insurance companies are convinced that, with a sufficient market uptake, platooning can provide decisive improvements to road freight transport, compared to other technologies (optional or compulsory) over the relevant time frame, then it is probable that they will adapt their policies in order to maximize said market uptake. This means that the cost of insurance will change for carriers, with respect to whether they buy platoon-enabled trucks or not, and whether they actually use the platooning service, or not.

Vehicle cost

From a carrier's standpoint, vehicles are one of the main cost components. The cost of a first-hand tractor unit is on average 88000 € in France in early 2020 (Comité National Routier, 2021), and a semi-trailer's cost is on average 28000 €. The ability for a truck to platoon comes at an additional fixed cost: the truck needs to be equipped with sensors, actuators and software, which all imply specific fixed costs. Therefore, carriers are in front of a decision: whether they purchase trucks which can platoon, or not. This decision is quite complex, because buying platoon-enabled trucks only gives the guarantee that trucks can platoon, not the guarantee that other trucks will be readily available to form platoons along all roads, at all times. In other words, the carrier must pay a certain price for the uncertain possibility of some value, which depends on the decisions of other carriers.

For carriers, this value will depend on:

- The economic life duration of the truck and its residual value (the value it will have on the second-hand market once the truck isn't useful to the carrier anymore; residual value of the platooning technology on the second-hand market);
- The savings carriers expect from platooning: this is discussed in the items above regarding fuel savings, productivity impacts, insurance costs, etc.
- The expected market uptake: the value carriers draw from platooning trucks is directly dependent on the market share of platooning, i.e. on decisions made by other carriers.

Due to the last item, carriers' decisions are characterized by complex, strategic interdependencies.

In addition, the platooning service provider may have an influence on vehicle cost as well, depending on the business model, who pays for the platooning specific equipment, and how it is priced.

The platooning service provider

By definition, platooning consists in synchronizing the trajectories of several vehicles. This synchronization is needed at several stages. An operational synchronization is required for platoons to be technically, safely feasible. A strategic synchronization is also, in order to find candidates for platoon formation and match them, and compensate them if needed for their contribution to overall savings. Such a service will be costly and requires a business model which will rely, one way or another, on financial transfers from carriers. In other words, making the platooning service provider work will be costly for carriers.

Tolls

Many countries have tolled highways. When this is the case, tolls can be a rather significant part of carriers' costs. Tolls are an income for private infrastructure managers. The question regarding platooning is then: would tolls depend on whether carriers use the platooning technology or not? Regarding the decisions of carriers, any difference of toll implied by platooning will be factored in.

Taxes

All cost components of carriers are affected by taxes: vehicle costs, fuel costs, wages, tolls, are directly influenced by generic or specific taxes. Generic taxes include labour taxes[8] and added value tax. Specific taxes include excise taxes on fuel or vehicles. Technically, taxes are factored in by carriers in their decision-making process. Regarding platooning, the main question regarding taxes is how they change depending on the decision of carriers to buy platoon enabled trucks or not. One

[8] Labor taxes can differ widely from country to country. Also, in some countries, such as France, there is a formal distinction between taxes and charges – such as social security charges. Taxes are understood in a general sense here, and refer to any kind of compulsory levy.

of the most complex and strategic underlying issue is the determination of taxes by governments and other relevant stakeholders. This will be discussed in the relevant section.

Compensations and tariff equalization

A specific issue of platooning is to ensure maximal participation and value. This is not a trivial issue, insofar as depending on the position of a vehicle in the platoon, the direct benefit will not be the same. Typically, for spontaneous platooning, the immediate cost savings will be low for the leader and much higher for followers (in other words, why would a truck slow down to wait another truck to form a platoon if they're not going to benefit from doing so?) Without an equalization mechanism, the incentive will not be high enough for vehicles to be leaders, which can lead both to opportunistic behaviour, to a lack of candidates to be platoon leaders, to a lack of platooning opportunities, and ultimately to a substantially decreased value and market uptake of platooning.

Summary: cost drivers and stakeholders

The discussion above is summed up below in a list which reminds all the cost components. For each cost component, directly relevant stakeholders are identified (**OEM**: Original Equipment Manufacturers; **U**: drivers; **C**: carriers; **R**: regulator; **I**: insurance companies; **PSPs**: Platooning Service Provider(s); **IM**: Infrastructure Managers). The list reads as follows: fuel consumption is the result of choices made by OEMs, whose technical decisions determine the fuel efficiency of vehicles; etc.

- Fuel consumption ← **OEM**
- Driver productivity ← **U** + **C** + **R**
- Operating constraints ← **U** + **C** + **R**
- Reliability ← **C**
- Probability/Severity of accidents ← **C**
- Insurance ← **I**
- Vehicle cost ← **OEM** + **PSP**
- Platooning service cost ← **PSP**
- Tolls ← **IM**
- Taxes ← **R**
- Compensation ← **PSP**

It appears from this list that carriers are at the nexus of stakeholder interactions and of the platooning market in general. As explained above, the value of platooning will be assessed by carriers with respect to the impacts on costs (listed above) and also with respect to the impact on the value for shippers.

Repercussion of the impacts of platooning onto shippers

The impacts of platooning for shippers has already been discussed in detail in a previous section. It is re-examined below with a complementary perspective: regarding platooning, through which channel does each cost position impact shippers? Four channels are listed: price (**P**), environmental impact (**E**), Lead time and lead time reliability (**L**), shipment safety (**S**). The list reads as follows: fuel consumption has an impact on prices, as well as on environmental impacts (through GHG emissions and local pollution); etc.

- Fuel consumption → **P** + **E**
- Driver productivity → **P**
- Operating constraints → **P** + **L**
- Reliability → **P** + **L**
- Probability/Severity of accidents → **P** + **S**
- Insurance → **P**
- Vehicle cost → **P**
- Platooning service cost → **P**
- Tolls → **P**
- Taxes → **P**
- Compensation → **P**

Consistently with this list, and as already explained previously, a variation of costs due to platooning is transferred through a variation of prices to shippers. This is true insofar as there is a real variation of prices, stemming directly and exclusively from the implementation of platooning. For example, shippers will perceive no impact of a change in taxes on freight transport prices if the corresponding taxes are defined regardless of the implementation and usage of platooning.

Changes in level of service will be accounted for by shippers as well: for example, a deterioration of lead time or lead time reliability means that shippers will not be ready to pay as much for freight transport, all other things equal. On the contrary, if safety is actually improved by platooning, then shippers will pay more for safer freight transport operations. Ultimately, shippers may put a value to fuel savings that goes beyond the mere financial expense, for a number of reasons, including: the actual objective to reduce their environmental impact, the need to advertise environmental efforts, the need to reduce their exposition to the political or financial risks associated to fuel prices and/or climate change, etc. Needless to say, the valuation of those impacts differs widely from one firm to another.

Be that as it may, carriers pay attention to the impacts of platooning on shippers, because changes in prices due to changes in levels of service are going to affect their turnover. The common assumption of perfect competition assumes that freight carriers draw a zero profit at the competition equilibrium. The implementation of platooning is liable to cause changes in prices and levels of service: carriers will opt for platooning only if the difference in level of service implies a difference in willingness to pay which more than offsets the difference in marginal costs. Here are too opposite examples, to illustrate the mechanism:

- Platooning implies a net cost decrease for carriers, but travel times deteriorate so much that the decrease in the willingness to pay of shippers more than offsets the cost decrease: each carrier would be better off not opting for platooning; the platooning technology will not penetrate the market.

- Platooning implies a net cost increase for carriers, but safety improves so much that the additional willingness to pay of shippers more than offsets the increased price they have to pay: each carrier would be better off opting in; the platooning technology will penetrate the market.

This very simple reasoning shows how the effects of platooning transit from carriers to shippers, and why carriers account for monetary effects which, at first glance, would appear to be outside their financial perimeter. This relevance of user costs (the users being the shippers) is a classic configuration in transportation economics.

Two very important facts are ignored with this reasoning, and must be paid specific attention to. First, the value of platooning for each carrier depends on how many other carriers opt in. This non-trivial market mechanism known as the club effect plays a central role in the market structure of the platooning technology. Second, governments may influence the market uptake of platooning for diverse reasons including the presence of externalities. These two points are discussed later on.

Carriers decisions and market uptake

As highlighted above, carriers are central to the question of platooning uptake. In order to fully understand their role in the platooning market, it is necessary to describe precisely the actual decision-making process of a carrier. This is a two-stage process: first, carriers decide whether they purchase platooning-enabled vehicles; then, they decide whether their trucks form or join platoons, each time a situation arises where such a decision has to be made. The classical approach in microeconomics is to first examine the latter (or lower-level) decision and then the former (or higher-level) one.

Decision to form or join a platoon (conditional to a vehicle being equipped)

Assuming a given vehicle is equipped and has to transport a given shipment or set of shipments from a given set of origins to a given set of destinations, within a given time frame, the carrier may be presented with opportunities to form or join platoons. They will do so if and only if the benefits outweigh the costs. The benefits will derive primarily from fuel savings for followers, and possibly from compensations by the platoon service provider, or from taxes or subsidies. One should distinguish the platoon formation protocol:

- Spontaneous (or on-the-fly) platooning: trucks are already on their routes. Joining or forming a platoon will come with coordination costs (either time loss, or detours, or both). The expected cost of these opportunities will decrease if there are more opportunities: there is a club effect.

- Orchestrated (or scheduled) platooning: one firm decides to synchronize truck movements; or several firms collaborate to synchronize truck movements. In that case, synchronization also comes with a cost, but a higher number of participants means more opportunities, and lesser expected costs: there is a club effect as well.

In any event, this decision is appreciated by carriers on a case by case basis: the fact that a truck is able to platoon doesn't automatically entail that it will join platoons all the time. However, this decision is appreciated without considering the fixed costs of having a platoon-enabled truck. The platooning service provider costs must also be considered, but only if they are priced on a trip or distance basis. If they are priced on another basis (e.g. fixed yearly subscription) then they need not be considered.

Decision to purchase a platoon-enabled truck

The decision to purchase a platoon-enabled truck is taken when the need comes, for a carrier, to replace a vehicle in their fleet, or to extend their fleet. This decision is based on the assessment, by the carrier, of the expected costs and benefits of platooning for that vehicle, *over its relevant life cycle (i.e. from its entry to its exit of the carrier's fleet)*. This includes the residual value of the vehicle at the end of its relevant life-cycle. In other words, the carrier will make their decision on the basis of their expectation of the value of the platooning technology, and the state of the market for second hand trucks.

In the frame of this decision, all costs are relevant, including the vehicle purchasing costs, and all costs coming from platooning service providers. In addition, the expected activity of the truck is particularly relevant, as well as the decisions of other carriers. For example, if the carrier expects to use the new truck on a wide, interurban, heavily trafficked network where there will be many opportunities for platooning, the expected benefit of platooning will be much higher than if the carrier expects to use the new truck on a regional, low trafficked network, over rather short distances. The interaction between the decisions of carriers (club effect) will not have the same nature and intensity depending on the anticipated usage of vehicles.

Focus on the club effect

As already discussed above, one of the most important and complex economic characteristics of the platooning technology is the interdependency between carriers' decisions. The club effect refers to a particular situation where the value of one good for one agent depends on the number of other agents choosing to consume that good. More formally, a club good is defined as a non-rival, excludable good: it is non-rival insofar as one agent consuming the good does not prevent another agent from consuming the same-good; and it is excludable, in the sense where it is technically possible to exclude some agents from consuming that good. Club theory was introduced in Buchanan (1965), raising many questions related to the size of a club (i.e. number of agents in the club), the size of the underlying facility (i.e. the cost and characteristics of the good which is shared among members of the club.) A considerable literature followed, with many practical public policy implications. Indeed, public goods are often shared, and present economies of scale which makes sharing more cost-efficient. Public policies can aim at increasing access to some club goods (this is, in a way, the objective of subsidizing public transportation), but must sometimes manage congestion (a characteristics of many club goods). Sometimes, club goods are supplied by private companies, and in those cases, the market structure naturally emerging may be considered as undesirable and require regulation.

In any event, the value of platooning clearly increases with the number of platooning-enabled trucks on a given network. This comes with three intuitive conclusions:

- First, there is a positive feedback loop, where the more carriers decide to opt in, the more platooning will be seen as valuable by other carriers.
- Second, it is very probable that there is a critical "mass", or threshold, which needs to be overcome for any significant market uptake to actually take place. In other words, the positive feedback loop can turn into a vicious circle maintaining platooning candidates out of the market.
- Third, multi-brand platooning makes sense both from a private and a public perspective, provided multi-brand platoons provide similar levels of performance as mono-brand platoons. Indeed, multi-brand platooning allows the economies of scale of platooning to expand outside the platooning submarkets consisting of the vehicles produced by each OEM.

Platooning is an economic issue, with a distinctively geographical dimension. It is actually very difficult to assess exactly how the transport demand geography and transport infrastructure topography influence the economic feasibility of platooning; however, one can qualitatively submit that some network configurations are more favourable than others. Some of those cases are illustrated in Figure 3 below.

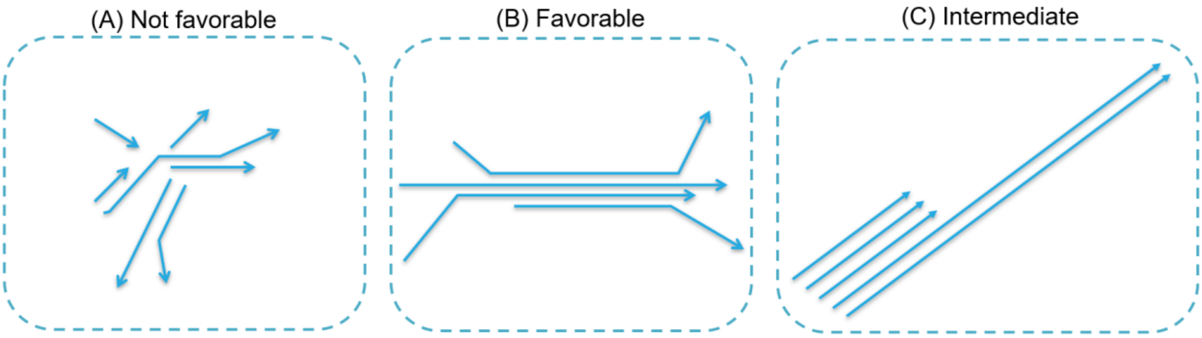

Figure 3: Infrastructure network configuration and platooning economic feasibility

Case (A) is the least favourable case for platooning: the network (not represented) is mostly grid-like, without a main corridor, and truck origins and destinations are almost isotropic. Truck trips are short too. The opportunities for platoon formation are scarce, and the benefit of platooning would be very low for carriers. It is probable that only few carriers would equip their trucks with the platooning technology. On the opposite, case (B) is the most favourable case for platooning: the infrastructure network is a long corridor, through which almost all trucks travel, and those trucks make long distance trips. There are a lot of platooning opportunities, and the coordination costs remain low. In addition, due to the trips' lengths, the benefits of platooning are maximal: this is an optimal spatial context for platooning. Case (C) is somewhere in between: the fact that all trips share a common direction weighs in favour of platooning, but the value of platooning will be limited for all the vehicles making short trips. The market can easily fall on one side or the other: either platooning extends to the full market, and its benefits will be very high for long distance trips; or the short distance market doesn't opt in, and the long market will be less efficient.

3.1.3. OEMs

Platooning is very directly relevant to OEMs as they design and build the vehicles that could ultimately be part of platoons. From the OEMs' perspective, platooning is an optional feature new trucks can, or cannot, be equipped with. The question for each OEM is then: should this option be made available to customers? And if yes, what should its price be? This question should be examined with respect to three distinct dimensions: the direct advantages and disadvantages for one OEM of deciding to make the option available, all other things equal; the expected strategy of competitors; the question of interoperability (multi-brand platooning).

- Expected costs and benefits: building platooning enabled trucks implies two types of costs. First, the fixed costs of research and development. Second, the per vehicle cost of including the corresponding equipment. The price and market uptake have to be sufficient to cover the initial investment and ongoing production cost for the OEMs. The price has to be lower or equal to the added value of platooning for carriers, otherwise the option will not sell[9].

- Strategic interaction of OEMs: due to competition, the price cannot increase much more above the average cost of platooning per vehicle. Indeed, according to classic economic theories of industrial organization, under perfect competition, prices must equate marginal costs. Under the general assumption that there are fixed costs, this result cannot hold, as each firm would make a negative profit. Under the specific assumption of horizontal differentiation and monopolistic competition, it is known that average costs must equate turnovers at the static market equilibrium with free entry (Anderson et al., 1992).

- Interoperability: multi-brand platooning brings more value to carriers than mono-brand platooning: opportunities to form platoons are more frequent, and the expected cost of platoon formation costs are lowered. However, the question of whether it is strategically sound for each OEM to provide an interoperable system is not as trivial as it seems[10]. The literature concludes that private incentives regarding compatibility may deviate from social incentives[11] but as with many issues characterized with positive feedbacks, it is very difficult to predict the spontaneous market behaviour in absence of regulation. It seems worthy to point that the regulator should, if not strongly enforce full compatibility, at least monitor closely the issue. It is not possible to submit a general doctrine for the regulation of this issue, but it should be noted that it depends, at least, from the relative market shares of the OEMs, from the costs of ensuring compatibility, and from the potential loss in terms of level of service for customers due to compatibility[12].

[9] More precisely, with variable demand, the expected additional turnover (function of both the price and market share – said price and market share being functions of one another) must cover the additional costs, otherwise the OEM will decrease their profit by offering the option at said price. In the rest of the deliverable, for the sake of simplicity and due to lacking information, it is simply assumed that platooning is sold for the same price for all vehicles, and that there are no fixed costs for carriers.

[10] The question is that of network externalities and compatibility. The concept of network externalities refers to the presence of an increasing value of a particular type of good for its users, when more users procure the same type of good (it is similar, to a very limited degree, with the concept of economies of scale). Producers on a market may have an incentive to produce goods which are compatible with the competition, because it increases the hedonic value of their goods; they can also have an incentive to produce incompatible goods, because doing so could reduce their market power. The concept of network externalities was introduced by Katz and Shapiro (1985), together with first conclusions regarding private and public incentives to provide compatible goods or not, and first steps towards the identification of market failures. The literature then grew considerably, and an overview is available in Shy (2001).

[11] In other words, OEMs could prefer to provide incompatible or partially compatible systems where fully compatible systems would be preferable from a social welfare standpoint.

[12] Said costs and level of service loss can come from additional development time if development requires coordination between OEMs; additional time to deploy software updates if those updates have to be developed in coordination between OEMs; and reduced performance of the platooning system if the requirement that the system allows multi-brand platoons comes with additional safety margins, and if those additional margins imply lowered gains.

3.1.4. Platooning Service Provider(s)

Platooning service providers are the firms in charge of providing some of the services required for platooning to work and provide value to carriers. There are several of these requirements. At least two of them are instrumental to the market uptake of platooning:

- Matching: it is the role of the PSP to identify adequate candidates to platooning. Irrespective of whether the case of orchestrated or on-the-fly platooning is considered, the PSP need information about the routes of the candidate trucks.

- Compensation: it is a particular feature of platooning that its benefits are absolutely not evenly distributed among trucks at all. In the worst-case scenario, the leader truck waits for the follower truck, the platoon is formed, then the follower truck leaves the platoon and the leader truck resumes its trip: all costs are borne by the leader truck, whereas the follower truck reaps all the benefits. Clearly, if no compensation mechanism is instated, the leader vehicle will never accept to wait for the follower vehicle, the platoon won't be formed, and there will be no platooning. A mechanism of compensation is, therefore, an absolute requirement.

The exact structure of the compensation scheme requires a specific analysis. A simple compensation scheme, where benefits are evenly shared, was assumed in this deliverable when it was necessary to specify one for modelling purposes. Undoubtedly, PSPs will design and test more innovative and sophisticated models, which should improve the value of platooning for carriers. However, PSPs will have costs which were also ignored in this deliverable; those costs need be covered for PSPs to draw a positive profit, otherwise they would exit (or not enter) the market.

From an economic perspective, PSPs aren't only a necessary agent to the platooning market; they are also the vector through which part of the gains of platooning are transferred to carriers. While they can transfer those gains in a clever and sophisticated way, it is important to keep in mind that they will not multiply them. PSPs are facilitators; but the core value of platooning lies elsewhere. Also, from economic theory, PSPs will be perfect facilitators (meaning that they will not subtract from the gains of platooning more than what they require to operate) in a context of perfect competition. If the structure of the PSP market is oligopolistic or monopolistic, it is probable that the uptake of platooning will be reduced. In addition, for the same reasons as those discussed with respect to OEMs in the previous section, it is not an absolute guarantee that PSPs will spontaneously decide to be compatible with each other. The regulator should monitor that issue as well.

Note that the analysis above doesn't presume that PSP should be independent firms, or part or subsidiaries of other firms (e.g. OEMs).

3.1.5. Insurance companies

The role of insurance companies will not be discussed in detail in this deliverable. The unique aim of this short section is to discuss briefly how insurance companies could be a vector accelerating the market uptake of platooning – under the condition, which remains to be proven in general (and is outside the scope of the ENSEMBLE project in particular) that platooning comes with specific, robustly identified improvements[13] to safety. Assuming this is the case, insurance companies can instate monetary incentives for carriers to equip their trucks with the platooning technology. Those incentives could (and probably should) depend on how often the trucks are part of platoons (this requires some form of monitoring, together with, probably, a number of technical and legal challenges.) Therefore, carriers would receive a signal of (part of[14]) the impact that they would have on road traffic safety by adopting the platooning technology and actually using it. In addition, one could argue that insurance companies are better informed and equipped to quantify that impact. As a consequence, and, again, assuming that platooning comes with specific safety improvements, insurance companies can also be a vector of these improvements, and improve the market uptake of platooning.

3.1.6. Infrastructure managers

Infrastructure managers (IM) are essential stakeholders of transport systems, as they provide access to, and maintain, the physical and technical assets which support transportation. Their primary objective is to provide safe, reliable and efficient pathways. They can also, depending on the transport system, provide information, energy, and even take an active role in determining what vehicles do and where they go (this is the case of the railway system, for example). In addition, they may condition right-of-way to payment of tolls. Those tolls can have different roles, such as financing, or demand regulation.

Demand regulation is to be understood in its widest sense here. Pricing for demand regulation is often based on the theoretical idea that the "right price signal" should be advertised to users so that they internalize the actual cost of their decisions, including externalities. Said externalities are typically: congestion, safety (insofar as it is an externality), GHG emissions, local pollution, noise, wear-and-tear (insofar as it is not already included in tolls), etc. From this standpoint, infrastructure managers should be considered as a vector for the implementation of governmental regulation, which is discussed thereafter.

Regarding platooning, the position of infrastructure managers is not trivial, and covers several directions:

- Regarding infrastructure funding: road project funding can rely, partly or fully, on public-private partnerships (e.g. concession contracts), where users ultimately contribute to the investment and maintenance costs of the roads. The determination of how the total cost is shared between public and private funders involves a wide range of varied considerations, among which the maximal turnover the infrastructure can generate. This turnover depends on the maximum throughput of the infrastructure and its level of service for users. Platooning

[13] In this particular case, "specific" means, strictly speaking, that platooning provides safety improvements that cannot be provided by the alternative technologies which will be made available or compulsory over the time frame of the analysis.

[14] Not all of the damages caused by a road accident are, or even can be, covered by insurance companies.

may modify this maximum throughput and level of service, by an improvement of traffic fluidity for example. As a consequence, trips would be faster, throughput higher, and travel time reliability better. This would certainly have an impact on the funding scheme of the infrastructure and the user charge. Given the complexity of the issue and its contingency to many unpredictable exogenous factors, this mechanism isn't further discussed or analysed in this deliverable.

- Regarding infrastructure investment and maintenance costs: platooning can have a direct and indirect impact on those cost positions. First, if platooning has an impact on infrastructure dimensioning and/or equipment in order to reduce wear-and-tear or to resist the consequences of accidents, infrastructure managers will legitimately consider platooning as a potential source of cost increase. Second, if platooning is proved to improve safety, this can come with cost reductions for infrastructure managers.

- Regarding I2V communication: if infrastructure managers are required to equip specific parts of their infrastructure network, and develop the assorted information systems, in order to be compatible with platooning, then platooning will be considered as a source of costs, to be balanced with other advantages and disadvantages in their decision process.

- Regarding rest areas: infrastructure managers may be required to adapt the layout of rest areas in order to be compatible with platooning, if the platooning formation protocol assumes that platoons are constituted in rest areas.

Platooning is a complex issue for infrastructure managers, even from a purely economic and financial perspective. There are in fact two types of issues: the first one pertains to transport regulation in general. While it concerns infrastructure managers very directly, it is not per se an infrastructure management type of issue. It is discussed thereafter. The second type of issues regroups all the questions which are of direct concern for infrastructure manager and which are at the core of their activity. The brief discussion above lists some of them, and presents some of the underlying questions. Further work will undoubtedly be necessary to accompany the large-scale implementation of platooning.

3.1.7. Regulator

The regulator refers here to all the agents and institutions in charge of writing, implementing, and monitoring the regulations ruling the transport system. The action perimeter of transport regulation is wide, extremely complex, implies a host of public agents of diverse competences, and is at the intersection of varied, sensitive and often misaligned public policy issues.

The first role of regulation regarding transportation is to authorize things. Underlying issues of safety are examined elsewhere in the project and shall not be discussed here (including working time regulations.) As far as this deliverable is concerned, the main issues regarding platooning are:

- Should the deployment of platooning be supported by regulation, and if so, how?
- If platooning interferes with public policy objectives (either positively or negatively), should the regulator react, or adapt?

Two domains, where regulators have ground to act regarding platooning, are discussed below: externalities, and market structure.

Externalities

Platooning is basically a technical improvement of road freight transport allowing to reduce the cost of transportation. However, several of its characteristics are relevant to important dimensions of public policy, especially regarding externalities. How regulators should react depend, on one hand, on the intensity of the differential[15] impact of platooning on externalities; on the other hand, on the current state of policy instruments already in place to internalize said externalities. Regarding the intensity of externalities, platooning impact should be fairly limited. Also, while the situation varies vastly from one country to another, there are already taxes and norms which, at least partly, have the effect of internalizing some externalities.

Regarding interurban road freight transport, the question about whether it “covers its costs” (meaning its marginal social costs) has been the object of a lot of literature. Be that as it may, there are taxes, charges, tolls, and norms already in place in the European Union. While it is not possible to state rigorously that the externalities of road freight transport are fully and precisely internalized in all member states, it isn’t reasonable either to assume that no such instruments are implemented. As a consequence, one shouldn’t compute the marginal external benefit of platooning and submit that platooning should benefit from that amount as a subsidy, disregarding the current level of taxes, charges and norms. For example, assuming that platooning would allow for a decrease in fuel consumption: in countries where fuel taxes are reasonably close to the marginal external cost of GHG emissions and pollution, no further action would be required.

Jobs and unemployment aren’t part of the externalities typically looked at when evaluating the impact of an innovation in the frame of a standard transport cost-benefit analysis. However, if platooning goes into a direction where significantly less drivers are needed, the impact it would have on the trucking workforce will become an important issue for policymakers[16].

Finally, regulators are interested in the impact of an innovation on public finances. This impact is to be expected if the innovation of interest is expected to modify tax revenues or subsidy expenses substantially. In the case of platooning, theoretically, one would expect a differential impact in terms

[15] As always, the impact of platooning should not be assessed in absolute but with respect to the counterfactual, i.e. the situation that would prevail without platooning.
[16] Despite the lack of visibility regarding when autonomous vehicles will become available for freight transportation, the impact on the job market has already been under close scrutiny. See, for example, OECD-ITF (2017).

of fuel tax revenue, and possibly a differential impact in terms of work taxes revenue, depending on how exactly platooning is implemented.

From the perspective of the regulator, the impacts of platooning in terms of its external effects is summed up as follows:

- Fuel consumption → **E**
- Driver productivity → **Emp**
- Operating constraints → **Emp + S**
- Reliability (→) **C**
- Probability/Severity of accidents → **S**
- Taxes → **F**

where **E** refers to the environmental impacts of freight transport in terms of pollution and GHG emissions; **Emp** refers to employment; **S** refers to safety; **C** refers to congestion; and **F** refers to public finances.

Market structure

The economic nature of the platooning technology makes it a specific market, subject to network externalities. As discussed above, this raises a number of issues which call for public action or, at least, monitoring by the regulator. There are three specific questions:

- Market uptake: it is a necessary (although not sufficient) condition that, for platooning to bring value to carriers, enough trucks be equipped with the platooning technology. This classic network externality can theoretically yield an inefficient self-fulfilling prophecy where every carrier is convinced that none of its competitors will use the technology, and thus won't equip their trucks. More realistically, even where there is unambiguous, actual value to platooning from the perspective of carriers, the market uptake can be slower than ideal because some carriers will prefer to wait, thus reducing the overall value of platooning during the transient stage where the technology spreads. Also, the market share of platooning can stay below its ideal value because some carriers, which find platooning almost profitable, will decide not to equip themselves, without considering the fact that their decisions reduce the value of platooning for the others. This mechanism is typical of network externalities and also of transport systems (Mohring, 1972), and gives grounds to a subsidy of platooning, both in the transient stage (to "kickstart" the market) and in the market maturity stage.
- Multibrand platooning: as explained above, a technology with network externalities brings maximum value to the society when everyone opts for a product which is compatible with all

other. However, it is not necessarily the case that the market will converge towards full compatibility, and many equilibria are theoretically predicted, and empirically observed, where free competition leads to only partially compatible or even fully incompatible products. This gives grounds to the regulator to monitor the market and potentially implement relevant actions.

- Monopoly: on the other hand, there are classic issues associated with monopolies, including inadequate pricing. Assuming the platooning technology is widely adopted, relevant action will depend closely on what actually happens and what the market structure becomes.

Synthesis

Regulation is not a core question of this deliverable. However, regulators are an important agent of all transport systems. Therefore, it is required to examine the regulators' issues and, as far as possible, to extrapolate their probable courses of action. As briefly sketched in the short discussion above, platooning isn't a trivial topic from the perspective of regulation. Perhaps surprisingly, the issue of market structure (i.e. how and when the technology will spread, and what to do about it, at all stages) is probably much more important than the topic of road freight transport externalities. Indeed, regarding the latter point, platooning isn't neutral regarding the externalities of road freight transport; but that doesn't mean that this requires specific action regarding platooning on those grounds.

3.2. Stakeholder interactions

The discussion in the previous section illustrates the complex interaction between all the stakeholders involved in platooning. A host of agents of different natures, preferences and constraints are interacting in and around the freight transportation system in an intricate way. The objective of this section is to disentangle these interactions and provide a rigorous overview of the direct and indirect effects of platooning, with the objective to identify direct and indirect drivers and obstacles to platooning market uptake.

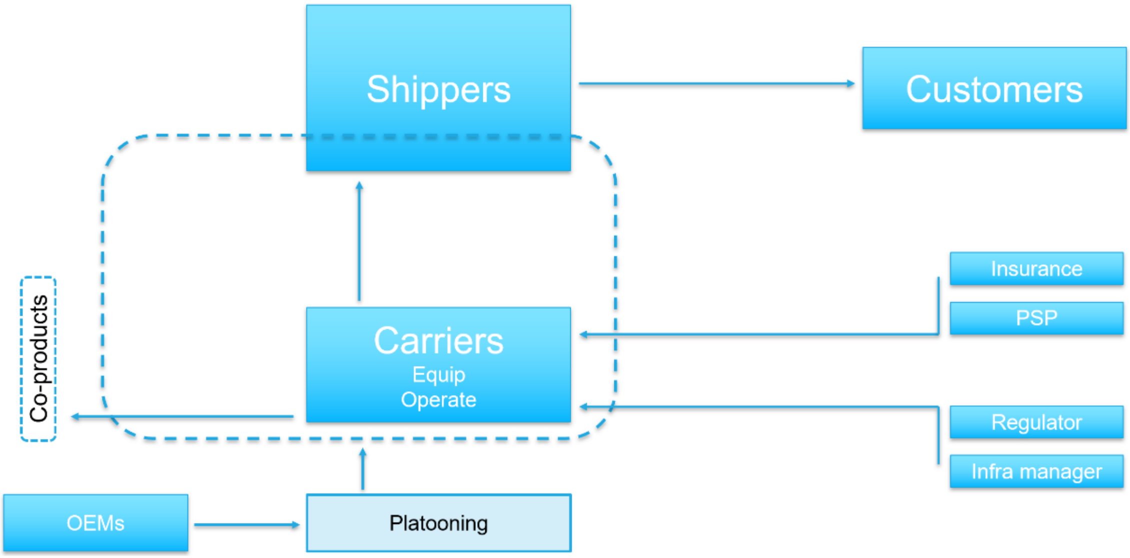

Figure 4: Stakeholder interaction w.r.t. platooning in the freight transport system

Figure 4 recapitulates the interactions of stakeholders in the freight transportation system. Each stakeholder category is represented by plain rectangles; arrows represent supplier-customer relationships (except for the regulator, which is not a supplier per se, but provides regulations). Platooning is made explicit as an element between OEMs and carriers: it is a technological characteristic of the vehicles which will be acquired by carriers. Figure 4 also makes explicit the most relevant decisions of carriers with regard platooning: equipping themselves (in vehicles) and operating those vehicles.

The production chain is rather straightforward: OEMs provide trucks to carriers which use them (and other inputs) to produce freight transportation (and co-products) to shippers. Shippers use freight transportation as an input to their own value chains, which are in turn targeted at their customers. A host of other stakeholders participate to the freight transportation system: insurance companies provide risk related services (such as reduction, mitigation, and pooling), platooning service providers provide support for platooning, infrastructure managers provide pathways, and the regulator implements rules and controls the system. However, they are only indirectly relevant to platooning, for reasons which have been addressed in the previous part and which shall be reminded below.

3.2.1. The core value chain of freight transportation, and the core value of platooning

As explained above, in order to understand how OEMs can provide value to carriers, it is important to understand how carriers provide value to shippers, and shippers to consumers. Regarding what is important with respect to platooning, shippers provide cost-efficient logistical level of service to their customers. In order to provide value to shippers, carriers need to provide services which fit the expectations and constraints of shippers w.r.t. their own logistical requirements. In turn, OEMs must provide carriers with vehicles which fit their own operating constraints and commercial objectives. In other words, insofar as platooning is concerned, the core value chain is simple and straightforward: it starts from the OEMs, go through carriers, then shippers, and eventually customers. This is illustrated by Figure 5 below.

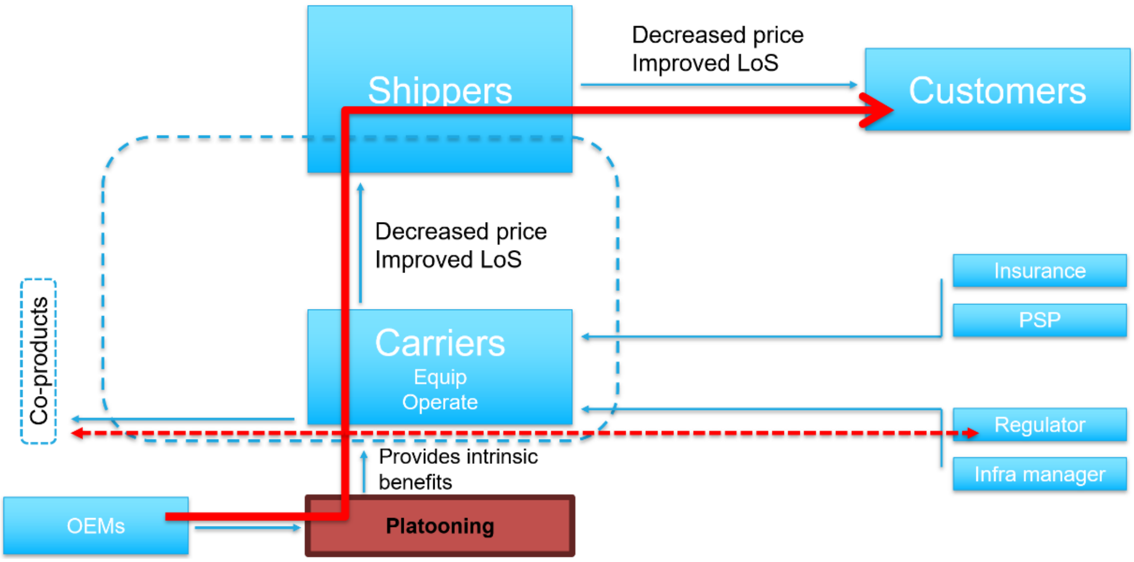

Figure 5: Core value chain of platooning

From a micro-economic perspective, platooning is a modification of the characteristics of trucks. The intrinsic benefits it brings to carriers depends on how it allows carriers to be more cost-effective, or to improve the level of service they provide to shippers, or both. Should level-of-service decreases (e.g. due to time loss or reliability worsened), then cost savings ought to more than compensate for that. Cost savings for shippers result from a modification of prices by carriers, and should account for investment costs by carriers.

There are two apparent deviations from the straightforwardness of the core-value chain, as illustrated by the dotted, two-headed horizontal arrow in Figure 5:

- Co-products: as previously discussed, if platooning allows carriers to produce a new type of service (such as administrative work) which is valuable to carriers (either because they benefit from those services directly, or because those can be sold to a third party), then additional value is associated to platooning.
- External benefits: also, if platooning brings value to society through externality reduction, this value can also be associated to platooning, under specific conditions.

However, it should be kept in mind that the potential for co-products depends directly on the possibility to have drivers work on something else during trips, when they are in a follower vehicle[17].

[17] Two precisions: first, at the support level, platooning only requires that the longitudinal control be out of the hands of the driver of a following truck. Lateral control is optional, and OEM specific, among other things. The

More importantly, we are interested in the adoption of the platooning technology by carriers. Carriers will only consider the costs which fall in their perimeter when deciding whether to acquire platooning enabled trucks, and whether to actually use platooning. As far as platooning is concerned, this means, first, that the possibility of delivering co-products acts in every meaningful way exactly as a cost reduction; second, that externality reductions should be considered if and only if that reduction is mirrored in the costs, taxes or turnover of carriers.

3.2.2. Potential amplifiers of the value of platooning

The core value chain of platooning is straightforward. However, other stakeholders or mechanisms can contribute to maximizing the value of platooning for carriers. This is what Figure 6 depicts.

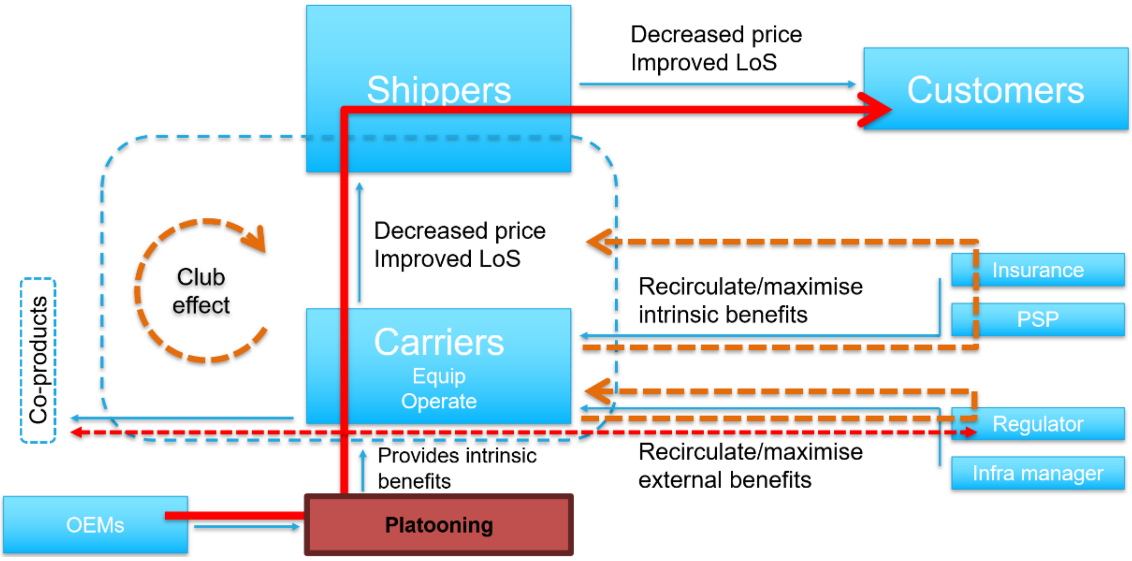

Figure 6: Potential amplification mechanisms

A number of mechanisms are illustrated here. They were discussed in detail previously in the report, so they will only be recalled here. Let us first discuss the issues of market structure:

- Club effect: one of the characteristics of platooning as a technology is that it requires a coordination between distinct vehicles[18]. Indeed, platooning brings value only when trucks are into actual platoons. Without ambiguity, the coordination requirement is an additional production constraint for carriers, and will cause additional costs (either directly or through a loss in level of service.) On average, those costs are lower when the platooning market is

possibility that the driver of a following truck works on something else while driving is non-existent. Second, if the driver of a following truck can be removed (i.e. if one assumes a platooning function so advanced that unmanned follower vehicles are an actual possibility), the corresponding benefits fall under the cost reduction category, not the co-product category, even if the then unrequired driver can do something else. This situation would be possible in the case of the Platooning Autonomous Function.

[18] By coordination, we mean that, most often, distinct vehicles will to adjust their routes so that they can platoon together. This doesn't presume that this coordination has to be done beforehand (orchestrated platooning) or on the fly (spontaneous platooning.)

larger: there is a club effect. Markets with club effects come with a number of regulatory issues calling for attention from regulators. In the case of platooning, regulators would have to monitor that platooning adoption is as wide as relevant[19], and to ensure that the platooning market would not present too much distortion from imperfect competition.

- Compensation and platooning service providers: platooning requires an adequate pricing scheme. Indeed, the leader truck benefits very little from joining a platoon, while often bearing a large share of the coordination cost. The platooning service provider can increase a lot the number of platooning opportunities by designing an adequate financial incentive structure.

The second issue is, broadly, that of the externalities[20]:

- Risks and insurance companies: in the hypothetical case where platooning would bring safety improvements, and a reduction of the frequency and/or gravity of accidents, insurance companies would play an important role to provide carriers with the adequate incentives, for them to correctly integrate those safety considerations when deciding whether to acquire platoon enabled trucks and whether to form platoons.

- Negative externalities and regulation: platooning can, theoretically, reduce some of the externalities of road freight transportation, mainly from a reduction in GHG emissions and an improvement in road throughput. Regulators may adapt fiscal instruments for prices to include those externalities.

These different mechanisms all contribute to a maximization of platooning market uptake, and therefore its benefits. They all share the same trait: by displaying, through prices, the true benefits (i.e. marginal social cost) of them partaking in platooning, they would substantially increase the private value of platooning for carriers. However, they cannot make benefits appear out of nowhere.

3.3. Risk assessment

Up to this stage, the question of risks was ignored. By definition, in this report, the notion of risk relates to the how a specific decision maker addresses the uncertainty of the outcome of a decision. This notion is of critical importance when considering irrecoverable investments, also known as sunk costs. On the one hand, there is a fixed cost; on the other hand, an uncertain benefit. The decision maker is sensitive to the uncertainty of the benefit because the cost is fixed; if not, they would be able to invest, observe the outcome, and discard – refund – their investments if they weren't satisfied with said outcome.

[19] As explained previously, this includes, in theory, the adaptation of market prices so that they include the positive externality of additional platooning users. In practice, this scheme of incentives would have to be adapted to each road and, possibly, date and time. It would not be easy to implement. Platooning service providers would face similar challenges.

[20] speaking, it is incorrect to state that risks and insurance companies is only an externality issue. Risks are associated to externalities for ease of presentation.

The presence and intensity of risks for a particular investment should be assessed with respect to the general volatility of a given market segment. In general, risk is priced through a penalty, or *premium*, on the interest rate representing the cost of money (Brealey et al., 2013.) In a firm, investments should be assessed to check that they perform better than a given internal rate of return (IRR), typically the weighted average cost of capital (WACC), which takes the market segment risk into account, as well as the financial structure of the firm.

In addition, the segment specific premium should be applied to a particular investment only if the risks associated to that particular investment is similar to that of the corresponding market segment. An investment with negative correlation with the uncertainty of the activity or profit of the market segment should be considered with a lot of interest: its realization would actually decrease the volatility of the firm's profitability. Symmetrically, an investment presenting more volatility than the firm's standard activity should be made with more caution than a risk neutral one.

In this section, we are going to focus on the case of the carrier, which makes the important decision from the standpoint of the economics of platooning: the decision to equip trucks, or not, with the platooning technology. Let us examine a selection of risks relevant to any freight carrier, and how platooning performs with respect to them:

- Traffic: freight carriers are vulnerable to market size variations; and in the case of road freight transport, market size is heavily correlated with the economic activity, i.e. GDP. Platooning is even more vulnerable to that risk, insofar as a reduction of traffic comes with fewer opportunities to form platoons and higher coordination costs.

- Fuel prices: costs and prices of road freight transport depend on fuel prices. In some cases, fuel prices variations are mechanically passed on to shippers[21]. This doesn't cancel the risk, even for carriers: a variation of fuel prices passed on to shippers can result in a variation of volume, therefore less volume for carriers. Regarding platooning, assuming gross savings are one-to-one correlated to fuel prices, then the volatility of net savings is higher[22].

- Specific equipment investment: the question is that of the residual value of the platooning equipment in the vehicles. If the equipment is specific to platooning and cannot be resold or repurposed to any other role, then the risk associated is maximal. Conversely, if the equipment were completely generic, the risk would be insignificant.

[21] It is a legal obligation in France to make the fuel cost explicit in road freight transport contracts, and to reevaluate those contracts when fuel prices vary.

[22] Just for the sake of illustration, assume buying a platoon enabled truck costs 1000 and yields 2000 fuel savings over the economic life cycle of the truck: the net value of the investment is 1000. An increase in fuel prices by 10% causes an increase in those savings by 20%, and conversely. As a result, the volatility of the net savings is two times that of fuel prices.

- Reaction of other carriers: the value of platooning for one carrier depends very directly from the investment decisions of other carriers. This is a specific source of uncertainty, which comes in addition to standard road freight transport activity.

- Substitute technology: in the general context of the constant improvement of road freight transport productivity, including energy efficiency; and in the particularly acute context of road freight decarbonation, several technological directions are currently being very seriously investigated to reduce fuel consumption or even to replace fuel with another energy vector. If such a technology were to mature in a timeframe relevant to platooning, the added value of platooning would have to be reassessed with respect to it. This risk is particular to platooning, and should be accounted for accordingly.

The conclusion of this brief analysis mostly disfavours platooning from a risk assessment perspective. As a consequence, the investment's internal rate of return should be increased by a penalty; in other word, carriers should be risk adverse regarding platooning.

3.4. Business model analysis: conclusion

The network of stakeholders relevant to platooning is a complex one. However, it can be simplified by distinguishing core benefits from indirect ones. Core benefits are benefits (or costs) which are readily visible by carriers: cost savings, changes in level of service, without an intervention of third parties. As explained above, the chain of direct benefits of platooning is straightforward: OEMS, carriers, shippers, end-consumers. **Platooning will yield direct benefits if, and only if, they can make carriers more efficient,** all costs considered.

Indirect benefits are benefits which can be made visible to carriers provided third parties introduce adequate mechanisms. This include: platooning service providers, which can optimize the coordination process through, among other things, an adequate pricing and compensation scheme; insurance companies which can contribute to the internalization of the platoon related safety improvements (if any), and regulators (possibly through infrastructure managers) which can internalize the benefits of platooning regarding pollution, GHG emissions and congestion.

In addition, two facts are critical to understanding the value of platooning for the economy and the position regulators should have with respect to platooning.

First, platooning (i.e. the decision by carriers to equip trucks so that they are able to platoon, and the decision by carriers to actually use platooning) is the result of a sequence of private decisions, made by carriers, who consider their own costs and benefits, and not external impacts. This is why, in order to understand and model the market uptake of platooning, it is crucial to analyse the market from the perspective of carriers. Moreover, it is important to keep in mind that the issue of platooning is both an issue of equipment and an issue of operation. Those issues should not be conflated: neither is it sufficient that two trucks are in a situation where platooning is possible for them to form platoons – they won't do so if the vehicles are not properly equipped; nor is it sufficient that trucks are equipped with the platooning technology for them to be in platoons all the time. As a consequence, **the platooning market uptake is necessarily hard to model and forecast**: it is closely dependent on economic and geographical contexts; **it is not a function of heavy-duty vehicles (HDV) traffic alone**, and **it depends closely on the economic life-cycle of vehicles** (such information is typically completely absent from public transport statistics, e.g. EUROSTAT databases).

Second, **third parties, including the regulator, can amplify the benefits of platooning, but they cannot make those appear out of nowhere.** Theoretically, there could be external benefits of platooning which, after internalization, would make market uptake possible. However, in practice, there is no sensible reason to expect substantial external benefits could exist without the co-existence of core benefits. For example, GHG emissions reductions only appear if there is a reduction in fuel consumption. Safety improvements for other road users would only exist if there are also improvements to the carriers' vehicles and freight. Thus, the statement that third parties can amplify core benefits, but not replace them. In any case, if there were robust expectations of external benefits, one could imagine that platooning be made compulsory. However, there are two serious caveats to that scenario. First, it is certainly possible to make it compulsory for trucks to be equipped with a platooning technology (although that decision would not come without its own technical and legal challenges), but it is much harder to see how one could enforce the formation of platoons on the road. Second, regulators will only decide to implement that obligation if there is a strong argument for the benefits it would yield; this brings us back to the statement above, that the case for the existence of these benefits is weak if there aren't sufficient core benefits to trigger a spontaneous market uptake.

Finally, **business model evaluation should not be confused with the socio-economic analysis of the costs and benefits of platooning for society**. Note that a socio-economic analysis requires an assumption regarding market uptake: all socio-economic analyses are built on a market analysis, although the latter is often left implicit.

4. QUANTITATIVE MARKET UPTAKE SIMULATION

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The objective of this section is to provide an in-depth analysis of platooning market uptake, based on an analytical approach. In line with the conclusions of the business model analysis (previous Chapter), platooning is considered to be a two-stage decision making process where carriers decide first whether to equip their trucks so that they are platoon enabled, and then whether to actually form platoons with their vehicles. The analytical development is focused on platooning with two vehicles. The economic life cycle of vehicles is considered: platooning involves an equipment decision, with fixed costs, associated to one vehicle, and variable benefits, associated to trips, routes, and decisions of other carriers. The modelling work also makes explicit the vehicle market dynamics: trucks are assets with a long lifetime, and retrofit is generally not considered as an option, since platooning requires access to internal vehicle control systems and consequently also affects type approval. The decision of carriers regarding whether to equip their trucks and, then, to have their trucks join platoons, is assumed to be entirely determined from the standpoint of carriers, without government obligation. Simulations with the model are based on assumptions of reduced fuel consumption. However, the model is adapted to account for any kind of cost reduction when platoons are formed.

For reasons of mathematical complexity, the model does not encompass the full diversity of possible configurations. First, only platoons of two vehicles are considered. This is a limitation compared to what the technology considered in ENSEMBLE allows; it reduces the platoon size to two vehicles. Also, the geographical context is represented in a simplified way. Extending the analysis to more complex and realistic networks raises methodological and data availability challenges which are outside the scope of today's state of the art[23]. Limitations of the model and their probable impacts on the quantitative results are discussed during the analysis.

The chapter proceeds in four sections. Section 4.1 presents a static microeconomic model which will be used as a basis for the whole chapter. Section 4.2 extends the static model to a dynamic framework. Section 4.3 presents the quantitative results. Section 4.4 concludes the chapter.

[23] To be more precise, it is possible to extend the analysis to more complex networks, but not without letting go of central characteristics of the model, including the two-stage decision process, and the consideration of the economic life cycle of the vehicles.

4.1. Static microeconomic platooning model

It is assumed that platooning mainly brings value to carriers via a reduced fuel consumption. However, platoon creation is a complex and potentially costly process. Several papers have investigated the issue. For example, Liang et al. (2016) investigate platoon formation in a case where a given number of heavy-duty vehicles (HDVs) are on a road and consider whether joining platoons or follow a given trajectory alone. In their paper, the authors consider in detail the fuel savings, and assume that the arrival times of vehicles are fixed (instead of considering a monetary penalty for arriving late, or cost savings for travelling faster). Van de Hoef and Johansson (2018) study the problem of finding a globally fuel-efficient plan of platoon formation over a road network, while respecting arrival time constraints. In this model, speed is assumed to be piece-wise constant. The platoon plan is designed and advertised by a centralized planner, with which the vehicles must provide their assignment data. The problem of finding an optimal plan is difficult. Finally, Johansson et al. (2018) consider the non-centralised case: what happens if each vehicle takes the optimal decision for them? This is a classic context of game theory, where one is interested in a non-cooperative (also known as Nash) equilibrium. In the later, arrival time can depart from (and actually exceed) the initial arrival time, but at a cost. Bakermans (2016) designed a simple model which helps grasping the underlying mechanisms: it is much simpler than the other models, but it lends itself to microeconomic analysis more easily, with a generic representation of the cost for carriers to change travel times and arrival times, with a value of time in a generalized cost function (a classic approach in transport economics.) A similar approach is followed here.

4.1.1. Modelling framework

On-the-fly platooning (or spontaneous) is considered. The trade-off between being in a platoon or remaining alone for a given pair of vehicles is investigated. $t = 0$, two vehicles are on a given road, in the same direction. The first one, the leader l, is at coordinate $d_{iv} > 0$ (the intervehicle distance) and will leave the road at coordinate $d_l + d_{iv}$. The second one, the follower, is at coordinate 0 and will leave the road at coordinate d_f. In contrast with Liang et al. (2016), van de Hoef and Johansson (2018) and Johansson et al. (2018), HDVs are assumed to run at the maximal legal speed in the benchmark scenario. In the following, it is assumed that if the vehicles form a platoon, then the platoon will also run at maximum speed[24].

In order to assess the costs and benefits of platooning for carriers, it is necessary to distinguish the fuel cost $p_G g$ (where p_G is the fuel price [€/L] and g the fuel consumption [L/km]), the distance-dependent cost c_d [€/km] (vehicle wear and tear, tolls, etc.), the time dependent cost c_h [€/h] (vehicle capital opportunity cost, wages, etc.) It is also necessary to account for the willingness of shippers to reduce travel time α [€/h]: even if the carrier does not bear this last cost directly, the willingness to pay of shippers for commodities to move faster will be mirrored in price: going slower means less

[24] If, for some reason, vehicles were required to move below maximum legal speed when in platoons, the business case of platooning would be considerably worse.

revenue. In other words, c_h is the carrier value of time, and α is the shipper value of time. All costs are in real[25] monetary units.

To travel a distance d at speed v, the transport cost is:

$$c(d, v) = (p_G g + c_d)d + (c_h + \alpha)\frac{d}{v}$$

4.1.2. Options and costs

Let us first consider the case where the leader leaves the road after the follower[26]: $d_l > d_f + d_{iv}$. This situation is illustrated by Figure 7.

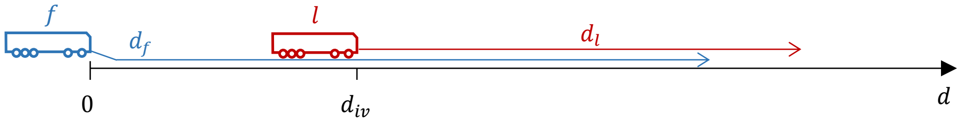

Figure 7: Initial situation

Under the assumption that both vehicles run at maximum legal speed, the follower vehicle cannot catch up the lead vehicle to form a platoon. On the contrary, the lead vehicle has two options:

- Option ∅: the leader and the follower do not form a platoon: it's the reference option. The fuel consumption is the same for both trucks and denoted by $g^{\emptyset}$. Both vehicles run at constant speed v_m.
- Option P: the leader and the follower form a platoon. The fuel consumption under this scenario is g_l^P for the leader and g_f^P for the follower (with $g_f^P < g_l^P < g^{\emptyset}$). The follower runs at speed v_m and the leader will slow down at speed v_w while waiting for the second vehicle and v_m afterwards[27]. The distance the leader has covered when the platoon is formed is d_w.

Consider option ∅. The costs for the leader and the follower are, respectively:

$$c_l^{\emptyset} = \left(c_d + p_g\, g^{\emptyset}\right) d_l + (c_h + \alpha)\, \frac{d_l}{v_m}$$

$$c_f^{\emptyset} = \left(c_d + p_g\, g^{\emptyset}\right) d_f + (c_h + \alpha) \frac{d_f}{v_m}$$

[25] Daily life prices are in *nominal* monetary units. By contrast, *real* monetary units are net of inflation. Prices which increase at the same rhythm as inflation are stable in real units.
[26] All the calculations below can easily be generalized to account for the other case. For the sake of simplicity and clarity, the generalization is skipped. Qualitative conclusions are unchanged. The reasons why generalizing the model to platoons with more vehicles is mathematically cumbersome, and without substantial relevance, are discussed in more detail in Section **Error! Reference source not found.**.
[27] By approximation, speed is assumed to be piecewise constant with respect to time.

Now, consider option P. The follower will cover distance $d_{iv} + d_w$ before the platoon creation, then d_P in the platoon, before leaving the road. With the notations above, $d_P = d_f - d_{iv} - d_w$. As for the leader, it will cover distance d_m before the platoon creation, then d_P inside the platoon, then $d_l - d_m - d_P$ after the platoon break, i.e. a total distance outside a platoon $d_l - d_P$. Note that for the moment we assume no compensation scheme[28]. Therefore, the costs for the leader and follower are, respectively:

$$c_l^P = c_d d_l + p_g g^\emptyset (d_l - d_P) + p_g g_l^P d_P + (c_h + \alpha)\left(\frac{d_w}{v_w} + \frac{d_l - d_w}{v_m}\right)$$

$$c_f^P = c_d d_f + p_g g^\emptyset (d_{iv} + d_w) + p_g g_f^P d_P + (c_h + \alpha)\frac{d_f}{v_m}$$

The cost increment for the follower of being in a platoon compared to staying alone is:

$$c_f^P - c_f^\emptyset = p_g\left(g_f^P - g^\emptyset\right) d_P < 0$$

This cost increment is always negative. The follower does not lose time, being always at maximum speed[29], but saves fuel once in the platoon. Therefore, under the modelling assumptions, it is always beneficial for the follower to opt for the platoon option.

The cost increment for the leader of being in a platoon compared to staying alone is:

$$c_l^P - c_l^\emptyset = p_g\left(g_l^P - g^\emptyset\right) d_P + (c_h + \alpha)\left(\frac{1}{v_w} - \frac{1}{v_m}\right) d_w$$

This cost increment can be positive or negative. It consists of two components: on one hand, the leader saves fuel once in the platoon; on the other hand, the leader loses time when slowing down to allow the follower to reach him: there is a penalty to forming a platoon. The profitability for the leader to form a platoon depends on several parameters, including trip length, the speed during platoon creation, the cost parameters, etc.

In order to further investigate this decision, it is necessary to derive d_P and d_w. To do so, note that at $t = 0$ the distance between the leader and the follower is d_{iv}. However, when the platoon is formed, this distance falls down[30] to 0. This is illustrated by the diachronic graph below (Figure 8).

[28] This assumption is relaxed later on.
[29] Provided the platoon does not have to dissolve and be created again for other reasons (such as to cross a bridge, etc.) The consequences of relaxing this assumption would degrade the overall profitability of platooning for carriers, as, each time, the follower would have to slow down in order for the platoon to break, and then the leader would have to slow down for the follower to catch up and form the platoon again.
[30] For simplicity we ignore vehicle length and minimal inter-vehicle distance.

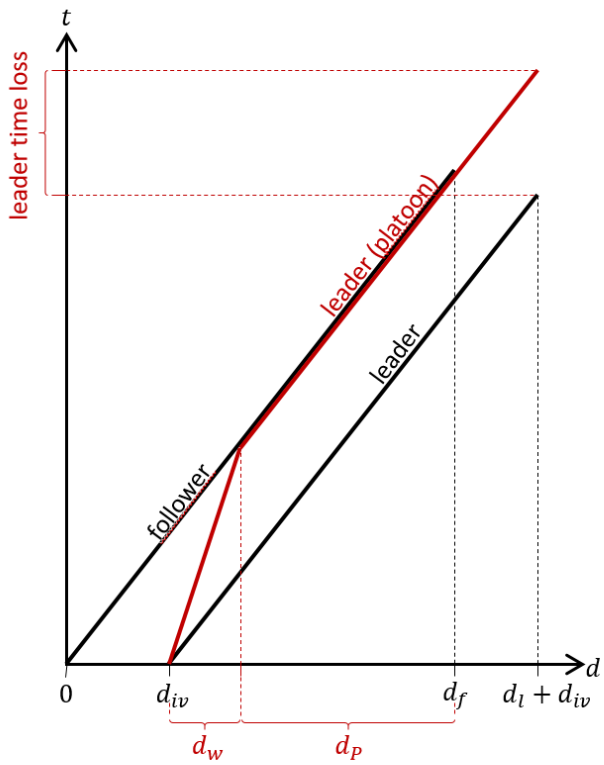

Figure 8: Platoon creation: distance-time profiles

Variables d_P and d_w are such that:

$$\frac{d_w}{v_w} = \frac{(d_w + d_{iv})}{v_m}$$

As a consequence:

$$d_w = \frac{\frac{1}{v_m}}{\frac{1}{v_w} - \frac{1}{v_m}} d_{iv} = \frac{v_w}{v_m - v_w} d_{iv}$$

And $d_P = d_f - d_{iv} - d_w$. Note that necessarily, $d_P \geq 0$. If $d_w > d_f - d_{iv}$, the platoon cannot be formed, the follower's trip length is too small. To recapitulate:

$$d_w = \frac{v_w}{v_m - v_w} d_{iv} \quad \text{if} \quad d_w > d_f - d_{iv}$$

This allows to derive the gain platooning brings to the leader:

$$c_l^P - c_l^\emptyset = p_g(g_l^P - g^\emptyset)\left(d_f - \frac{v_m}{v_m - v_w} d_{iv}\right) + \frac{(c_h + \alpha)}{v_m} d_{iv}$$

The platooning option is profitable for the leader if $c_l^P < c_l^\emptyset$ i.e.:

$$p_g(g^\emptyset - g_l^P)\left(d_f - \frac{v_m}{v_m - v_w} d_{iv}\right) > \frac{c_h + \alpha}{v_m} d_{iv}$$

This condition can be written as:

$$d_{iv} < \overline{d_{iv}} \quad \text{with} \quad \overline{d_{iv}} = \frac{p_g(g^\emptyset - g_l^P)}{\frac{c_h + \alpha}{v_m} + p_g(g^\emptyset - g_l^P)\frac{v_m}{v_m - v_w}} d_f$$

The threshold distance is proportional to trip length d_f, and decreases with v_w in a nonlinear way. Figure 9 illustrates, qualitatively, how the threshold varies with d_f and v_w: the higher the trip length, the lower the threshold distance; on the contrary, the closer the waiting speed is to the maximum legal speed, the longer the threshold distance. Keeping in mind that the lower the threshold distance, the less HDVs will form platoons, this means that a favourable configuration for platooning will be where trucks share long distances in common, and if the difference between the waiting speed and the maximum legal speed is large. Of course, the latter parameter comes with its own host of issues, safety wise.

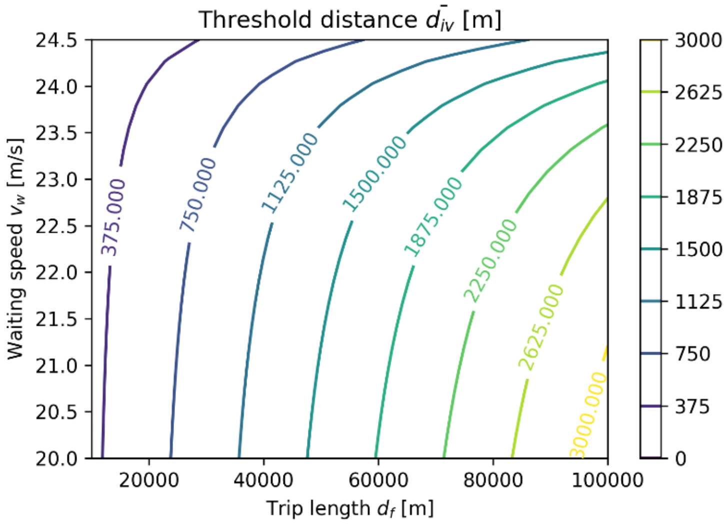

Figure 9: threshold distance as a function of shared trip length and waiting speed[31]

The sensitivities of the platooning option's value for the leader to the various parameters of the model are listed below. Note by "economic conditions" we refer to the set of parameter combinations such that the leader will consider waiting the follower to join a platoon. A corollary implication is that by

[31] The only objective of this figure is to illustrate the relationship between the model's parameters and variables. It is not numerically calibrated and the reader should not pay attention to the values. Calibrated simulations are presented later on the report.

"widening economic conditions" we refer to a situation where the set of parameter combinations just defined increases (in a geometric meaning) with the variation of a given parameter.

- p_G: higher fuel prices improve the economic conditions for platoon formation.
- $g_l^{\emptyset}$: higher fuel consumption improves the economic conditions for platoon formation.
- $g_l^{\emptyset} - g_l^P$: the economic conditions for platoon formation widen if platooning allows more fuel savings.
- The conclusions stand if the monetary savings allowed by platooning come from other causes: any vector through which platooning would bring direct monetary benefits to carriers will have the same effect on the economic conditions for platoon formation.
- d_f: an increase in the follower trip length improves platooning value. Platooning is more likely to happen when trucks share a long part of their paths.
- d_{iv}: an increase in the initial inter-vehicle distance reduces platooning value. This is related to traffic flow: the higher the relevant traffic density, the wider the economic conditions for economic conditions. This was discussed already in the previous qualitative business model discussion, and is accounted for very precisely in the rest of the report.
- v_m: the economic conditions for platooning formation are wider when the legal speed is higher: note that this can hardly be considered as an instrument: a modification of v_m would have many other implications.
- v_w: an increase in the waiting speed decreases the probability of platoon formation. In this model, the sooner the leader is in the platoon, the sooner the follower benefits from fuel savings. Ideally (from a financial standpoint), the leader should stop on the road and wait for the follower. Obviously, this is quite theoretical.
- c_h and α: both these parameters decrease the value of platooning if they are increased: the time loss due to joining a platoon will be all the more disadvantageous when the values of time of the carrier and shipper are high.

Note that in most cases, the widening of the economic conditions of platoon formation come together with an increased value of platooning, but the two issues are, strictly speaking, different. The value of platooning is, in the end, the parameter to focus on; it is the basis of the decision for the carrier to equip their vehicles with the platooning technology.

4.1.3. Optimal decisions for carriers

The sensitivity analysis shows that the value of platooning depends on the inter-vehicle distance d_{iv}. This inter-vehicle distance decreases when there is more relevant traffic, and equipped with the platooning technology. In other words, the more platooning brings value to carriers, the more carriers will participate to platooning, the more platooning will bring value to carriers: this is the network externality, or club effect, that was discussed in the business model section of this report.

A bit more precisely, the market equilibrium should be considered as a two-fold question, insofar as it is based on two sequentially dependent decisions:

- Low-level decision: conditionally on being equipped with the platooning technology, should a truck join a platoon?
- High-level decision: should a carrier equip a given truck with the platooning technology?

In any case, the notion of **relevant traffic** is central to the economic issue of platooning: for each truck considering the decision to form a platoon, and for each carrier considering the decision to equip their trucks with the platooning technology, their decision will be made on the basis of their amount of opportunities for platoon formation their vehicles expect to meet. This is not all truck traffic; on the contrary it is reduced to the trucks which are equipped with a compatible platooning technology and which consider forming a platoon.

Low-level decision: share of vehicles joining platoons, conditional to relevant traffic

The first step of the analysis is to focus on the low-level decision, conditional to relevant traffic. A simple analytical traffic model is introduced. The analysis is limited to 2-vehicle platoons.

A single road of length d_r is considered, with a flow of Q trucks entering and leaving it at its extremities[32]. Also, denote by ρ_P the proportion of trucks ρ_P equipped with the platooning technology. The flow of vehicles which may use platooning is the relevant traffic $Q_P = Q\rho_P$:

For a given flow of vehicles of uniform speed v_m arriving at random and independently at the origin of the road, it is standard to assume their arrival can be modelled as a Poisson process of parameter Q_P. The time between two successive vehicles is then a random variable following an exponential distribution of parameter Q_P. If the vehicles all go at speed v_m, then the inter-vehicle distance also follows an exponential distribution, of parameter Q_P/v_m (the average inter-vehicle distance is v_m/Q_P):

$$d_{iv} \sim \mathcal{E}\left(\frac{Q_P}{v_m}\right)$$

[32] A more general approach implies first to consider trucks entering and leaving in many different places, second to consider a road network. Indeed, in order to analyze platooning market penetration, one should keep in mind that there are three distinct levels to keep in mind: the infrastructure, the vehicle itinerary, and the vehicle activity over a given period of time (say the time during which the vehicle will be operated by the carrier, which can be several years).

Two issues should be considered: the simple one is the probability that a vehicle finds it worthwhile to wait for the vehicle behind him, conditional to not being already in a platoon, or waiting at max speed to join the vehicle in front of him. The more complex one is to calculate the overall platooning behaviour on the road.

Conditional probability

Denote by F_{iv} the cumulative distribution function of d_{iv}. Then, for any distance $d \geq 0$:

$$F_{iv}(d) = 1 - \exp\left(-\frac{Q_P}{v_m} d\right)$$

The probability, for a vehicle outside a platoon, that it is worth waiting for the next vehicle in order to form a platoon, is:

$$\pi_w = \mathbb{P}\{c_l^P < c_l^{\emptyset}\} = F_{iv}\left(\overline{d_{iv}}\right)$$

Or, equivalently:

$$\pi_w = 1 - \exp\left(-\frac{Q_P \overline{d_{iv}}}{v_m}\right)$$

Figure 10 shows how π_w depends on the parameters of the model: the probability that it is worthwhile for a HDV to join a platoon as a leader increases with the relevant traffic Q_P and with trip length d_f.

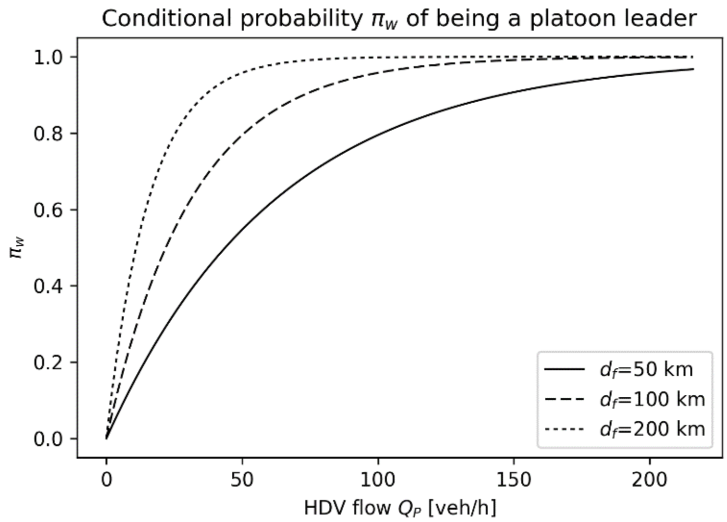

Figure 10: influence of d_f and Q_P on π_w[33]

Probability π_w increases with relevant traffic Q_P and decreases with the threshold distance $\overline{d_{tv}}$. However, this probability cannot be considered as the proportion of vehicles joining platoons in traffic already: one needs to account for the fact that each vehicle needs to decide whether to wait for the previous vehicle (if the previous vehicle finds it worthwhile to slow down), or to try and form the platoon with the one following itself. This higher-level issue is now addressed.

Global model for a given road

We now consider the whole traffic flow. In order to limit the problem's complexity, we do not investigate a global optimum, but model a situation where vehicles enter the road sequentially and randomly. Each vehicle is indexed by $i = 1, 2, \ldots$ They will apply the following rule: if vehicle i (as a leader) finds it relevant to wait for vehicle $i+1$ (the follower), then vehicle $i+1$ will join vehicle i. However, if vehicle i is already in a platoon or does not want to wait for vehicle $i+1$, then vehicle $i+1$ will consider forming a platoon with vehicle $i+2$, etc. Note that this process does not yield a global optimum[34]. Also, the issue of compensation should not be discarded: without financial

[33] The only objective of this figure is to illustrate the relationship between the model's parameters and variables. It is not numerically calibrated and the reader should not pay attention to the values. Calibrated simulations are presented later on the report.
[34] Consider 3 vehicles, the second 4 km behind the first and the third 1 km behind the second. Assume the threshold distance is higher than 4 km. Then two arrangements are possible: form a platoon with the first and the second vehicles, or form a platoon with the second and the third). The sequential process presented here will put the first and second vehicle together, whereas it would be optimal to put the second and third together, given the fact that it would be much faster, and thus much more efficient to form the platoon in the second case than in the first. However, identifying the optimal strategy is a difficult mathematical issue, probably not very useful in this theoretical case, and it is our hope that the simple model designed in this section is reasonable enough to grasp the essential economic mechanisms of truck platooning.

compensation, vehicles will prefer to be followers, and not leaders. This topic is discussed elsewhere in this report.

Mathematically, this can be represented as follows. First, introduce the sequence of binomial variables $\boldsymbol{P} = \{P_1, P_2, \dots\}$ where:

$$\begin{cases} P_i = 0 & \text{if vehicle } i \text{ is not leader of a platoon,} \\ P_i = 1 & \text{if vehicle } i \text{ is leader of a platoon with } i+1 \end{cases}$$

These variables represent the state of each vehicle. Then, denote by $\boldsymbol{D} = \{d_{iv,1}, d_{iv,2}, \dots\}$ the sequence of intervehicle times, with $d_{iv,i} \geq 0$ the inter-vehicle time between vehicle i and vehicle $i + 1$. With these notations, the process presented above is the following one:

- If vehicle i is follower in a platoon, it cannot be leader of a platoon with vehicle $i + 1$:

$$P_{i-1} = 1 \quad \Rightarrow \quad P_i = 0$$

- If vehicle i is not follower in a platoon, it can become leader of a platoon with vehicle $i + 1$. This will happen if $d_{iv,i} \leq \overline{d_{iv}}$, *i.e.* with probability π_w.

$$P_{i-1} = 0 \quad \Rightarrow \quad \begin{cases} P_i = 0 & \text{with probability } 1 - \pi_w \\ P_i = 1 & \text{with probability } \pi_w \end{cases}$$

As a matter of fact, sequence $\boldsymbol{P}$ is a Markov chain, which allows us to investigate its statistical properties. Its state transition diagram is shown in Figure 11, with state 0: vehicle i is not a platoon leader and state 1: vehicle i is a platoon leader.

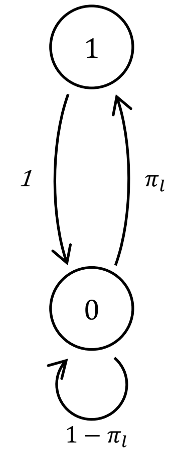

Figure 11: state transition diagram of the 2-vehicle platoon model

The state transition matrix of $\boldsymbol{P}$ is:

$$M_P = \begin{bmatrix} 1 - \pi_w & 1 \\ \pi_w & 0 \end{bmatrix}$$

A particularly important value is the probability that any vehicle is leader of a platoon. The steady state of the process is characterized by the fact that in the long run, the probability that a given vehicle is a platoon leader is stable, and so is the probability that it is not a platoon leader. These steady state probabilities are respectively $1 - \pi_l$ (probability of being in state 0, i.e. not being a platoon leader) and π_l (probability of being in state 1, i.e. being a platoon leader). In the steady state:

$$M_P \begin{bmatrix} \pi_l \\ 1 - \pi_l \end{bmatrix} = \begin{bmatrix} \pi_l \\ 1 - \pi_l \end{bmatrix}$$

After replacing the transition matrix M_P:

$$\begin{bmatrix} \pi_l \\ 1 - \pi_l \end{bmatrix} = \begin{bmatrix} 1 - \pi_w & 1 \\ \pi_w & 0 \end{bmatrix} \begin{bmatrix} \pi_l \\ 1 - \pi_l \end{bmatrix}$$

This allows to derive π_l as a function of π_w:

$$\pi_l = \frac{\pi_w}{1 + \pi_w}$$

Now, it is possible to derive the probability that a vehicle is in a platoon: quite naturally, the probability π_f that vehicle i is a follower is the probability that vehicle $i - 1$ is a platoon leader. As a consequence, $\pi_f = \pi_l$. Then, the probability π_P that vehicle i is in a platoon is the sum of the two mutually exclusive events: vehicle i is a platoon leader (with probability π_l) or vehicle i is a platoon follower (with probability π_l as well). As a consequence, $\pi_P = 2\pi_l$ or:

$$\pi_P = \frac{2\pi_w}{1 + \pi_w}$$

It can also be written as follows:

$$\pi_P = 1 + \frac{1}{1 + 2\exp\left(\frac{Q_P \overline{d_{iv}}}{v_m}\right)}$$

The relationship between the conditional probability of being a platoon leader and the probability of being a platoon is increasing, but not linear. It is not a trivial relationship, but its behaviour is intuitive. For small values of π_w, the probability for a vehicle to be in a platoon evolves as $2\pi_w$: for each leader, there is a follower. However, for large values of π_w, a correction mechanism limits the increase of π_P, which gets close to 1 when π_w gets close to 1. Figure 12 illustrates this relationship.

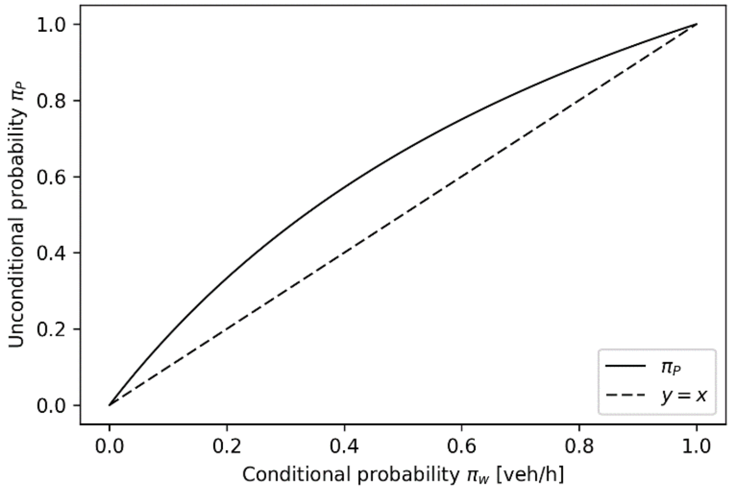

Figure 12: relationship between π_w and π_L[35]

However, the qualitative behaviors of π_P and π_w are similar: the sign of the change of π_P when any of the model's parameters change is the same as that of π_w.

The unconditional probability of being in a platoon is higher than the conditional probability π_w of being a platoon leader. This is especially visible in intermediate circumstances where the conditional probability π_w is significantly different from 0 and 1. The relationship between Q_P and π_P is illustrated by Figure 13.

[35] The only objective of this figure is to illustrate the relationship between the model's parameters and variables. It is not numerically calibrated and the reader should not pay attention to the values. Calibrated simulations are presented later on the report.

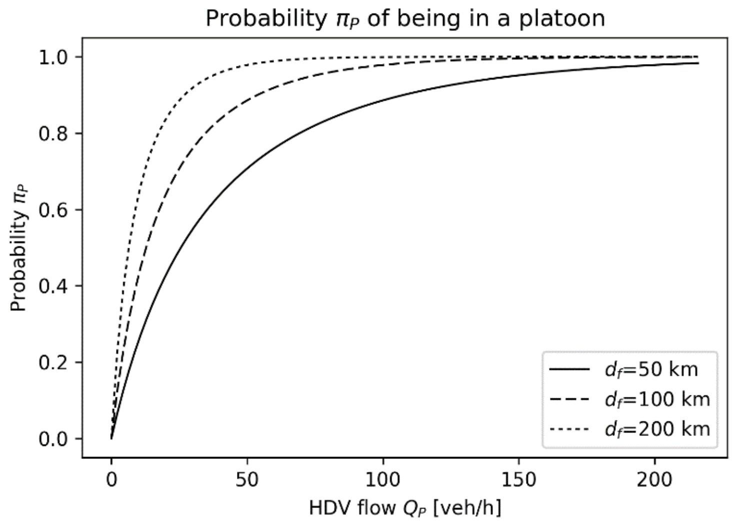

Figure 13: influence of Q_P and d_f on π_P[36]

The prominence of platooning in traffic behaves as expected with the parameters: a shorter common distance for candidates to platooning results in less platoons; whereas a denser eligible traffic results in more platoons.

A comment on platoons of more than two vehicles

Accounting for platoons with more than two vehicles can be addressed by extending this model. This is not a trivial work. If n-vehicle platoons are technically feasible, n states should be distinguished, denoted by k. Either vehicle i is the last vehicle of a platoon of size $k+1$ with $\in \{1; n-1\}$, or vehicle i is not a platoon leader ($k=0$). To derive the state graph, note that if vehicle $i-1$ is in state k then vehicle i will either be in state 0 or in state $k+1$. The latter case only happens if it is worthwhile for the already constituted platoon to slow down for the incoming vehicle to join it from the rear. Probabilities $\pi_{(k)}$ of transition $k \rightarrow k+1$ depend on k and decrease strongly with k. From there, the steady state can be derived, and all variables of interest can be computed.

However, this is a long, tedious, analytical work, and it adds very little to the understanding of the issue. Indeed, there is a penalty to form a platoon, depending on how much time the front vehicles lost, and that time penalty is proportional to the number of vehicles sustaining it. In particular, the probability that a platoon of size 3 is formed from a platoon of size 2 and a single vehicle is much lower than that of the formation of a platoon of size 2, etc. The additional economic benefits are even lower, as they should be computed net of the coordination costs. The balance between additional

[36] The only objective of this figure is to illustrate the relationship between the model's parameters and variables. It is not numerically calibrated and the reader should not pay attention to the values. Calibrated simulations are presented later on the report.

efforts and insights wasn't in favour of developing this model further. Note that the analytical extension would also need quite a lot of work regarding the top level decision model, detailed below.

Top level decision model: equipment in platooning technology

The previous section was focused on the proportion of vehicles forming platoons, assuming they are equipped with the platooning technology. In this section, the decision for a carrier to equip its fleet with the platooning technology is examined. A static approach is preferred: the main objective is to illustrate the network effect discussed in other parts of the report, in other words the fact that the decision of each carrier depends on the decisions of all other carriers. This section is theoretical; later on, a numerical model of dynamic simulation is presented.

In the case of this simple model, a homogenous vehicle economic life-cycle is assumed:

- Each vehicle is assumed to run L kms per year.
- The cost of the platooning technology amounts to a fixed yearly fee c_P to the carrier, per vehicle.

Two additional, strong assumptions, are required:

- Carriers are risk neutral: they equate the value of a decision with an uncertain outcome to its expected value. This is a strong, optimistic assumption (see Section 3.3), however, there are some pessimistic assumptions elsewhere in the model; also, there is no reasonably robust data to account for the actual risk adversity of carriers regarding platooning.
- Fully consistent expectations: each carrier acts based on what they expect other carriers to do; and the aggregate outcome of these decisions is consistent to what carriers expect at an aggregate scale. This assumption can be construed as some sort of Nash equilibrium with sufficient foresight from carriers[37].

Under this set of assumptions, the market equilibrium is simple to derive. Indeed, assume proportion ρ_P of vehicles are equipped. Then, with relevant traffic Q_P, the probability that a given truck is in a platoon is π_P. Conditional to being in a platoon, the truck has a $1/2$ chance of being the leader, and also of being the follower.

[37] One example of such a situation would be that, beforehand, all carriers expect that, say, 60% of the vehicles will be equipped with the platooning technology; and as a result, decide *ex ante* to equip their own vehicles, or not, in a way such that 60% of the vehicles are actually platoon enabled. In general, this needs not be true: assume, for some reason, that half the carriers expect that 100% of the vehicles will be platoon enabled, and the other half do not. Then the first half will equip their trucks with the platooning technology. As a result, only half of trucks will be equipped; this is a problem for the carriers who made that decision insofar as they will get a lower benefit than expected. In that latter decision their *ex ante* expectations weren't consistent with the *ex post* market behavior.

If the vehicle is a follower, then the fuel savings are, per km, $p_G\left(g^{\emptyset} - g_f^P\right)$

If the vehicle is a leader, then the fuel savings are, for a trip[38] with a given d_{iv}:

$$p_g\left(g^{\emptyset} - g_l^P\right)\left(d_r - \frac{v_m}{v_m - v_w} d_{iv}\right) - \frac{(c_h + \alpha)}{v_m} d_{iv}$$

To address the decision of the carrier to invest in the platooning technology, it is necessary to account for the number of trips. Each vehicle makes L/d_r trips per year; a proportion $1 - \pi_P$ of them outside a platoon, a proportion $\pi_P/2$ as a platoon follower, and a proportion $\pi_P/2$ as a platoon leader. It is also necessary to account for the fact that the distribution of d_{iv} conditional to the vehicle being a platoon leader is not the same as the unconditional distribution of d_{iv}. Denote the former by d_{iv}^P:

$$d_{iv}^P = E\{d_{iv,i} | P_i = 1\}$$

d_{iv}^P depends on the platoon formation process. With the process assumed here, the distribution of d_{iv} is exponential bounded to the $[0, \overline{d_{\iota v}}]$ interval. This allows to calculate d_{iv}^P:

$$d_{iv}^P = d_{iv} - \frac{\overline{d_{\iota v}}}{\exp\left(\frac{Q_P}{v_m}\overline{d_{\iota v}}\right) - 1}$$

The conditional expected inter-vehicle distance d_{iv}^P is equal to the average inter-vehicle distance corrected by a negative bias all the greater than the distance threshold $\overline{d_{\iota v}}$ is low before d_{iv}. The relationship between $\overline{d_{\iota v}}$ and d_{iv}^P is illustrated by Figure 14.

[38] The calculations are exactly the same as in Section 1.2, except for the fact that d_f, the length of the follower's trip, is replaced by d_r, the length of the road.

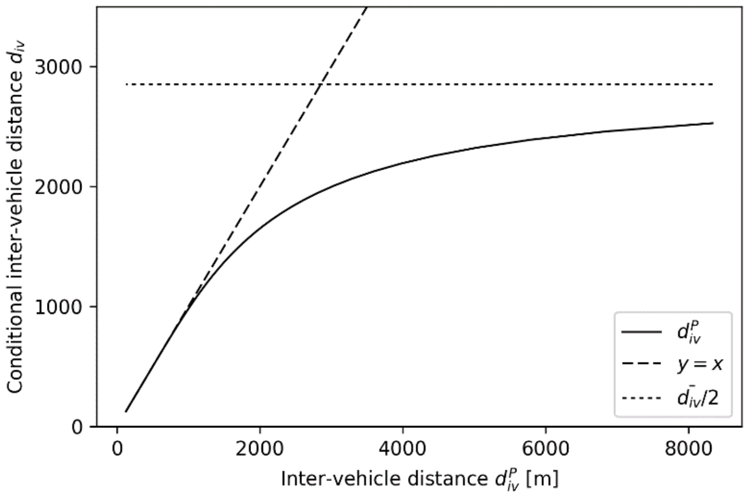

Figure 14: Relationship between d_{iv} and d_{iv}^P [39]

When the average inter-vehicle distance is low (e.g. if the HDV traffic flow is sufficiently dense), then the conditional inter-vehicle distance is very close to the average inter-vehicle distance: $d_{iv}^P \approx d_{iv}$. In the contrary case, the conditional inter-vehicle distance departs from the average distance: only trucks close enough to one another will form platoons. In this situation, the conditional distribution of d_{iv} is close to uniform on interval $[0, \overline{d_{iv}}]$, and we have $d_{iv}^P \approx \overline{d_{iv}}/2$. Those approximations can be formally derived with Taylor expansions, the calculations are not detailed.

We can now calculate the average savings for a vehicle using the platooning technology over a fixed time period. The probability that the vehicle is a platoon leader is π_l, and the probability that it is a platoon follower is π_l as well. The probability that the vehicle is not in a platoon is $1 - 2\pi_l$. The average savings for a platoon follower are:

$$\Delta c_f^P = p_g(g^\emptyset - g_f^P)d_f$$

The average savings for a platoon leader are:

$$\Delta c_l^P = p_g(g^\emptyset - g_l^P)\left(d_f - \frac{v_m}{v_m - v_w} d_{iv}^P\right) + \frac{(c_h + \alpha)}{v_m} d_{iv}^P$$

The average savings for one trip are:

$$\Delta \mathrm{c}_{\mathrm{trip}}^{\mathrm{P}} = \pi_l(\Delta c_l^P + \Delta c_f^P)$$

[39] The objective of this figure is to illustrate the qualitative relationship between the model's parameters and variables. It is **not** numerically calibrated and the reader should **not** pay attention to the values. Calibrated simulations are presented later on the report.

Assume each vehicle makes a total distance D per year, i.e. D/d_f trips per year. Then the average savings due to platooning over a year are:

$$\Delta c_{\text{year}}^{\text{P}} = \frac{D}{d_f}\pi_l\left(\Delta c_l^P + \Delta c_f^P\right)$$

As illustrated by Figure 15, these savings depend on the corridor length d_f on one hand, and on the relevant traffic Q^{P} on the other hand.

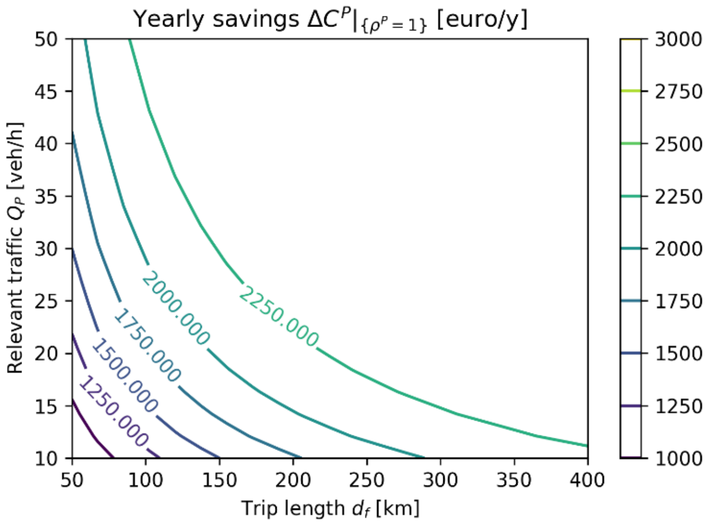

Figure 15: Yearly savings as function of trip length and relevant traffic[40]

Quite intuitively, global savings increase in condition favourable to platooning: long trips, and strong eligible traffic density. However, marginal savings are decreasing: there are diminishing returns to eligible traffic density. If the economic circumstances are met (relevant geographic conditions and sufficient market size), then the savings tend towards a maximal asymptotical value.

The cost of the platooning technology needs to be accounted for. By assumption, the cost of the platooning technology is assumed to be a fixed cost K^P per year and per vehicle. The total net savings due to platooning are:

$$\Delta C^P = \frac{D}{d_f}\left(\pi_l \Delta c_l^P + \pi_l \Delta c_f^P\right) - K^P$$

[40] The objective of this figure is to illustrate the qualitative relationship between the model's parameters and variables. It is **not** numerically calibrated and the reader should **not** pay attention to the values. Calibrated simulations are presented later on the report.

4.1.4. Market equilibrium

The decision criteria identified in the previous section is for an individual carrier, and it is conditional on their expectations regarding what other carriers are going to do. In other words, ΔC^P depends on $\mathrm{Q^P} = Q\rho^P$: the return on investment, for a carrier, of equipping a given HDV depends on the proportion of equipped HDVs. In this model, ΔC^P is the same for all carriers. Therefore, the non-coordinated equilibrium is simple. Either all carriers find it optimal to equip all their HDVs, conditional to all other vehicles being equipped, or none. The condition for all HDVs to be equipped is simply:

$$\Delta C^P|_{\{\rho^P=1\}} \geq 0$$

As a consequence, in terms of market share, the simple model presented here has an "all-or-nothing" response to parameters. Indeed, denote by Π^P the share of equipped vehicles. Then:

$$\Pi^P = \begin{cases} 1 & \text{if} \quad \Delta C^P|_{\{\rho^P=1\}} \geq 0 \\ 0 & \text{else} \end{cases}$$

For example, Figure 16 illustrates how the market penetration of platooning depends on corridor length d_f and relevant traffic $\mathrm{Q^P}$.

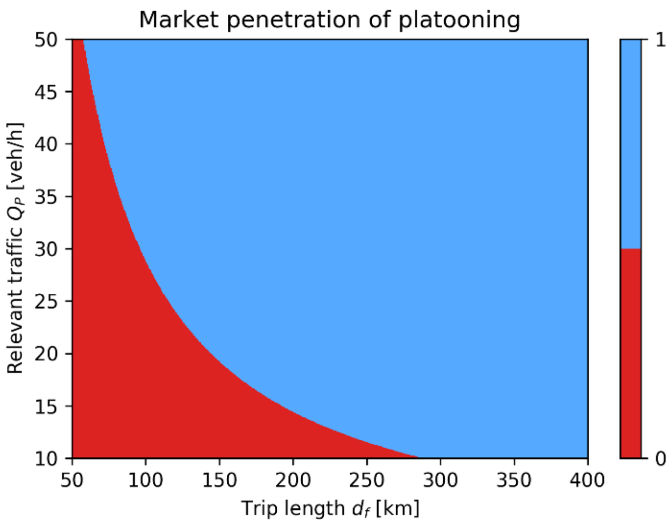

Figure 16: Market share of platooning equipped trucks in fleet, function of trip length and relevant traffic[41]

Consistently with Figure 15, the delimitation between market share 0% and market share 100% is oriented top left – bottom right on Figure 16. As expected, it depends directly on the price of the technology: the higher, the more the delimitation will move towards the top right corner of the graph,

[41] The objective of this figure is to illustrate the qualitative relationship between the model's parameters and variables. It is **not** numerically calibrated and the reader should **not** pay attention to the values. Calibrated simulations are presented later on the report.

meaning the conditions for full market penetration will not be so easily reached, as intuitively expected.

A last issue remains open: it is not because 100% of vehicles are equipped with the platooning technology that every truck on the road will be in a platoon. Indeed, the actual share of trucks in platoons among all trucks on the road is:

$$\Pi_r^P = \Pi^P \pi^P \frac{d_f - d_{iv}^P - d_w\left(d_{iv}^P\right)}{d_f}$$

In other words, out of a theoretical 100% share of trucks running in platoons, should be removed the trucks which won't join platoons at all, and, for those which are going to form platoons, the distance they run before platoon formation. Figure 17 illustrates how the share of platoons among the traffic depends on some of the model's parameters.

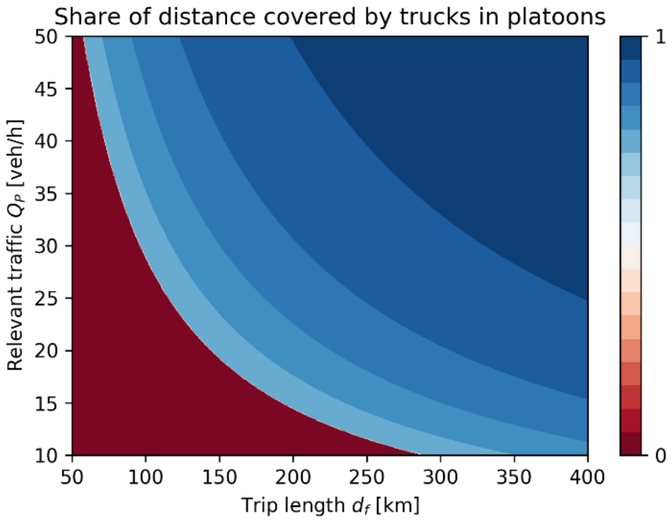

Figure 17: Share of trucks in platoons in traffic, as a function of trip length and relevant traffic[42]

Unsurprisingly, the closer from the situation where platooning gets irrelevant to carriers, the lower the share of platooning in traffic. As one can observe from the figure, when no trucks are equipped, the share of platooning in traffic is obviously zero. However, on the other side of the picture, the situation is not symmetric. Indeed, even in the frame of our ideal model, where 100% of the fleet is equipped with platooning, the share of trucks in platoons can get as low as about a third of the total traffic.

[42] The objective of this figure is to illustrate the qualitative relationship between the model's parameters and variables. It is **not** numerically calibrated and the reader should **not** pay attention to the values. Calibrated simulations are presented later on the report.

The bi-level nature of the issue of truck platooning is strikingly clear:

- Truck drivers will joint platoon only under favourable circumstances. On average, there should be enough trucks sharing common routes and enough relevant traffic for trucks to find suitable matching candidates, i.e. other trucks willing to form a platoon, with a low platoon formation cost. The savings allowed by platoons should be enough to more than compensate coordination costs. The value of platooning is that of those savings, when they are realized, and net of the coordination costs.

- Carriers will acquire the platooning technology if there are enough opportunities for platooning for the trucks which will be equipped. This comes at the cost equipping each truck, and brings the net benefit discussed above.

Both levels are interconnected: the amount of opportunities for a truck to find a suitable candidate depends on the proportion of trucks which are equipped. The proportion of trucks which are equipped depends on the opportunities for trucks to form a platoon. Both levels depend on the intrinsic savings brought by platooning. The bi-level structure of the market, and the interdependency between the decisions of carriers can be considered as a positive reinforcement loop. Such a loop should not be considered as an automatic enhancement of the value of platooning: on the contrary, it results in the presence of thresholds, or critical mass, which, in turn, depend on the intrinsic savings allowed by platooning.

There is even a third level, not modelled, but not secondary: the decision of OEMs and more generally of investors to actually develop the technology to full market readiness, including operational PSP service. Conceptually, the issue is very similar to that of the fixed cost, for a carrier, of truck platooning equipment against the uncertain benefit of benefiting from the technology: OEMs and investors need to balance the fixed (but uncertain) cost of developing the technology fully against the uncertain willingness of carriers to actually acquire for it.

The conclusions of this static modelling exercise are exactly consistent with those of the qualitative business case analysis developed in Section 3 of this report. Section 3 further insists on the importance of the spatial context, and of the actual activity pattern of each truck. Those aspects could have been introduced in the static model, but at a considerable cost and with limited additional insights, notwithstanding the lack of suitable data to calibrate such a model.

An important aspect, that was ignored until now, is that of the dynamic nature of the market. The static model developed in this section has not been developed with the only objective to elaborate or confirm the qualitative discussion presented in Section 3. Its second main purpose is to be the main component of a dynamic model of platooning, developed in the next section.

4.2. Dynamic microeconomic model of platooning market uptake

One of the main characteristics of the truck market is that trucks are durable assets. They have a lifespan of several years. For example, in France, long haul semitrailers are held by carriers for about six years on average (Comité National Routier, 2021), after which they are typically sold to other carriers, in other countries, who use them for many more years. As a consequence, the market presents inertia: a new technology without retrofit will take years to diffuse, even if all new vehicles come with it.

The previous sections essentially discussed the nature of platooning from a static perspective. This was necessary to understand and highlight the internal microeconomic structure of the market. However, there was an implicit assumption that all carriers would take their own equipment decisions simultaneously, with full information about what other carriers would decide, resulting in an equilibrium where decisions are consistent with expectations. In this section, the dynamic dimension of the market is made explicit.

The section proceeds as follows: first, a fleet renewal model is presented. Second, parameters are determined for calibration. Eventually, simulations are discussed.

4.2.1. Fleet renewal model

The renewal model introduced in this section is a rather simple one. It is designed so as to easily integrate the carrier decision model developed in Sections 4.1.2 and 4.1.3. Time is discrete, and starts at $t = 0$, when the platooning technology first becomes available. Fleet size, denoted by F, is constant over time. All trucks have a lifespan of T time periods. Trucks are replaced when they exit the fleet, i.e. when they reach the end of their technical life[43]. At $t = 0$, the ages of the trucks in the fleet are spread between 0 and T with uniform density $f = F/T$. At the end of each period t, the amount Plt_t of platoon enabled trucks in the fleet is publicly disclosed; and so is the adoption rate ρ_t. Each carrier decides to equip their new trucks based on that public information. The model doesn't assume that carriers consider the rate can increase in the future[44].

At time $t = 0$, a proportion p_0 of the exiting trucks are replaced by platoon enabled trucks. As it is done in numerous papers about the economics of innovation, think of this proportion as early

[43] This simplifies two issues. First, trucks are typically not used up to the point where they can no longer run in many European countries; they are then sold and used in other countries. Second, there is a residual value, and that value depends on what other alternatives appear in the market at a given time. Take the example of a carrier who has owned a given truck for five years and who planned to keep it for an additional year, based on the current economic conditions (including the carrier's current knowledge about how truck technologies change over time). If a technologic shock appears in the market, the carrier may reevaluate their decision, and sell the truck sooner. These two features of the truck market would require considerable work and data to be integrated in the model; they were left aside.

[44] This is the myopic assumption. A correct treatment of the strategic expectations of each carrier in a quantitative model would also a very complicated mathematical and microeconomic issue.

adopters: either they assume, for some reason, that the technology is going to overcome the market, or they draw some particular, idiosyncratic benefit from it, not represented in the model.

The case of own-account platooning

One case, not discussed in detail in this report, is that of platooning between trucks of a given carrier or, for some very large shippers, for own-account transport. There can be situations where, from plant or warehouse A to plant or warehouse B, the freight flow is so large that several full semi-trailers are dispatched from A to B each week or even each day. In some of these cases, one could reduce the shipment frequency in order to directly dispatch platoons and benefit from platooning internally. By the way, in this particular case, the issue of financial compensation between the leader and the follower of a platoon is void.

This situation is ideal, and one should not expect it to be met often in practice, quite the contrary. First, intense commodity flows from point A to point B (not from zone to zone) are far from being that frequent. Second, doing so incurs inventory costs for shippers, because the commodities have to be accrued longer before being dispatched, and this comes at the cost of higher inventory costs, higher warehousing costs, and longer delivery lead times: there is no reason for that trade-off to tilt systematically, or even often, on the side of dispatching platoons. In a way, this question is conceptually very similar to that of using road transport vs rail transport, and in practice road transport is often chosen. For a thorough theoretical and empirical discussion of the matter, the reader can consult Baumol and Vinod (1970), and Combes and Tavasszy (2016). However, in the frame of this work, said platooning adopters can be considered to be part of early adopters.

Let us now resume the presentation of the fleet renewal process. From $t = 1$ onward, companies which need to renew dying trucks need to decide if they acquire a platoon enabled truck, or not. This trade-off depends on the monetary gains platooning is expected to generate, which in turn depend on the share of the trips the companies expect their future truck to operate within platoons. As explained in the previous sections, the higher the number of platoon-enabled trucks on the roads, the more numerous the opportunities for traveling within platoons, and the higher the share of the trips to be made within platoons.

The adoption rate of platoon-enabled trucks changes from one period to the next. As per the assumptions made beforehand, the decisions of carriers to buy platoon enabled trucks, or not, at period t, is assumed to depend on the rate of adoption ρ_{t-1} made public at the end of the previous period. Denote by P_t the probability that a carrier buys a platoon-enabled truck. Then, at period t, P_t depends on all the parameters of the model, including the adoption rate at the end of the previous period. For readability, and given the pivotal role of ρ_t, P_t is denoted as a function of ρ_{t-1}: $P_t = P(\rho_{t-1})$.

The fleet model distinguishes several epochs, or generations: during the first epoch, all trucks needing replacement are conventional ones. During the next epochs, some of the trucks needing replacement are platoon-enabled. The mathematical treatment should be different. As a matter of fact, the reader may be surprised by the approach, which seems unnecessarily complicated: it is made necessary by the choice of the authors to introduce a random component in the model and to keep track of the decisions of carriers between time periods. This is the translation, in the model, of the spatial heterogeneity discussed in Section 3.1.2 of this report (see, in particular, Figure 3 and its discussion). This spatial heterogeneity highlights the fact that some carriers will be more interested in platooning than others, for reasons which are both exogenous and stable in time. It is necessary that this time stability is accounted for in the model, and this cannot be done with the introduction of an i.i.d. process, be it implicit or not[45]. Several approaches can be imagined to address this issue; the one opted for in this model is to make the process quite explicit, by tracking the decisions of carriers at an aggregate level. More concretely, when trucks need replacement, we examine whether they are conventional, or platoon-enabled. It is assumed that if the trucks are already platoon enabled, then the carrier will not go back to conventional trucks. On the contrary case, the carrier may opt for a platoon enabled truck.

In practice, the dynamic model's architecture is as follows. Three epochs are considered: the time frame being more or less of a decade per epoch, it is enough to provide adequate highlights about the market's behaviour in the long run. At any time period, exactly $f = F/T$ trucks are replaced. They all have a common, fixed lifetime of T periods. Depending on the epoch:

- A $t = 0$,
  - A one-time contingent of early adopters acquires platoon enabled trucks. As a result, the number of platoon-enabled trucks entering the fleet is $p_0 f$. Symmetrically, $(1 - p_0)f$ conventional trucks enter the fleet.
  - The total number of platoon-enabled trucks in the fleet is $Plt_0 = p_0 f$.
  - The total adoption rate at the end of period 0 is $\rho_0 = p_0/T$.
- From $t = 1$ to $T - 1$ (first epoch):
  - The proportion of platoon-enabled (resp. conventional) trucks entering the fleet it $P(\rho_{t-1})f$ (resp. $\big(1 - P(\rho_{t-1})\big)f$).
  - The total number of platoon-enabled trucks in the fleet is

[45] i.i.d. means independent and identically distributed. Representing the choice of a group of stakeholders over repeated time periods by a probability implies that the underlying source of alea is i.i.d., or very similar to i.i.d. This is not the case here, where, if some carriers choose platooning at a given time period, they will never go back to conventional trucks afterwards, because the benefit from using platoon-enabled trucks can only improve in time.

$$Plt_t = f\sum_{i=0}^{t} P(\rho_{i-1})$$

- And

$$\rho_t = \frac{1}{T}\sum_{i=0}^{t} P(\rho_{i-1})$$

- From $t = T$ to $2T - 1$ (second epoch):
  - The number of conventional trucks to be replaced is $\left(1 - P(\rho_{t-T-1})\right)f$. As a consequence, from the replacement of this segment of the fleet, $P(\rho_{t-1})\left(1 - P(\rho_{t-T-1})\right)f$ platoon-enabled trucks enter the fleet, and $\left(1 - P(\rho_{t-1})\right)\left(1 - P(\rho_{t-T-1})\right)f$ conventional trucks enter the fleet. All these new trucks will be replaced at $t + T$.
  - The total number of platoon-enabled trucks at the end of period t is:

$$Plt_t = f\sum_{i=0}^{t} P(\rho_{i-1}) - f\sum_{i=0}^{t-T} P(\rho_{i-1})P(\rho_{i-1+T})$$

  - The platooning adoption rate at the end of period t is:

$$\rho_t = \frac{1}{T}\sum_{i=0}^{t} P(\rho_{i-1}) - \frac{1}{T}\sum_{i=0}^{t-T} P(\rho_{i-1})P(\rho_{i-1+T})$$

- From $t = 2T$ to $3T - 1$ (final epoch of the simulation):
  - The number of conventional trucks to be replaced is $\left(1 - P(\rho_{t-1})\right)\left(1 - P(\rho_{t-T-1})\right)f$. As a consequence, from the replacement of this segment of the fleet, $P(\rho_{t-1})(1 - \rho_{t-1})\left(1 - P(\rho_{t-T-1})\right)f$ platoon-enabled trucks enter the fleet, and $\left(1 - P(\rho_{t-1})\right)^2\left(1 - P(\rho_{t-T-1})\right)f$ conventional trucks enter the fleet. All these trucks are replaced at $t + T$.
  - The total number of platoon-enabled trucks at the end of period t is:

$$Plt_t = f\sum_{i=0}^{t} P(\rho_{i-1}) - f\sum_{i=0}^{t-T} P(\rho_{i-1})P(\rho_{i-1+T}) \\ - f\sum_{i=0}^{t-2T}\left(1 - P(\rho_{T+i-1})\right)P(\rho_{i-1})P(\rho_{i-1+2T})$$

- The platooning adoption rate at the end of period t is:

$$\rho_t = \frac{1}{T}\sum_{i=0}^{t} P(\rho_{i-1}) - \frac{1}{T}\sum_{i=0}^{t-T} P(\rho_{i-1})P(\rho_{i-1+T}) \\ - \frac{1}{T}\sum_{i=0}^{t-2T}\left(1 - P(\rho_{T+i-1})\right)P(\rho_{i-1})P(\rho_{i-1+2T})$$

The model can be extended to any time period, but gets increasingly complex, with additional terms in each equation for each additional epoch of T periods.

The main characteristics of the model are the following ones. First, as the share of platoon-enabled trucks increases in the fleet, the population of trucks which can shift from conventional to platoon-enabled decreases. Second, the adoption rate can only increase when other economic parameters are constant over time. Third, the profitability of platooning can also only increase when other economic parameters remain stable over time.

Consequently, during the first periods following the advent of platooning, the number of trucks that would switch to it would be low because even if the number of companies that can do so is high, platooning profitability would be too low. After a certain number of periods, the number of trucks that switch to platooning would be also low. However, the reason here would not be the profitability. At that stage, profitability would be near its highest level thanks to an important adoption rate. The reason here is the low number of trucks that would have not switched yet to platooning. This leads the curve describing the evolution of the platooning adoption rate over time to have a “low plateau” during the first periods following the advent of platooning, and a high plateau after a certain number of periods. This is consistent with the “S shaped” adoption rate curve characterized by the literature related to the economics of innovation. Determining the length of the low plateau and when the high one starts is impossible analytically. The simulations presented later show that many characteristics play a crucial role in explaining their variations.

4.2.2. Platooning equipment model

Let us now focus on the probability that a given carrier buys a platoon-enabled truck when renewing a platoon, at time t. The decision is modelled as a probabilistic one, to mirror the heterogeneity of the constraints and preferences of carriers. It is a variation of the model developed in Section 4.1.3. From that model, if the truck covers distance D each year, then the net value of acquiring a platoon enabled truck is:

$$\Delta C^P = \frac{D}{d_f}\left(\pi_l \Delta c_l^P + \pi_l \Delta c_f^P\right) - K^P$$

If $\Delta C^P \geq 0$, then it is profitable to acquire a platoon enabled truck. The decision depends on D, and on the fixed cost of the platooning equipment K^P.

What works for one vehicle can work for a fleet, if one accounts for the fleet heterogeneity. There are several ways in which trucking companies and truck economic life-cycle differ. In the following model, we focus on the heterogeneity in distance. More precisely, what is addressed is the heterogeneity in distance travelled on a platooning compatible network. To do so, we consider that a given truck i covers a number N_i of trips of length d_f each year. We also assume that N_i is a realization of a random variable with expected value N and error ε_i:

$$N_i = N + \varepsilon_i$$

When a firm considers the replacement of truck i, they will opt for a platoon-enabled truck if and only if $\Delta C^P \geq 0$. Therefore, after adequate variable manipulation, the probability that a given truck is replaced by a platoon-enabled one is:

$$P(\rho) = \Pr\left\{N\left(\pi_l \Delta c_l^P + \pi_l \Delta c_f^P\right) - K^P \geq 0\right\}$$

where ρ is the share of platoon-enabled vehicles in the truck traffic Q, or, equivalently: $Q^P = \rho Q$. This defines the probability P, function of ρ, which enters the equations describing the dynamics of the platooning market share. The development of a static equilibrium, as written in Section 4.1.4, is no more required: the dynamic model, as explained above, is based on an incremental evolution of market shares.

4.3. Simulations

On the basis of the theoretical framework developed in the previous section, it is possible to compute the evolution of the platooning market over a series of scenarios and sensitivity tests. The simulations are presented in this section. Before getting to the results, the numerical assumptions are discussed below.

4.3.1. Numerical assumptions

First of all, it should be noted that the simulation proceeds in iterative steps of **one week** each. Each simulation proceeds over about eight years.

The simulation is based on a representative fictional corridor. The length of the corridor is important: the longer, the more benefit trucks yield from platooning, as the cost of platoon formation is fixed and the benefits of platooning increase with the distance covered by a platoon. The value of 360 km is opted for, as its order of magnitude is consistent with the distance a truck driver can typically drive between two breaks. A sensitivity test is presented, with corridor length 250 km. One can think about a network where platoons need to dissolve regularly, either because not many trucks share the same route as part of their trips, or because highways get close to cities and platoons have to break because of too many cut ins or cut throughs of other vehicles, or because traffic congestion is too important and speed too slow for platooning to bring actual benefits.

Truck traffic has to be intense for platooning to have actual value: relevant traffic density has a direct downwards influence on coordination costs. In the median case, a rather large value is defined, with a traffic of 15000 vehicles per day, spread over 12h. A sensitivity test is produced with a higher value of 20000.

Cruise speed and waiting speed have a very direct impact on the value of platooning. In the median case, cruise speed is assumed to be 80 km/h and lead trucks are assumed to slow down by 10 km/h during platoon formation. A sensitivity test is analysed, where cruise speed is 90 km/h, to examine how much the results differ in countries where that latter value is the actual speed limit for semi-trailers.

Regarding the cost component of trucking, fuel consumption and other costs are distinguished. In addition, the opportunity cost of having freight delivered later is accounted for. The cost was calibrated as follows: according to the Comité National Routier, the hourly cost of trucking consists of a workforce cost (about 15 €/h) and a fixed vehicle cost (15 €/h). The opportunity cost of delivery delay is about 5 € (assuming a payload of 10t and a shipper value of time of 50 c€/t/h). Those components add up to a hourly cost of 35 €/h. Regarding fuel cost, the value is assumed to be 1,1 €/L. A sensitivity test is produced, where the cost increases by 5 % year on year; this sensitivity test illustrates the evolution of the business case of platooning should the tension on oil markets increase continuously in the near future, or an increased fiscal pression in European countries, as one possible instrument towards decarbonation.

An additional parameter in the calculation of costs is the average number of trips per year, N_0. This number is the result of the maximal theoretical number of trips a truck can make over a corridor of given length, over 6 days per week, 9 hours per day, 250 days per year. The parameter depends on the corridor's length. Its value, for a corridor length of 360 km, is about 427 trips per year, or approximatively 8,2 trips per week.

Eventually, the fixed cost of the platooning equipment is unknown. For the simulations, all simulations are computed with values ranging from 2000 € to 6000 €. One sensitivity test assumes that this cost decreases by 5% year on year.

Given the chicken and egg nature of the platooning market, a very important assumption is the share of early adopters. In particular, if this share is zero, then the market share of platooning will stay at zero, regardless of the other parameters. In the model, early adopters are represented by an exogenous insertion of platoon enabled trucks in the fleet, during the model's first week. Each week, about 0.3% of the fleet is replaced. In the median case, it is assumed that 50% of the first wave (i.e. 0.15% of the total fleet) are early adopters. Sensitivity tests are computed, at 40% and 60%.

All numerical values are recapitulated in Table 1 below.

Variable	Value	Unit	Sensitivity test
Truck Traffic	15000	vehicles/direction/day	+5000
Cruise speed	80	km/h	+10
Waiting speed	70	km/h	-10/+10
Hourly trucking cost	35	€/h	-
Fuel price	1,1	€/L	-
Fuel price evolution	0%	YoY	+5%
Corridor length	360	km	-110
Early adopters	50%	(share of first wave)	-10%/+10%
Price of platooning equipment	4000	€/vehicle	-2000 to +2000
Evolution of the price of platooning equipment	0%	YoY	-5%

Table 1: Business case dynamic simulation, median case parameters and sensitivity tests

Regarding the fuel savings allowed by platooning, two scenarios are distinguished: a base case, consistent with the Platooning Support Function as defined in the ENSEMBLE project, and an improved case, where fuel savings are higher. In the base case, according to the literature with an adaptation to real life conditions, it is assumed that the leader vehicle saves 0% while the follower vehicle saves 5%. In the improved case, it is assumed a technology improved over what the Platooning Support Function allows, and that the fuel savings of the leader and follower vehicles are 0% and 10% respectively. Those assumptions are summarized in Table 2 below.

Assumption set	Leader truck fuel savings	Follower truck fuel savings
Base case (consistent with PSF)	0%	5%
Improved case	0%	10%

Table 2: Fuel savings assumptions

4.3.2. Numerical results: base case and median case

Based on the values presented in the previous section, simulations were computed. They are discussed below.

Simulation 1: base case

In the base case simulation, central values are assumed for all parameters (see Table 1) and the base case is considered regarding fuel savings (see Table 2). Under this set of assumptions, and for any reasonable choice of values for all parameters, there is no uptake of the market in the medium term. In other words, **there is no business case for spontaneous market uptake**. Platooning can only have a spontaneous market uptake with an improved core benefit: 5% fuel savings is too low, with believable equipment and coordination costs.

Simulation 2: median case

In the base case simulation, central values are assumed for all parameters (see Table 1) and, regarding fuel savings, the improved case is considered (see Table 2). The simulation is shown below:

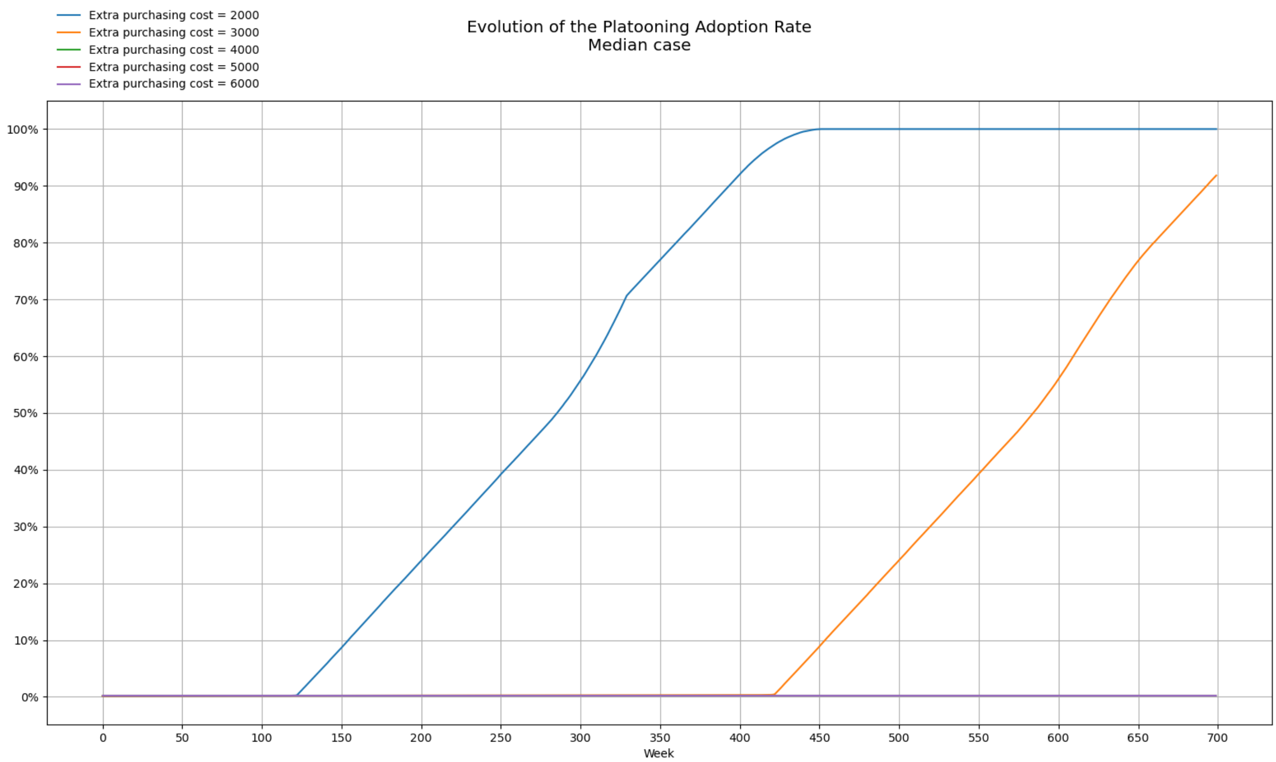

Figure 18: Median case simulation

As illustrated by Figure 18, market uptake is possible in the median case. However, it is slow, and only happens for low values of the platooning technology. Market uptake takes off visibly after two years and a half in the case where the technology is really cheap (2000 €). The take-off is delayed by more than three years if the technology costs 3000 €. For other values, market uptake doesn't happen over the course of the simulation.

Note that in this simulation, as in all the subsequent ones, the market uptake behaves as follows: first, it takes off, or not. When it takes off, it very quickly gets to a stable slope, which corresponds to the fleet renewal rhythm (assumed uniform). This is a result of the assumption that platooning equipment cannot be retrofitted on existing trucks. Then market uptake accelerates a bit, when some of the trucks which were renewed as conventional trucks during the previous epoch are replaced by platooning trucks. This explains the nonlinearity of the curve around the medium part of the simulation.

The market uptake means that equipping vehicles for platooning is profitable for freight carriers. However, the calculation of the net benefits should account for the associated costs, i.e. the equipment costs and the coordination costs.

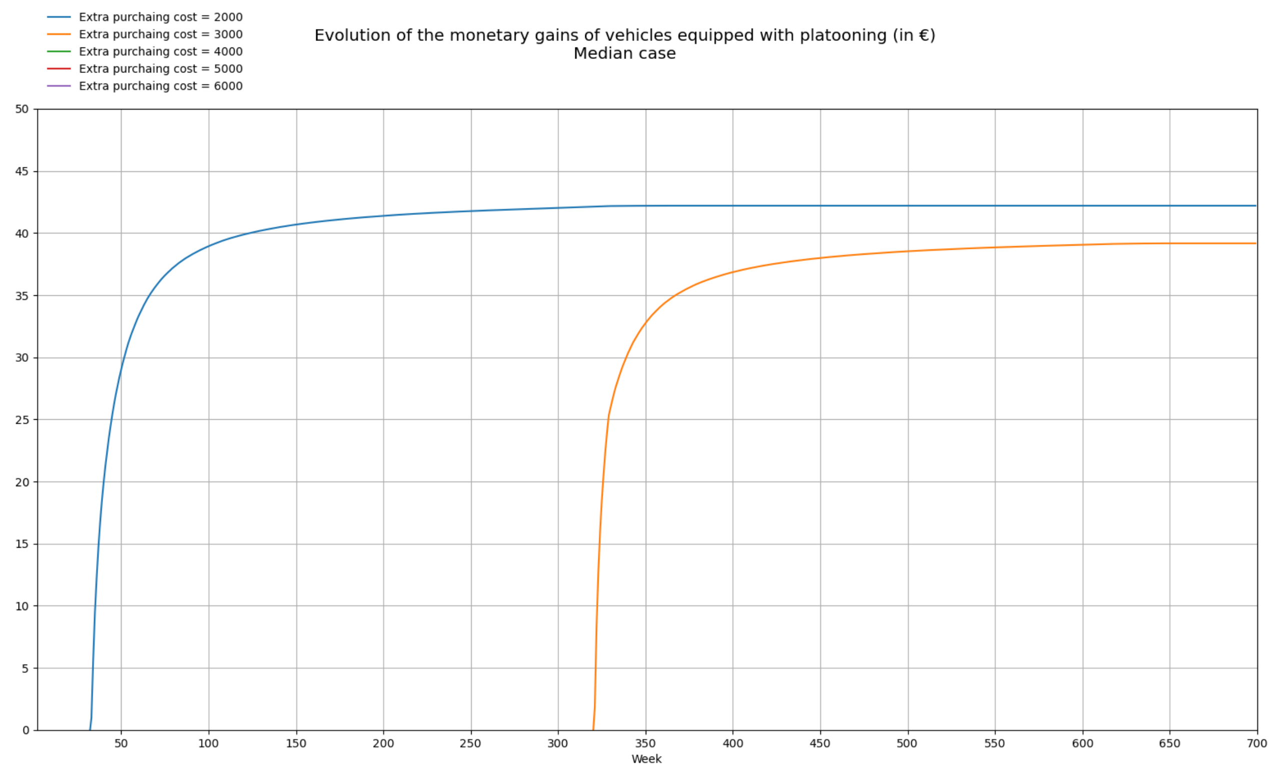

Figure 19: net monetary benefit of platooning, per vehicle, in euro per week

Figure 19 shows the average net benefit of platooning per equipped vehicle, per week. The benefits are conditional to market uptake: if there is no market uptake, the net benefit is zero. If there is a small market uptake, the average benefit is small. However, the benefit per vehicle per week increases very quickly with market uptake, then more slowly, up to an asymptotical value which cannot be exceeded. Due to the fact that these costs are computed net of all expenses, this asymptotical value decreases when the equipment cost increases.

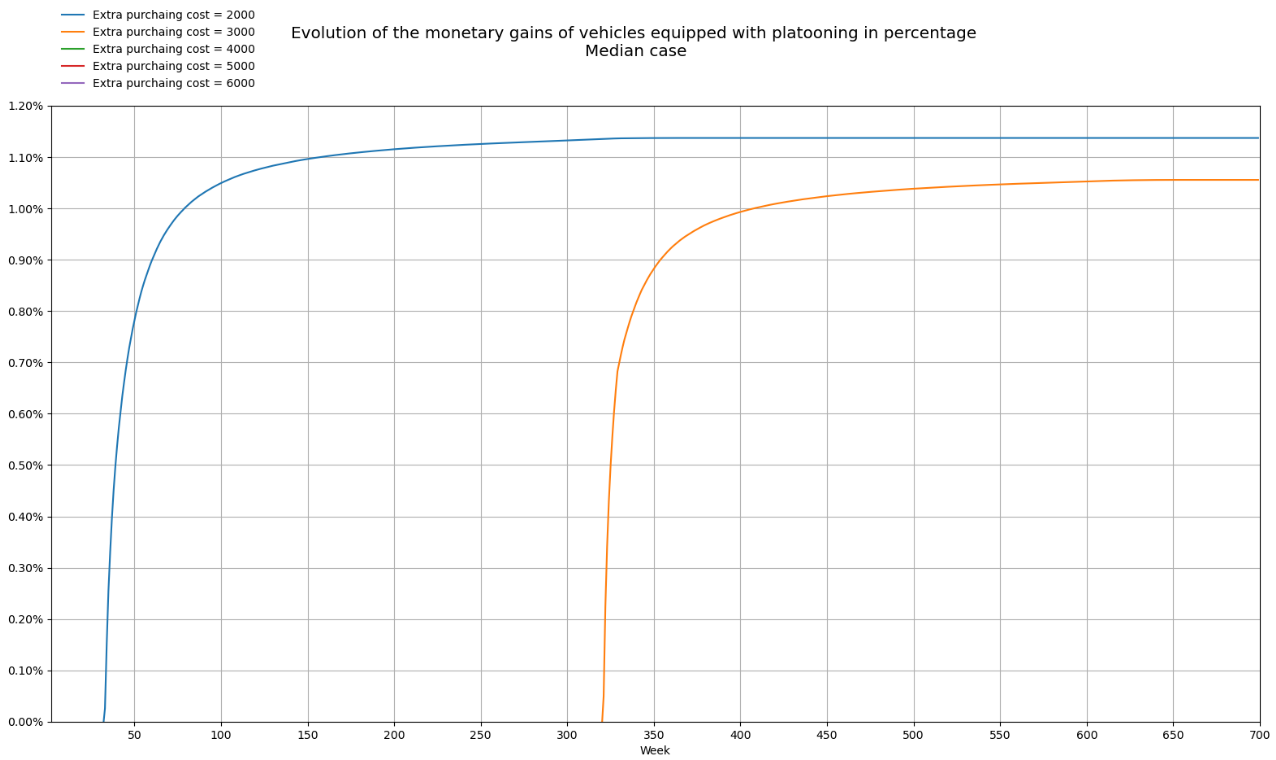

Figure 20: relative monetary benefit of platooning, per vehicle

Figure 24 illustrates the benefits of platooning in terms of relative impact on trucking costs. Those costs are computed on a per week basis, and encompass fuel costs, driving costs, and actuated capital costs. They are average benefits for equipped vehicles. It should be noted that these net gains are relatively low in proportion to the generalized[46] costs of trucking, and that the maximal net benefit is about half the gross benefit due to fuel consumption savings. Asymptotical per vehicle benefit can reach values between 1% and 1.2% of generalized carrier costs, which is low, but still significant.

At the scale of the fleet, total benefits are limited by market uptake, which, in turn, is limited by the fleet renewal rhythm. This is illustrated by Figure 21 below, in relative terms. Asymptotical values are the same as for Figure 20 above, which is intuitively correct as 100% of the fleet is equipped in the long term when market uptake happens. In real life, one would need to account for the trucks which, due to their economic life cycle, would remain outside the platooning market, and correct the overall benefit relevantly.

[46] Note that the cost functions account for the shipper value of time, its perimeter is wider than the pure costs of carriers. However, the ratios are relevant: carriers do not bear the opportunity cost of travel time for shippers, but would need to correct their prices in case of a deteriorated level of service, and that would impact their revenue accordingly.

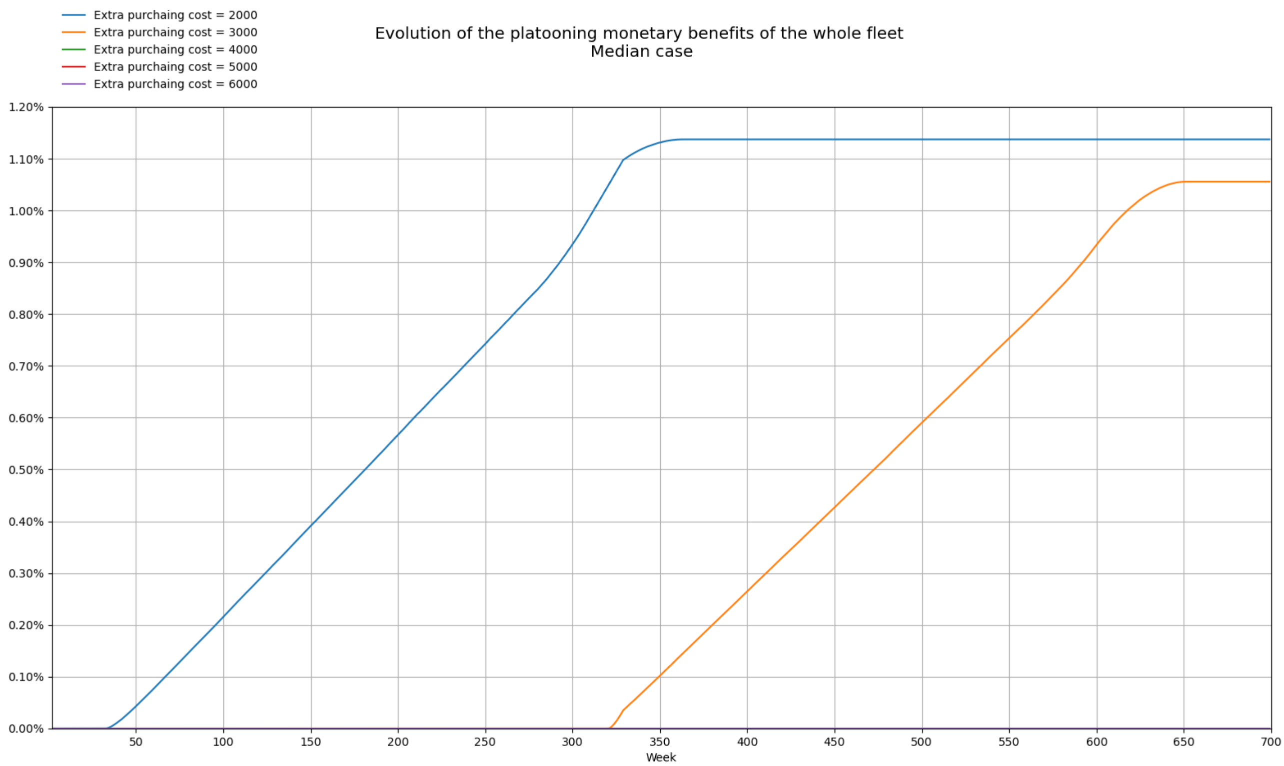

Figure 21: relative benefit of platooning, whole fleet

The core value of platooning, in these simulations, is that it allows for a reduced fuel consumption. This deserves a detailed examination. Note that the environmental benefits of platooning, if any, also stem from those fuel savings. According to Figure 22 below, those fuel savings behave mostly like monetary savings: without market uptake, there are no fuel savings. Once market uptake starts, individual fuel savings increase quickly, until an asymptotical value is reached. This asymptotical value corresponds to the theoretical value that would be reached on the market once all vehicles are equipped and virtually always in platoons.

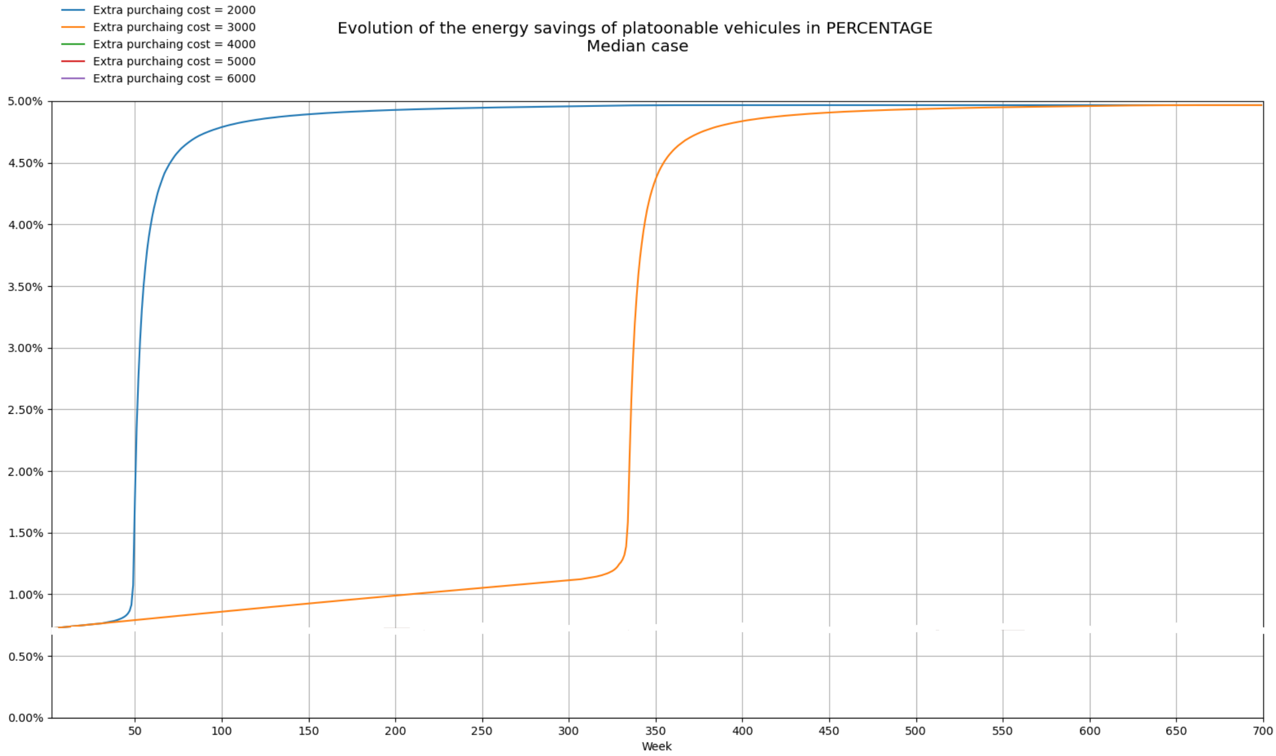

Figure 22: relative fuel consumption savings of platooning, per vehicle

Finally, Figure 23 illustrates the dynamics of the relative fuel savings for the whole fleet. Those savings behave similarly to the monetary benefits depicted by Figure 21: their increase is limited by the rhythm of fleet renewal, and reach an asymptotical value after a full renewal cycle. This asymptotical value is 5%, i.e. the average savings if all vehicles are in platoon, one follower for one leader.

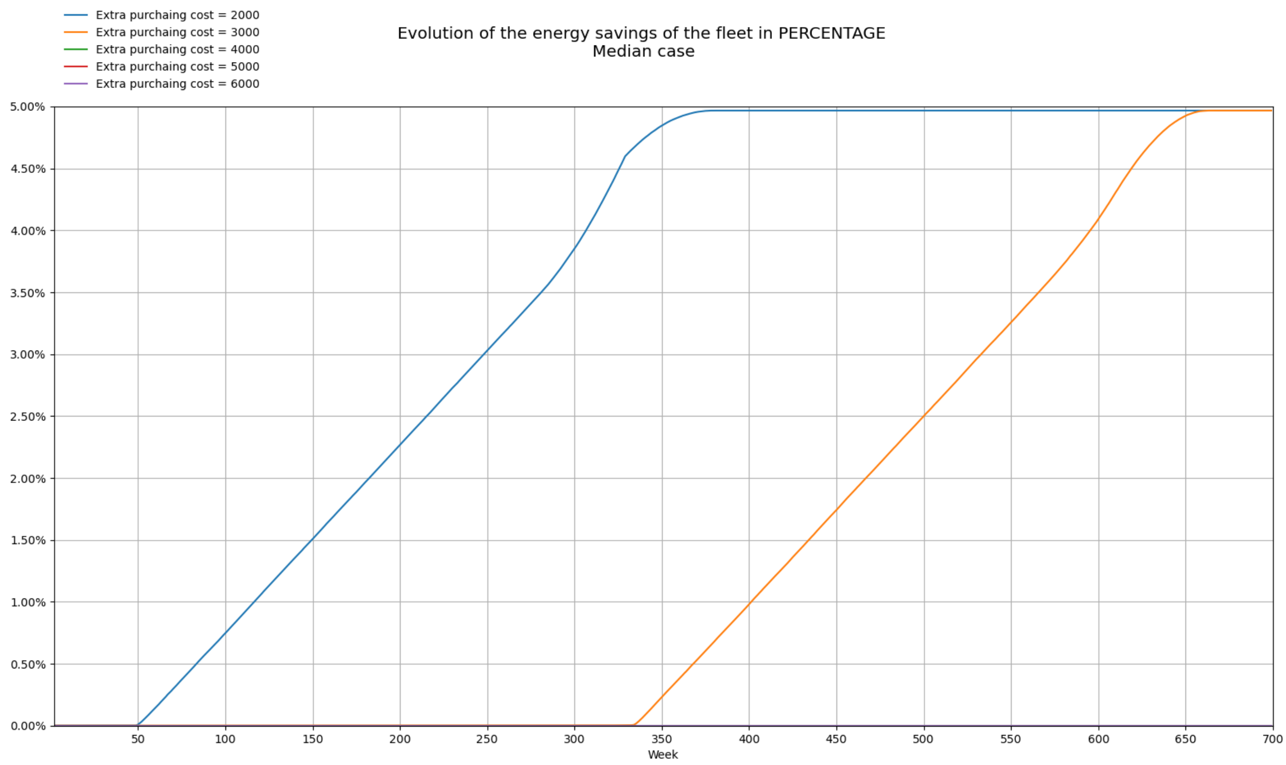

Figure 23: relative fuel consumption savings of platooning, whole fleet

Based on the two simulations: base case, and median case. Regarding the base case, it appears that platooning, as specified in the Platooning Support Function, has no business model in the current economic environment with reasonable assumptions of costs: coordination costs and platooning equipment costs cannot be compensated by the limited fuel savings platooning would make possible.

The median case shows, quite clearly, that this can be overturned if platooning were to yield higher benefits. If fuel savings were to reach a value of 10% for the following vehicle, then market uptake would happen, and yield actual fuel savings and monetary benefits once enough vehicles are equipped. This conclusion only holds if the equipment cost remains low.

4.3.3. Sensitivity tests

In this section, the market uptake is calculated in a series of variations of the median case. For the sake of brevity, fuel consumption savings and monetary savings are not presented, except in the case of Simulation 6, which assumes constantly increasing fuel prices. The results about monetary savings and fuel consumption savings are easily intuited though, as they behave with market uptake.

Simulation 3: more traffic

This simulation assumes a heavy-duty vehicle traffic of 20000 vehicles per day per direction, instead of 15000.

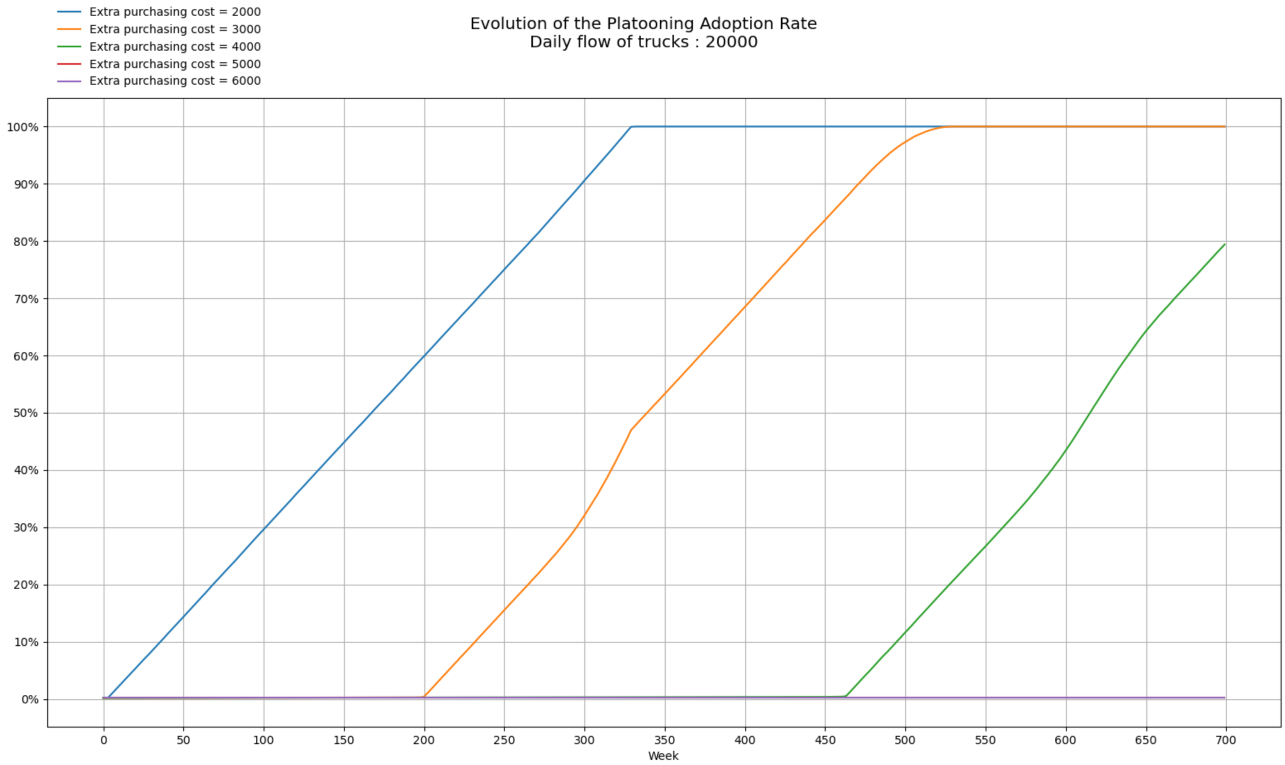

Figure 24: Median case, sensitivity test – higher traffic

Traffic density is one of the important drivers of the value of platooning: more traffic means more opportunities to find a matching candidate to form a platoon, and a lower coordination cost. This is mirrored in Figure 24, where the market uptake happens much faster than in the median case for similar conditions, and where market uptake happens, if late, with a cost of the technology of 4000 €.

Simulation 4: lower waiting speed

As discussed previously, the business case of platooning comes directly from fuel savings. However, fuel savings only happen when the platoon is formed. Therefore, the faster a platoon is formed, the more fuel is saved. This raised the issue of the speed of the lead vehicle when it slows down so that the follower vehicle can catch up and form a platoon: the lower this speed, the shorter the distance covered by the two vehicles before the platoon is formed and fuel savings start happening. Of course, the waiting speed shouldn't be too low, as that would raise serious road safety issues; thus, the 70 km/h assumption in the median case. The sensitivity test below shows, however, how sensitive the market uptake is to this design decision.

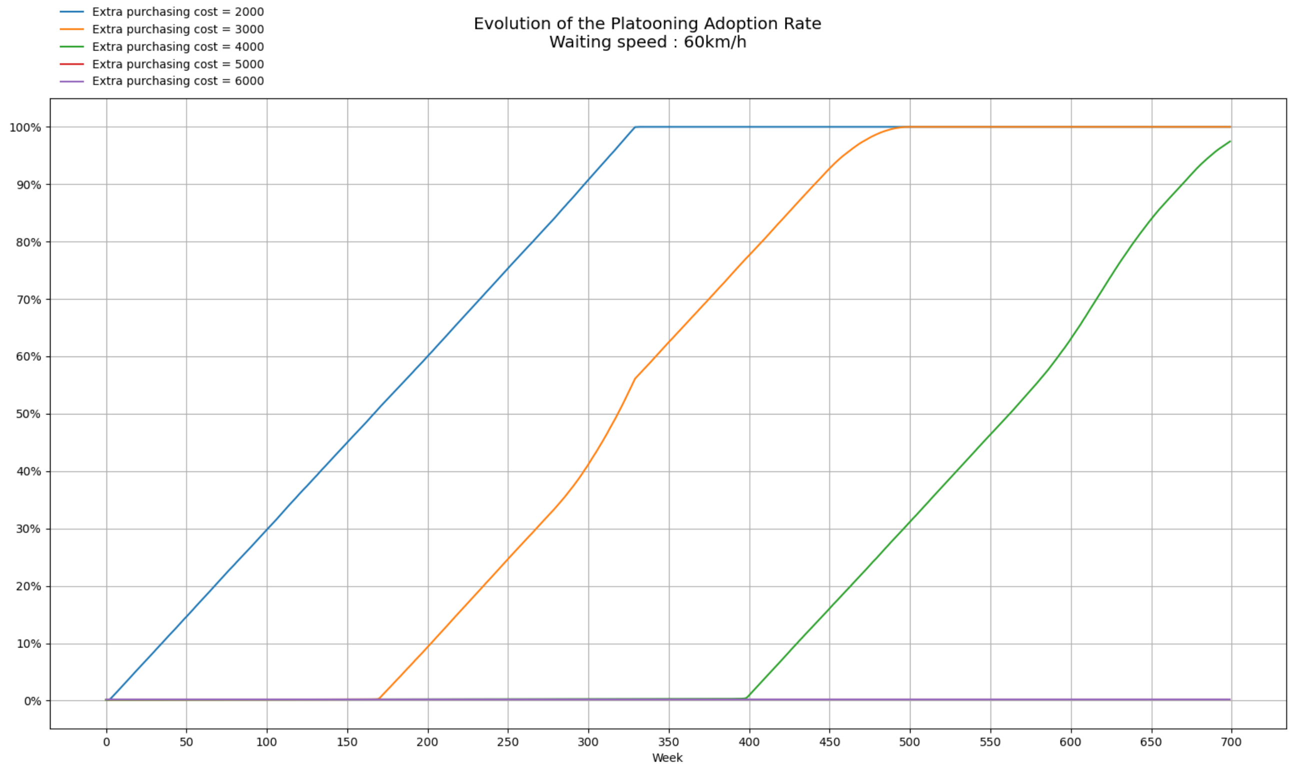

Figure 25: Median case, sensitivity test – lower waiting speed

Compared to Figure 18, the change is striking: market uptake happens much sooner, and for values of the cost of the technology which are much higher. Indeed, in this case as well as in the previous one, market uptake happens with a technology cost of 4000 €.

Simulation 5: Cruise speed 90 km/h and waiting speed 80 km/h

As explained above, the legal speed limit for trucks is not the same in all countries. This sensitivity test examines how much the conclusions of the median case depend on this particular variable. The waiting speed is taken to be 10 km/h lower than the cruise speed.

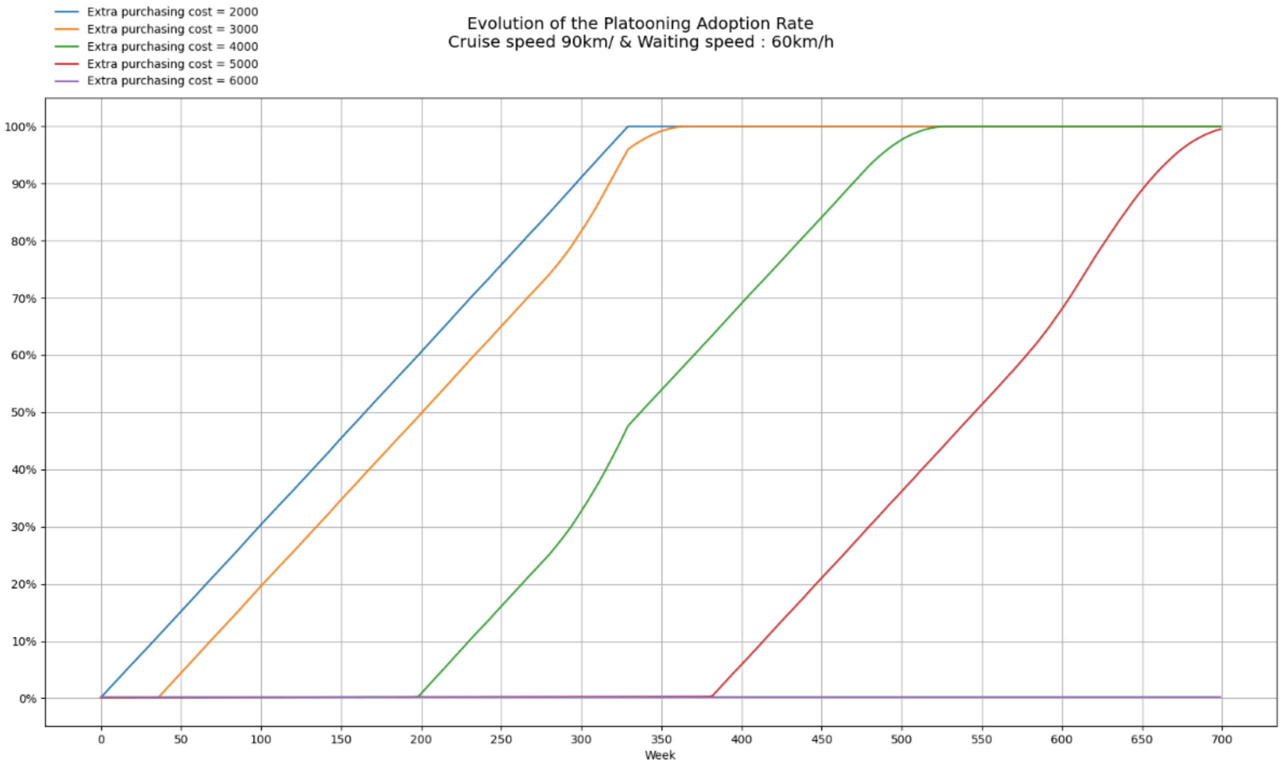

Figure 26: Median case, sensitivity test – higher cruise speed

The results of the simulation, as shown in Figure 26, are quite spectacular: the business case is substantially better. This is due to a somewhat indirect feature of the model, which actually mirrors an economic reality for platooning; in countries where trucks can run faster, they cover more kilometres per year. This represents additional opportunities to benefit for platooning, compared to the same fixed equipment cost; as a consequence, there is a strong shift towards the acquisition of the technology when compared with the median case. Market uptake happens much sooner, and is feasible, under the median case assumptions, for the whole range of tested values of the platooning equipment costs.

Note that the sensitivity test assumes the same fuel consumption at 80 km/h and 90 km/h. In reality, fuel consumption at 90 km/h is higher than at 80 km/h; therefore, the fuel savings due to platooning will be even higher, and the business case even better than the one calculated here.

Maximum legal speed is outside the scope of the instruments that can be acted upon to influence the market uptake of platooning. However, the sensitivity test contributes to showing how much the business case depends on the infrastructure networks and their regulation. All other things equal, countries with higher maximum legal speed are more favourable environments to the spontaneous uptake of platooning.

Simulation 6: fuel costs increasing over time

In this simulation, fuel costs are assumed to increase by 5 % per year, from the same starting value as in the median case.

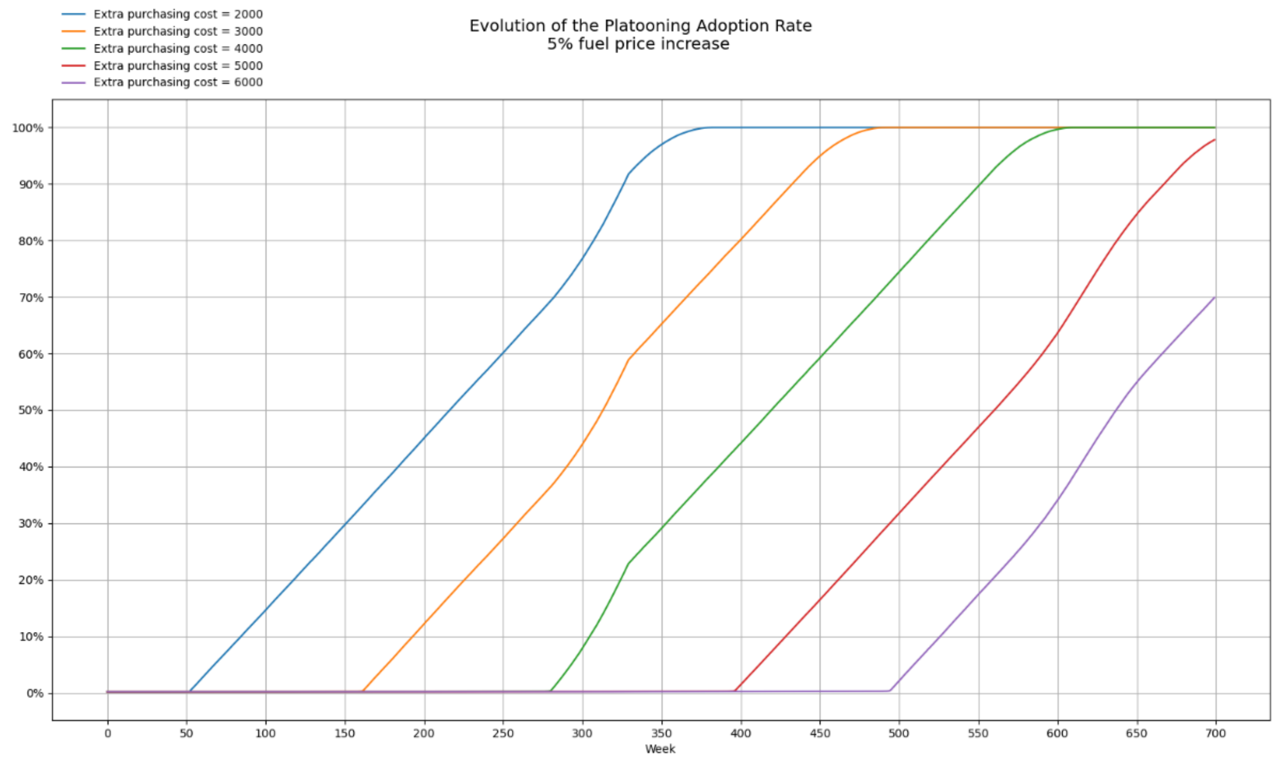

Figure 27: Median case, sensitivity test – fuel costs increasing over time

Unsurprisingly, the simulation shows a much faster uptake of platooning, and shows that the business case is valid for all tested values of the equipment cost. The equipment cost still has an influence on the moment where market uptake starts: to simplify, for all values of the equipment cost, it is as if there is a threshold past which fuel costs become high enough for platooning to be profitable. While this report doesn't address the possibly virtuous impact of platooning on the environmental impact of trucking, clearly, if fuel prices were to increase due to an increased fiscal pressure, the business case of platooning would be only improved.

In this scenario, the monetary benefits are higher than in the median case. Moreover, they increase in time (see Figure 20 and Figure 21), due to the increasing share of fuel in the carriers' expenses when fuel prices increase continuously.

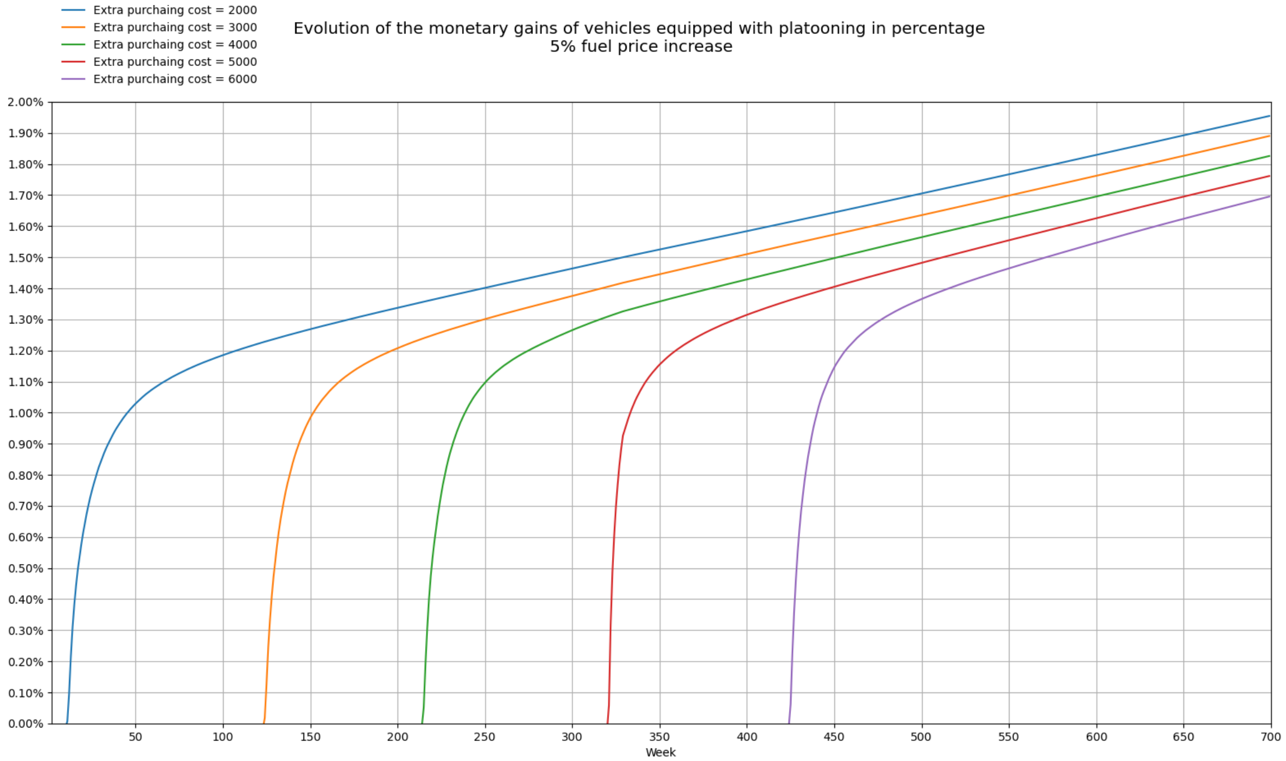

Figure 28: Median case, sensitivity test – fuel costs increasing over time. Relative monetary benefit of platooning, per vehicle, fuel price increasing over time

One also observes from Figures 28 and 29 that the benefits of platooning decrease with the cost of the equipment technology.

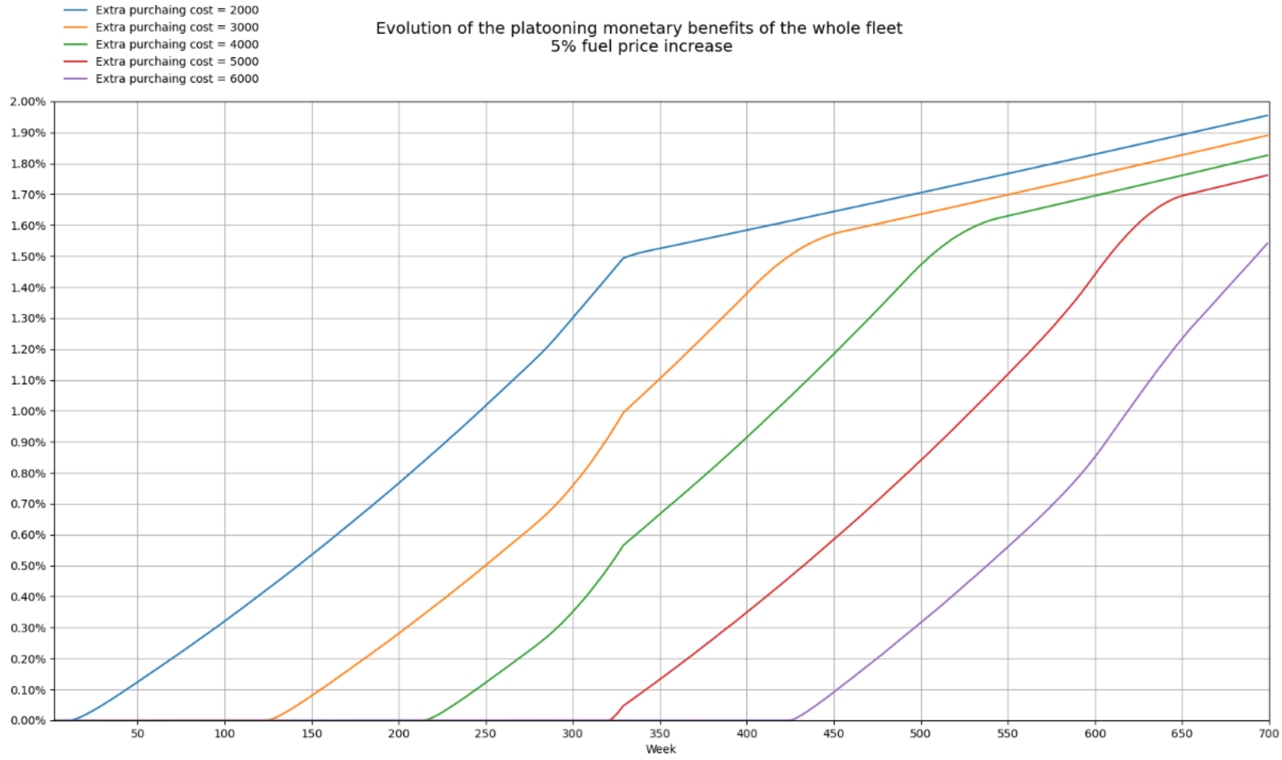

Figure 29: median case, sensitivity test – fuel costs increasing over time. Relative benefit of platooning, whole fleet, fuel price increasing over time

In terms of fuel savings, the conclusion is only partially similar (Figure 29, Figure 30). Indeed, increased fuel prices improve the business case of platooning and speeds up market uptake. However, physical gains in terms of fuel consumptions remain bound by the same asymptotical limit than in the median case, due to the technical characteristics of platooning.

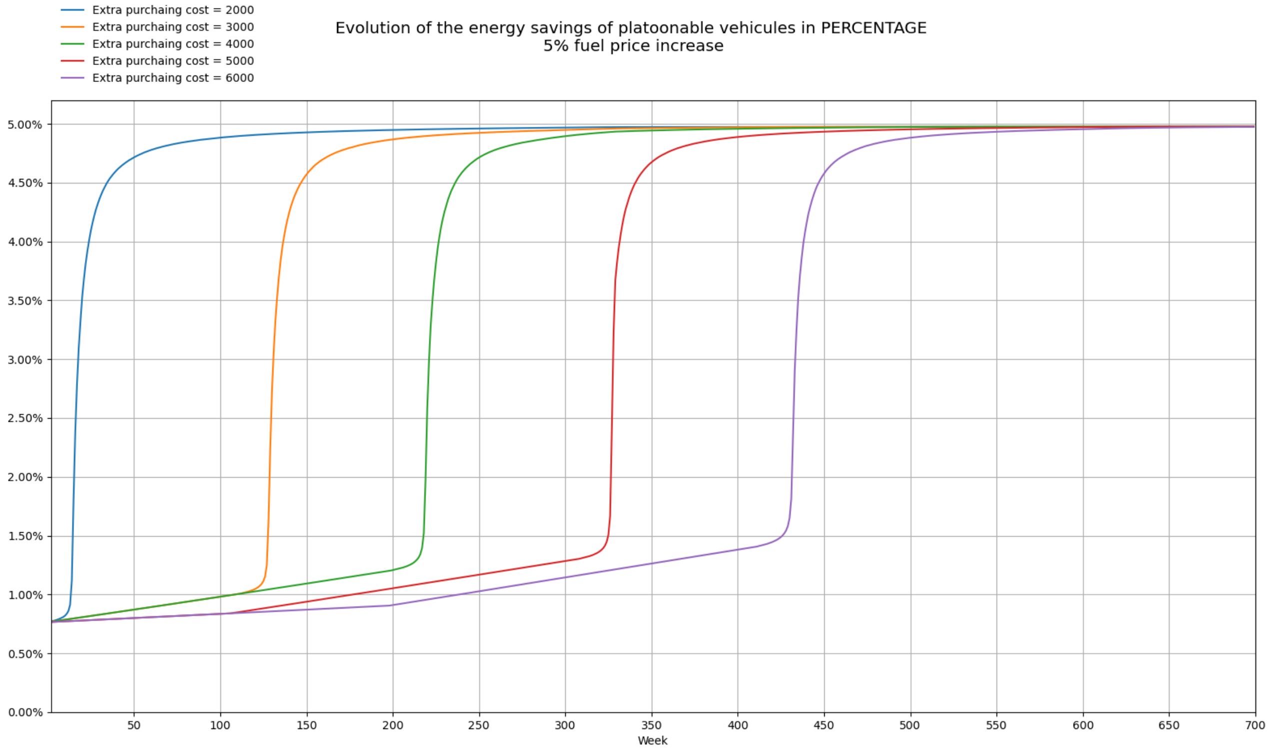

Figure 30: median case, sensitivity test – fuel costs increasing over time. Relative fuel consumption savings of platooning, per equipped vehicle, fuel price increasing over time

The same behaviour is observed at the vehicle and at the fleet level. As in all other cases, the fleet level differs because of the rhythm of fleet renewal.

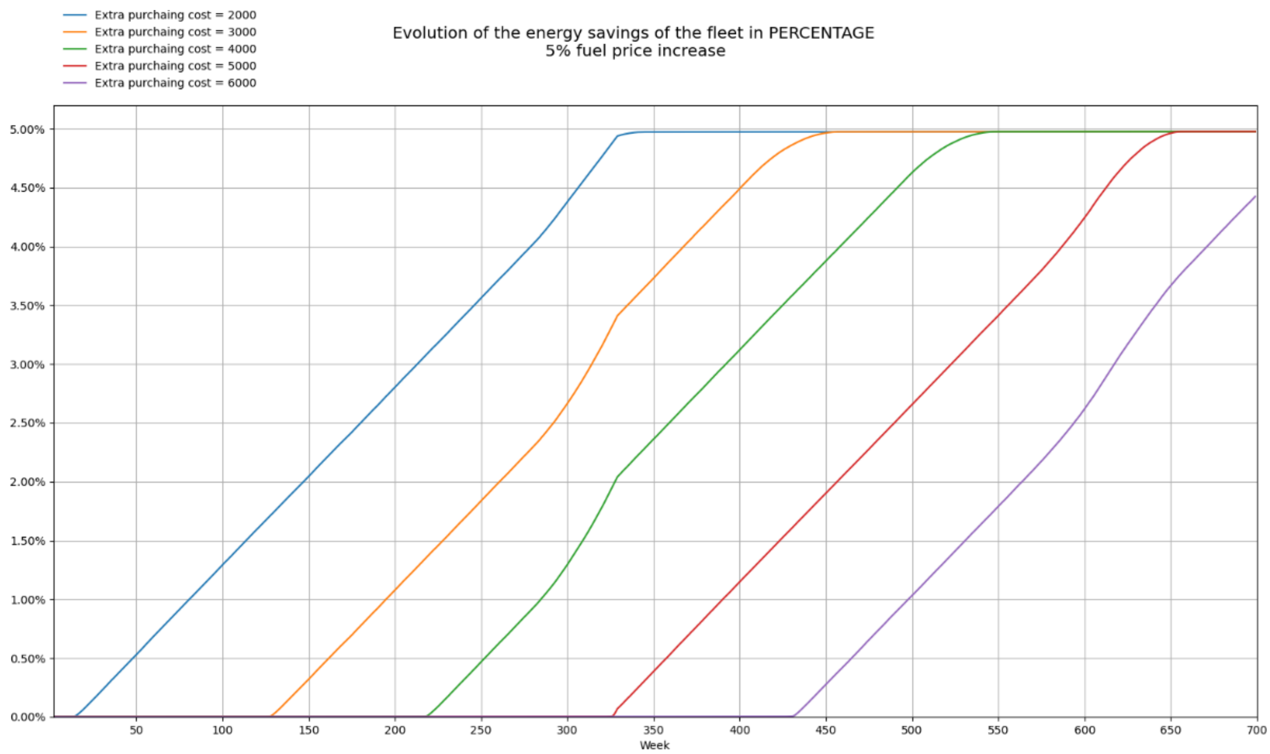

Figure 31: median case, sensitivity test – fuel costs increasing over time. Relative fuel savings of platooning, whole fleet, fuel price increasing over time

Simulation 7: platooning equipment cost decreasing over time

This sensitivity test is somewhat symmetrical to the previous one: the cost of the equipment technology is assumed to decrease by 5% per year, from the same starting value as in the median case.

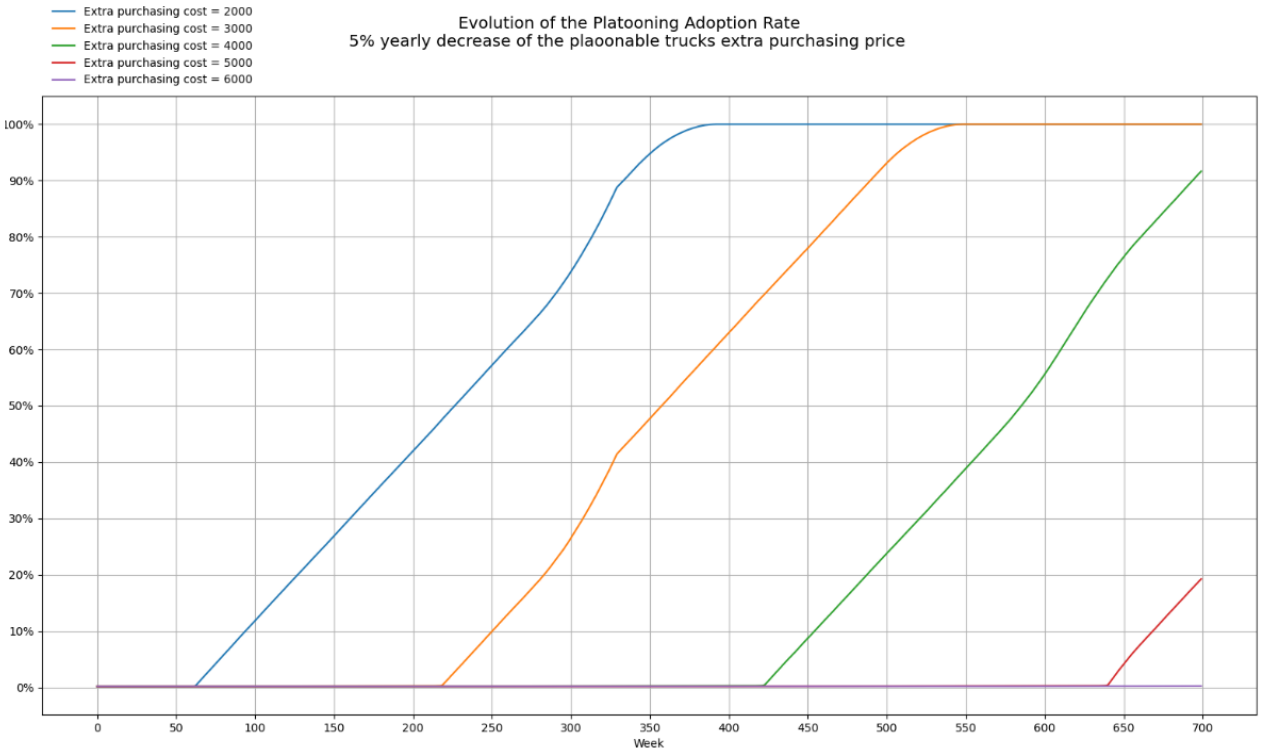

Figure 32: Median case, sensitivity test – platooning equipment cost decreasing over time

As the result shows, conformingly with intuition, the market uptake of platooning happens sooner and over a wider range of equipment cost values than in the median case. Quantitatively, though, the impact isn't as strong as that of the evolution of fuel prices. There is no simple explanation to this limited comparison, but one should keep in mind that the cost of the technology isn't the only cost component of platooning; and that even if it fell down to zero, there would still be platoon formation costs, borne by carriers, and that those could, alone, prevent market uptake.

Simulation 8: shorter corridor

The previous simulations were computed with a corridor length of 360 km. This is a favourable environment, where a platoon formed at the entry of the corridor is supposed to be able to stay intact for the whole length of the corridor. Note that if this isn't true, and the platoon has to dissolve due to any event, the cost of forming the platoon again wouldn't necessarily be high, as the two candidates to platoon formation would be quite close to one another. This depends closely on the spatial configuration of the infrastructure networks and of the vehicles' routes. This point is not considered in the simulations.

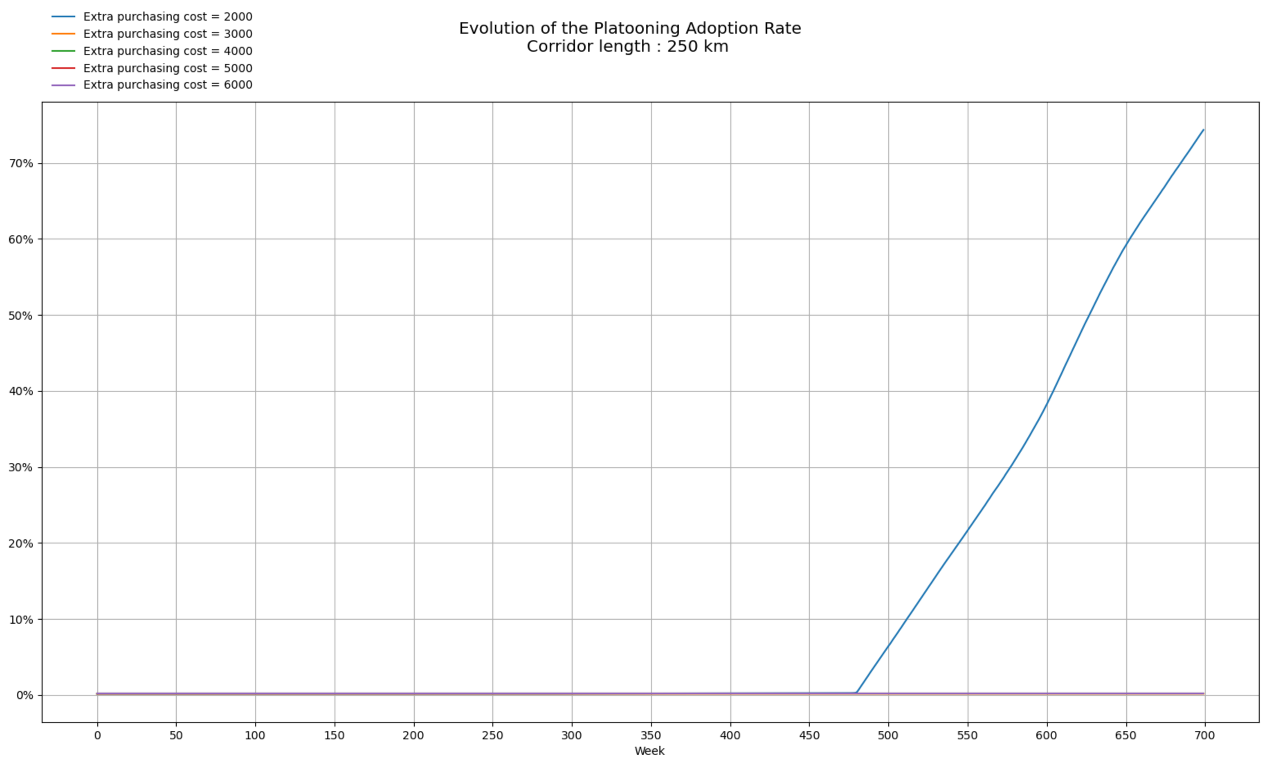

Figure 33: Sensitivity test – shorter corridor

In this sensitivity test, it is supposed that platoons can run at most 250 km before final dissolution. Given that the equipment and platoon formation costs are the same as in the median case, the business case of platooning worsens severely. From all practical viewpoints, it can be considered as non-existent.

Simulations 9 and 10: fewer (or more) early adopters

As previously discussed, due to the economic structure of the market of platooning, market uptake is closely dependent on the share of platoon enabled trucks at the end of the first period of the simulation. The positive feedback loop may or may not happen, depending on the issue's various parameters; however, it has to be kickstarted in a way or another. This report discusses how early adopters may be firms with fleets large enough to benefit directly from platooning with their own vehicles; they can also be carriers buying trucks equipped for free with the platooning equipment as part of an OEM marketing plan. Regardless of how and why those early adopters entered the market, the two following simulations illustrate how their share influences market uptake.

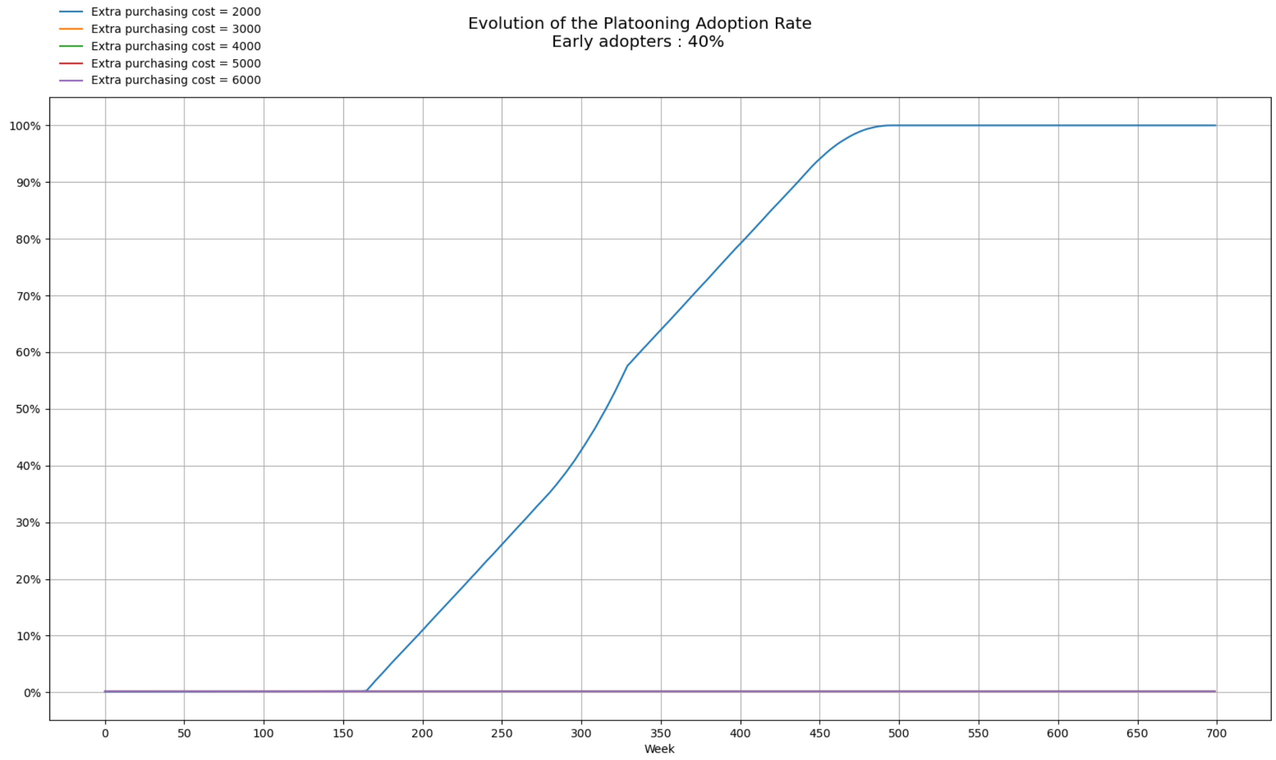

Figure 34: Median case, sensitivity test – fewer early adopters (40% of the first wave)

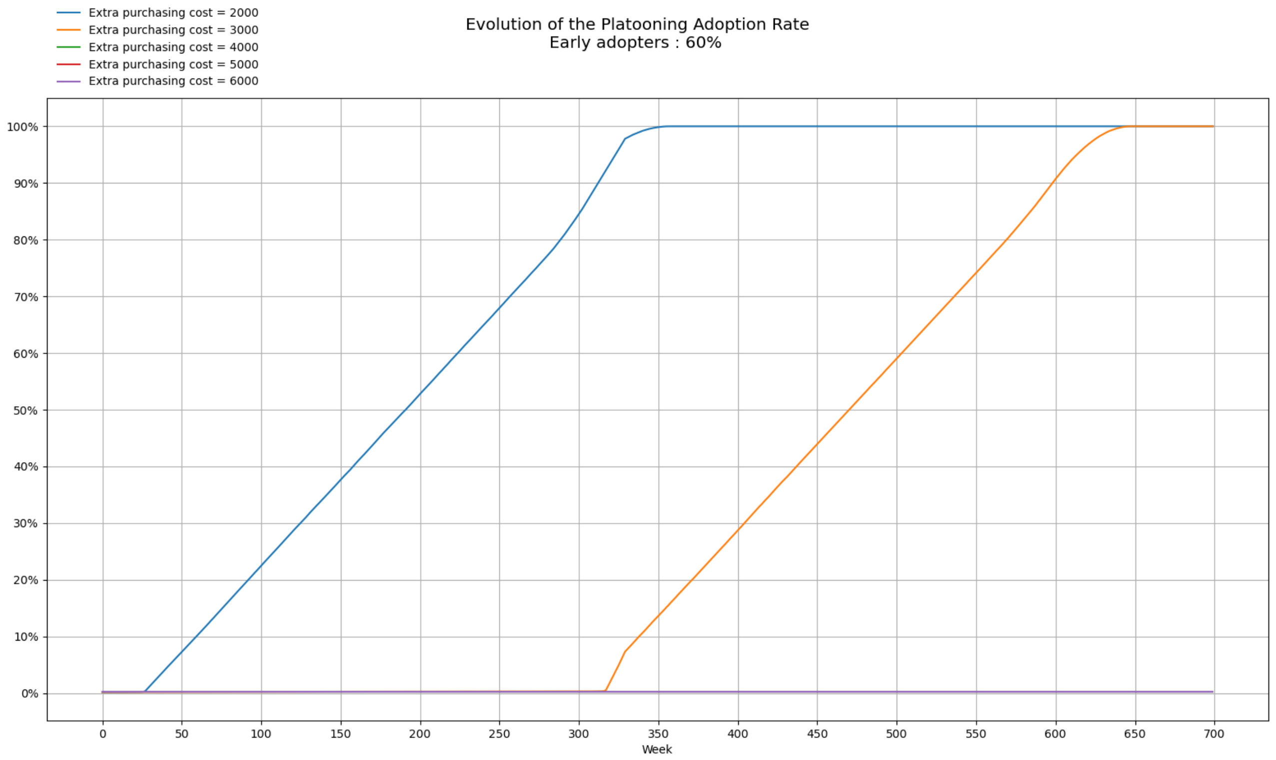

Figure 35: Median case, sensitivity test – more early adopters (60% of the first wave)

From these two simulations, it appears that even a small variation of the share of early adopters in the first wave can have a big impact on the dynamics of the market. Remind that the first wave represents about 0.3% of the fleet. The variations tested above represent 0.03% of the fleet. A tiny modification in one or another direction can shift by more than two years the moment when market uptake actually takes off, and can make viable, or not, the business case of platooning. It is not a surprise *per se*, as positive feedback loop models are typically very sensitive; however, one should keep in mind that the way the technology is introduced in the market is a critical issue.

4.3.4. Complementary comments

Despite its complexity, the model cannot simulate everything. Several important issues were not addressed in the sensitivity tests above. Some of them are conceptually no different from the sensitivity tests already computed. Take the example of workforce costs. If one imagines that platooning would reduce workforce costs for the following vehicle, either because the driver would rest, or because they would be absent whatsoever, that would be very similar in terms of benefits to the impact of a huge reduction of fuel consumption for the following vehicle[47]. Consistently with the sensitivity tests realized above, the business case of platooning would be clear and market uptake would be fast, provided the cost of the platooning equipment wouldn't be too high.

Another issue needing discussion is that of the impact of new energy vectors on platooning. Indeed, the urgent and difficult topic of road freight decarbonation comes with a variety of potential future technologies, including battery electric trucks or hydrogen trucks. The physical equation of platooning, based on reducing the drag of the vehicles in the convoy, doesn't change; but the financial equation would change. Indeed, the core issue of these distinct energy vectors is that of replacing variables costs (fossil fuel consumption) with fixed costs (mainly on-board energy storage devices). The drag reduction only applies to the variable costs, but those variable costs would be a much smaller share of the overall cost of trucking with alternative energies[48]. The business case of platooning would directly suffer in those cases.

4.4. Conclusion

From a micro-economic perspective, platooning should be considered as a bi-level problem. The low-level decision problem, for an equipped vehicle, consists in deciding whether to form or join a platoon or not; and a high-level decision problem, which consists in deciding whether to buy platoon-enabled trucks or conventional ones.

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[47] With one caveat: to remove the driver from the following vehicle means, for the carrier, to deploy an organization that makes it possible and practical. The management of drivers would be more complex than it is today.

[48] Assume two trucks, an internal combustion engine one and an electric one, with the same TCO over 10 years. Assume fuel consumption amounts to 30% of the diesel truck TCO, and electricity to 10% of the electric truck TCO (those are imaginary figures, for the sake of illustration). Then a reduction of aerodynamic drag due to platooning would amount, at best, to a TCO reduction of 1.5% for the diesel trucks (5% of 30%) and 0.5% for the electric truck (5% of 10%).

The objective of this section was to develop a quantitative model to compute the monetary benefits of platooning. The micro-economic structure of platooning, as represented in the model, makes explicit the following characteristics of the platooning market:

- **The benefits of platooning depend on the frequency at which a truck is in a platoon, and on the distance covered in a platoon**.

- **There is a coordination cost to forming a platoon**: the probability that two vehicles pass at the same location at almost the same moment, and then follow the same route over a long distance, is rather low. In all other cases, the two vehicles have to modify their routes to form a platoon, necessarily causing a delay cost.

- The delay cost consists of: the hourly cost of the driver, the opportunity cost of capital of the vehicle, and the willingness to pay of the shipper for the freight delivery not to be delayed.

- The coordination cost is random, but has to be paid each time a platoon is formed.

- For a vehicle to be platoon enabled, the vehicle has to be equipped. In other words, **there is an equipment cost to enable platooning**, and the decision can only be made for new vehicles.

The focus was put on accounting explicitly for the interdependence of the decisions of carriers. Indeed, as explained in Chapter 3, a very important characteristics of the platooning market is that it exhibits **network externalities**, more precisely a club effect: **the value of platooning for one carrier increases with the number of carriers deciding to opt for platooning**. The complexity of the issue prevents the model to be applied on a larger, more complex network. Complementary highlights are presented in other parts of the deliverable, with more geographic detail, and less economic relevance.

The main conclusions of the simulation are as follows:

- In the base case scenario, fuel savings for the leader vehicle (0%) and for the following vehicle (5%) are too low for market uptake to happen, even for a very low cost of the technology. In other words, **in the base case scenario, there is no business case for platooning** under the current economic environment, with reasonable assumptions.

- In an improved scenario where the following vehicle saves 10% of fuel consumption, and if the platooning equipment isn't more expensive (an extremely optimistic assumption), with sufficient truck traffic density and a favourable configuration of the economic life cycles of the vehicles, **there is a spontaneous market uptake**.

- In the model, only two vehicle platoons are considered. This underestimates the benefits of platooning. This underestimation isn't too bad, because the coordination costs to form platoons of three vehicles or more are much higher.

- Assuming longer platoons, the asymptotical maximal fuel savings are 10%. Fuel costs represent about 30% of trucking costs. As a consequence, **at most, platooning would yield 3% gross benefit**. This is a very optimistic target.

- Once the costs of platooning (equipment, and coordination) are accounted for, simulations show that **the net benefit of platooning are substantially lower than the gross benefit, i.e. about 2% at most.**

- Due to the fact that the platooning equipment can only be mounted on new vehicles, **market uptake is capped by the fleet renewal speed**.

A number of sensitivity tests have been realized. The results show that market uptake is extremely sensitive to a number of parameters. Due to the network externalities, market uptake can be delayed or anticipated by several years depending on the economic environment. In more detail, the sensitivity results show that:

- As expected given the nature of the platooning market, **a higher truck traffic density means a better business case**. Note that this is not just a question of vehicle throughput: relevant traffic, in practice, regards vehicles sharing similar trajectories, at least partly.

- The cost of forming a platoon depends on the time it takes to actually form a platoon. This time is lower if the candidate platoon leader can slow down stronger. This raises non-trivial road safety issues, of course. However, **if the waiting speed (i.e. the speed of the leader vehicle while it slows down for the follower vehicle to catch up) is lower, the business case of platooning is improved**.

- **The business case of platooning also improves on road networks where the maximal legal speed is higher**. Indeed, the benefits of platooning are proportional to the distance covered by vehicles over a given period of time. When vehicles move faster, they cover more kilometres over the same distance, and increase proportionately the amount of opportunities to obtain returns on an investment on platooning equipment.

- **An increase of fuel prices[49] over time strongly improves the business case of platooning**. If fuel prices were to increase steadily over time, platooning would become a much safer, much more profitable investment for carriers.

- **A decrease of the price of platooning equipment improves slightly the business case of platooning**. It has a direct effect on the cost-benefit balance, but it is not the only cost, which limits the impact.

[49] In real terms, i.e. once corrected for inflation.

- **An adverse geography is a very strong limitation to the business case of platooning**. Qualitatively, all other things equal, the platooning market is much more viable over networks with a few long corridors than other grid like, high density networks.
- **The share of early adopters has a very strong influence over the business case of platooning**. Kickstarting platooning can have a very direct impact and accelerate market uptake by years. **However, it will not create a market when platooning is structurally unprofitable**.

All simulations are based on assuming a reduction in fuel consumption. This means two additional comments are required. First, if deep road freight decarbonation means that trucks will shift from internal combustion engines to other energy vectors such as batteries or hydrogen, the business case of platooning will deteriorate, as the cost reduction associated to lower aerodynamic drag could be lower. Second, above conclusions do not hold if the cost reduction inside a platoon comes from another source. For example, if platooning allows for workforce cost savings, those do not present the same risk profile (as defined in Chapter 3.)

5. MULTI-FLEET TRUCK PLATOON COORDINATION

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Trucks need coordination to form platoons efficiently and seamlessly in the transportation system. To date, most platoon coordination strategies aim to optimize the overall profit of the trucks in the platooning system, which is suitable when considering single-fleet platooning. However, when trucks from different fleets cooperate, each fleet owner aims to optimize its overall profit, including the profit of all the trucks in its fleet. The research efforts in Johansson et al. (2021a) and Zeng Y (2020) model the strategic interaction among trucks and carriers as non-cooperative games and consider Nash equilibria as multi-fleet platoon coordination solutions. The research effort in Johansson et al. (2021b) proposes a Pareto-improving multi-fleet platoon coordination solution, in which the fleet owners leave coordination to local coordinators at hubs and each fleet owner is better off in the multi-fleet solution than by performing single-fleet platoon coordination. In this section, we develop a distributed real-time MPC (Model Predictive Control) multi-fleet platoon coordination solution that does not suffer from the inefficiency in seeking an equilibrium solution by iterations among trucks. In our solution, each truck optimizes its waiting times at hubs along its route to maximize its utility, which captures the profit of the fleet it belongs to, and the solution respects trucks' delivery deadlines.

In this section, we first introduce the model of the road network and the predictive model of the departure times of trucks at hubs in their routes. Then, the multi-fleet platoon coordination solution based on dynamic programming is introduced. Lastly, we perform a realistic large-scale simulation study over the Swedish road network where truck trips and fleet size distribution are generated from real data. The simulation study shows significant benefits related to multi-fleet platooning, both environmental and economical. Moreover, the simulation study suggests that all fleets, small to large, have significant advantages of multi-fleet platooning.

5.1. Road network

We consider the transport system illustrated in Figure 36, including a road network and trucks that belong to different fleets. The road network is represented by the directed graph denoted by $\mathcal{D}(\mathcal{H}, \mathcal{E})$, where $\mathcal{H}$ is the set of hubs at which trucks can form platoons and $\mathcal{E}$ is the set of road segments connecting hubs. We consider the set of trucks $\mathcal{M} = \{1,2,\dots,M\}$, and each truck belongs to exactly one of the fleets in the set $\mathcal{F} = \{\mathcal{F}_1, \mathcal{F}_2, \dots, \mathcal{F}_S\}$. Each truck i has a fixed route between its origin o_i and destination d_i in the road network and can form platoons at the hubs along its route. The route of truck i is represented by the set

$$\mathcal{E}_i = \{e_i(1), e_i(2), \dots, e_i(N_i - 1)\},$$

where $e_i(k)$ denotes the road segment between its k-th and $(k+1)$-th hub.

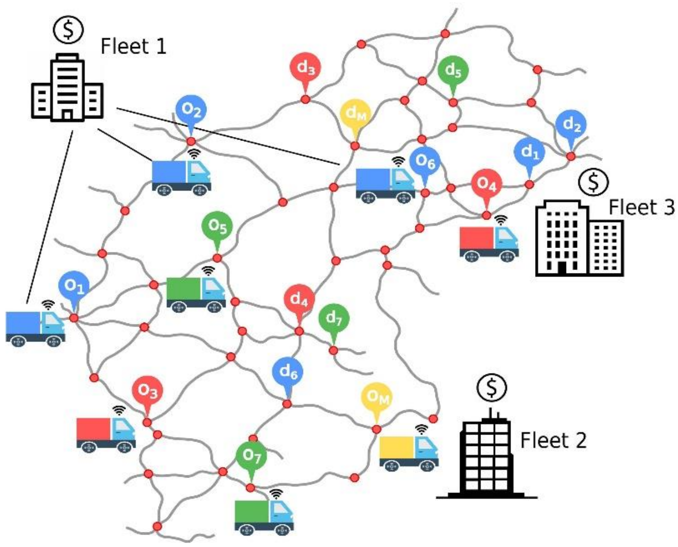


Figure 36: Multi-fleet platooning system

5.2. Arrival and waiting times at hubs

The arrival time and waiting time of truck i at its k-th hub is denoted by $a_i(k)$ and $w_i(k)$, respectively. Moreover, the travel time on the road segment $e_i(k)$, connecting the k-th and $(k+1)$-th hub, is denoted by $c_i(k)$. Then, the arrival times at hubs of truck i are computed by the following equations

$$a_i(1) = t_{i,start}$$

$$a_i(k+1) = a_i(k) + w_i(k) + c_i(k), \qquad k = 1,2,\dots,N_i - 1.$$

This model can predict the arrival time of a truck at its next hub given its arrival time and waiting time at the current hub. The time that truck i arrives at its first hub in its route is denoted by $t_{i,start}$. Its delivery deadline is denoted as $t_{i,end}$. That is, we require that $a_i(N_i) \leq t_{i,end}$, where $a_i(N_i)$ is the arrival time of truck i at its destination.

5.3. Multi-fleet platoon coordination strategy

We develop a high-level coordination technique that is suitable for solving the multi-fleet platooning problem that captures that trucks belong to different fleets. More specifically, based on the above system description, we propose to solve the problem of scheduling the waiting times of each individual truck to maximize its fleet's benefit from forming platoons. Before proposing the coordination solution, we first explain how to predict platooning partners and the utility function of individual trucks that captures its fleet's benefit.

5.3.1. Predicted platoon partners

Each time a truck arrives at a hub, it decides on its waiting time at the current hub and updates its prediction of the waiting times at the remaining hubs in its route. The waiting time computed for the current hub is implemented and the predicted waiting times at the remaining hubs are used as predictions by others.

A group of trucks form a platoon if they depart from a hub and enter the same road segment at the same time, and each truck controls which platoons to join along its route by deciding on its waiting times. Here, we explain how to predict the platooning partners given the predicted waiting times of other trucks. Let $\mathcal{R}_i(k+h|k)$ denote the predicted platooning partners of truck i on its $(k+h)$-th road segment predicted when it decides on its waiting times at its k-th hub. That is, $\mathcal{R}_i(k+h|k)$ includes the other trucks that are predicted to depart from the $(k+h)$-th hub at the same time as truck i and have the next road segment in common. More precisely, a truck $j \neq i$ that has the road segment $e_i(k+h)$ in its route is part of the set $\mathcal{R}_i(k+h|k)$ if

$$a_i(k+h|k) + w_i(k+h|k) = \hat{d}_{j,i}(k+h|k),$$

where $\hat{d}_{j,i}(k+h|k)$ denotes the predicted departure time of truck j at the $(k+h)$-th hub of truck i used by truck i when it makes the decision at its k-th hub.

5.3.2. Utility

The utility of each truck includes the reward that its fleet gains from forming platoons and its loss caused by waiting at hubs.

Reward function:

Recall that $\mathcal{R}_i(k+h|k)$ denotes the set of trucks which truck i predicts to platoon with on its $(k+h)$-th road segment. Let $r_i(k+h|k)$ denote the size of $\mathcal{R}_i(k+h|k)$, and let $p_i(k+h|k)$ denote the subset of $\mathcal{R}_i(k+h|k)$ which only contains trucks from the same fleet as truck i. Note that both $r_i(k+h|k)$ and $p_i(k+h|k)$ are functions of the waiting times of truck i and of predicted waiting times of other trucks.

When truck i arrives at its k-th hub, it aims to join platoons at its remaining hubs to maximally increase the profit of its fleet. That is, it aims to join platoons at the remaining k-th to $(N_i - 1)$-th hubs. The increased profit which truck i predicts to cause for its fleet from its k-th hub to the end of its trip is:

$$\Delta R_i^f(k) = \sum_{h=0}^{N_i-1-k} \Delta R_i^f(k+h|k),$$

where $\Delta R_i^f(k+h|k)$ is the predicted increased reward at its $(k+h)$-th road segment, which is defined as:

$$\Delta R_i^f(k+h|k) = R_{i,in}^f(k+h|k) - R_{i,out}^f(k+h|k),$$

where $R_{i,in}^f(k+h|k)$ is the predicted platooning reward of truck i's fleet if truck i forms the platoon with the trucks in $\mathcal{R}_i(k+h|k)$ and $R_{i,out}^f(k+h|k)$ is the predicted platooning reward of the fleet if truck i does not join the platoon. More precisely, if $r_i(k+h|k)$>0, we have:

$$R_{i,in}^f(k+h|k) = \xi_i c_i(k+h) \frac{p_i(k+h|k)}{r_i(k+h|k)+1}$$

And:

$$R_{i,out}^f(k+h|k) = \xi_i c_i(k+h) \frac{p_i(k+h|k)-1}{r_i(k+h|k)},$$

where ξ_i is the platooning profit per follower truck and travel time unit. This platooning reward model is accurate if the follower trucks have equal benefit and share the benefit evenly with the leader. Therefore, the fleet's predicted increased reward caused by truck i at its $(k+h)$-th road segment is:

$$\Delta R_i^f(k+h|k) = \begin{cases} 1 - \dfrac{r_i(k+h|k) - p_i(k+h|k)}{r_i(k+h|k)(r_i(k+h|k)+1)}, & \text{if } r_i(k+h|k) > 0 \\ 0, & \text{otherwise.} \end{cases}$$

Loss function:

The waiting cost may be due to cost for delayed delivery of goods or costs for drivers. The waiting cost which truck i causes for its fleet from the k-th to the $(N_i - 1)$-th hub is

$$\Delta L_i^f(k) = \sum_{h=0}^{N_i-1-k} \epsilon_i w_i(k+h|k),$$

where ϵ_i denotes the monetary loss per time unit. This is illustrated in Figure 37.

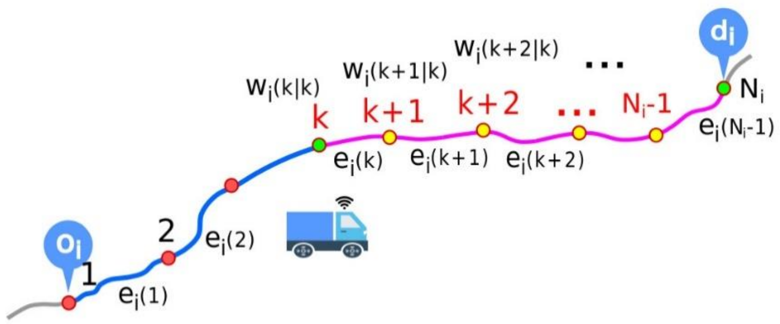


Figure 37: The predicted loss function

Taken the reward and loss functions together, the utility of truck i at its k-th hub is denoted by

$$J_i(k) = \Delta R_i^f(k) - \Delta L_i^f(k).$$

5.3.3. Optimization problem

To maximize the fleet's increased benefit from forming platoons, the distributed model predictive control (MPC) problem of truck i at its k-th hub is formulated by

$$\max_{\boldsymbol{w}_i(k)} \quad J_i(k)$$

$$\begin{aligned} s.t. \quad & a_i(k|k) = t_{i.arr} \\ & a_i(k+h+1|k) = a_i(k+h|k) + w_i(k+h|k) + c_i(k+h), \qquad h = 0,1,\dots,N_i - 1 - k \\ & a_i(N_i|k) - t_{i,end} \le 0, \end{aligned}$$

where, as previously defined, $J_i(k)$ includes the increased platooning reward and waiting cost at the remaining hubs caused by truck i, and it is a function of truck i's computed waiting times at the k-th hub and the predicted departure times of other trucks. The first constraint in the optimization problem sets the arrival time to the current hub in the predictive model. The last constraint in the optimization problem ensures that truck i respects its delivery deadline. The optimization variable $\boldsymbol{w}_i(k)$ includes not only the optimal waiting time of truck i at its current hub k but also the predicted waiting times at its following hubs, namely,

$$\boldsymbol{w}_i(k) = [w_i(k|k), w_i(k+1|k), \dots, w_i(N_i - 1|k)].$$

5.3.4. Dynamic programming solution

We use Dynamic Programming (DP) to solve the MPC optimization problem. Before solving the problem, the first step is to create a DP graph illustrated in Figure 38. In the DP graph, the nodes at each hub are associated with departure times of predicted platoons (obtained by the predicted departure times of other trucks) or the departure time when truck i departs from the hub alone without waiting. Since it is never optimal to wait at a hub unless a platoon is joined, departure times that are not part of the DP graph are redundant when seeking optimal solutions. The weight on each edge in the DP graph is the utility for joining the platoon at the edge's target node, including the platooning reward and waiting cost. The MPC problem is then solved by finding an optimal path from the start node to the destination in the DP graph. This is achieved by standard DP, and for detailed introductions on DP see, e.g., Bellman (1966) and Bertsekas (2019).

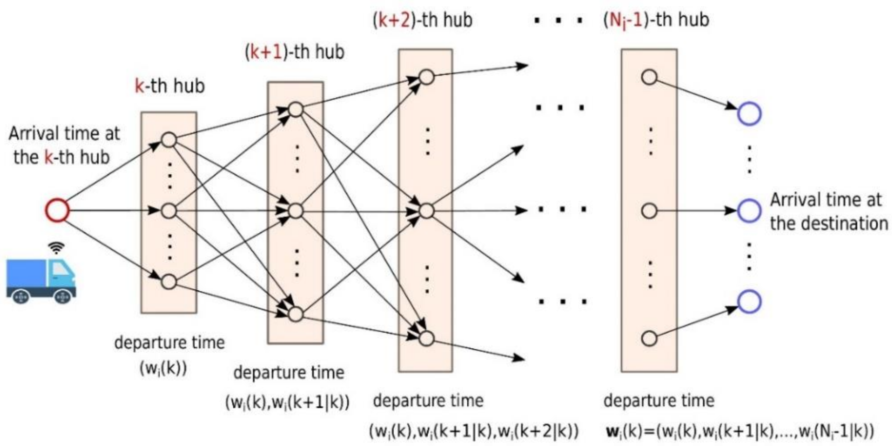


Figure 38: DP graph

5.4. Simulation procedures

The main purpose of the simulation is to evaluate the improved platooning revenue brought by the multi-fleet platoon coordination method in large-scale transport network. This section will give the simulation environment settings and the implementation results, including the road network model, delivery mission generation, fleet distribution and so on. It is worth mentioning that, the developed method is applicable in any hub-based transport system (both the Swedish and European transport network). Constrained by the data that is available, the simulation in this document is conducted over the Swedish road network and the logistics information in Sweden.

5.4.1. Road network and mission generation

We consider the road network in Figure 39, in which the nodes represent hubs at which platoons can form. The set of hubs are 105 real road terminals obtained from the Samgods[1] model, where only one road terminal is selected for each district. We then assume that the truck flows between road terminals are equal to the truck flows between the districts in the Samgods model. The routes between each pair of hubs are obtained from OpenStreetMap[2]. The mission of each truck is randomized such that its origin and destination belong to the set of hubs, and the Samgods[1] model is used to get a realistic distribution of the transport missions over the Swedish road network.

[1] Samgods is the national model for freight transportation in Sweden.

[2] OpenStreetMap: (https://www.openstreetmap.org)

More precisely, the probability of for hub i and j to be drawn as origin and destination, respectively, is

$$P_{ij} = \frac{f_{i,j}}{\sum_{ij} f_{i,j}},$$

where $f_{i,j}$ is the truck flow from the road terminal i to j in the Samgods model.

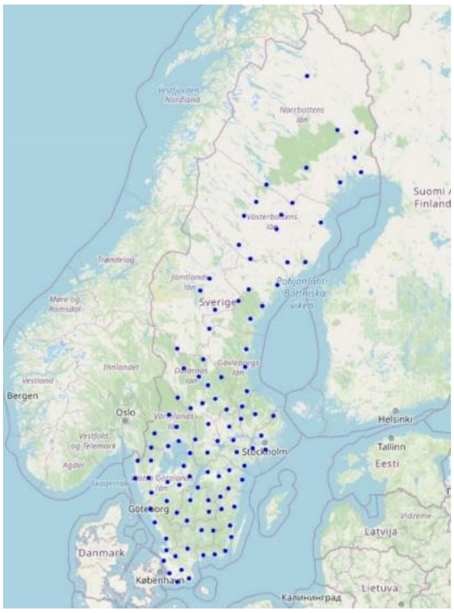
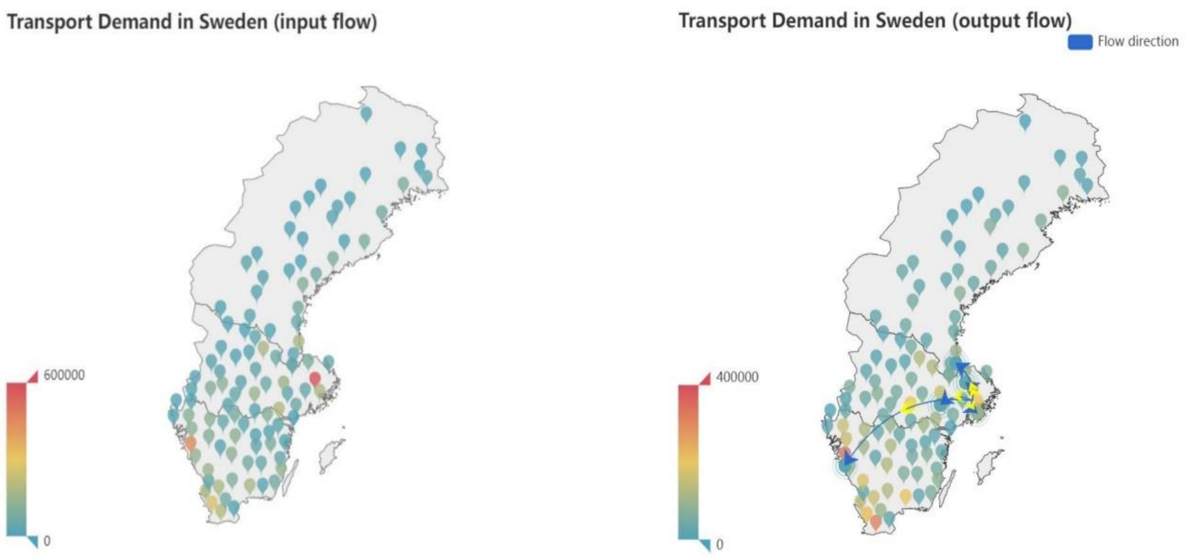


Figure 39: Swedish road network with 105 major hubs

The input and output flow of the 105 hubs in Sweden per year are shown in Figure 40.



(a). Input flow of each district **(b). Output flow of each district**

Figure 40: The goods transport demand of the 105 major districts in Sweden

5.4.2. Fleet distribution

To generate fleets and their sizes, we use data from TRAFA[3] showing the distribution of the number of employees at transport companies in Sweden. The fleet size distribution that we use is shown in Figure 41, where the x-axis gives the number of trucks in a fleet and the y-axis shows the corresponding fleet percentage. As is shown, about 89.7% fleets have less than 10 trucks. Accordingly, the fleets with the size between 11 and 100 trucks are defined as medium size, which is about 9.8% of the fleets. The other fleets are referred to as large size fleet with each fleet having more than 100 trucks, which accounts for around 0.5% of the total fleets.

In line with the data in Lastbilstrafik[4] (2020), around 5000 trucks start their missions in the Swedish road network in each hour. This together with fleet size distribution, the number of each type of fleet is determined.

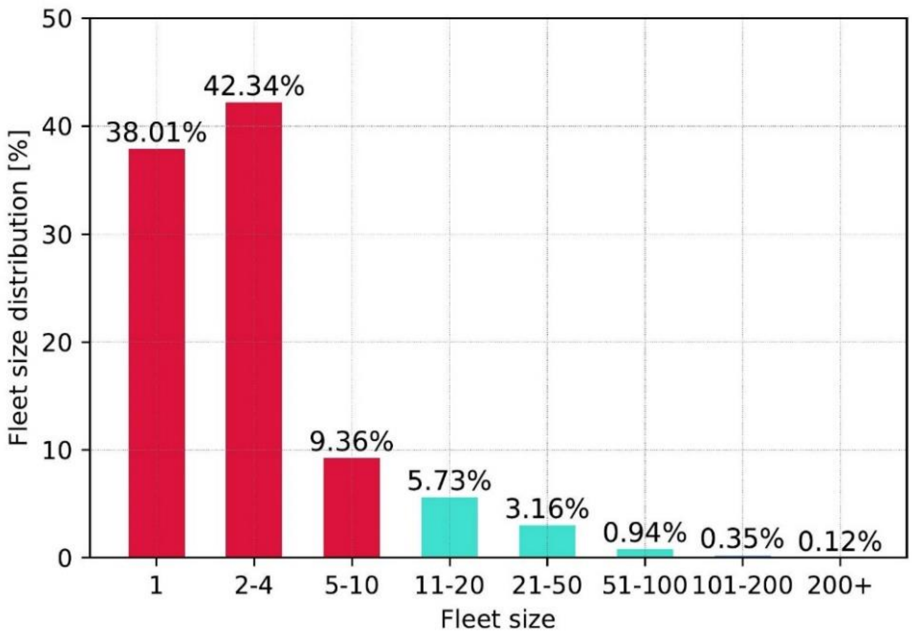


Figure 41: The fleet size distribution

Table 3 shows detailed information for each type of fleet. Given this, the 5000 trucks are assigned to exactly one of 855 fleets.

[3] TRAFA: (https://www.mynewsdesk.com/se/trafikanalys/pressreleases/trafikanalys-lanserar-en-ny-version-av-trafa-se-1227180)

[4] Lastbilstrafik: (https://www.trafa.se/globalassets/statistik/vagtrafik/lastbilstrafik/2020/lastbilstrafik-2020.pdf)

Fleet type	Number of trucks in a fleet	Number of fleets	Fleet percentage
Small fleet	1	325	89.7%
	3	362	
	7	80	
Medium fleet	15	49	9.8%
	34	27	
	74	8	
Large fleet	148	3	0.5%
	340	1	

Table 3: Fleet size distribution

5.4.3. Parameter settings

For every truck traveling in the Swedish road network, its parameters are given below:

- Trucks start their trips at a random time between 8:00-9:00 a.m.;
- The velocity of each truck is 80 km/h;
- The total travel time of a truck per day is less than 10 hours;
- The waiting time of a truck at all hubs is less than 10% of its total travel time;
- The fuel consumption of follower trucks is assumed to be reduced by 10%;
- The price of the fuel (Diesel) is 18 SEK per litre (~ 1.70 Euro);
- The monetary saving is 0.72 SEK per follower per kilometre (~ 0.07 Euro);
- The platooning benefit is $\xi_i = 57.6$ SEK per follower per hour (~ 5.50 Euro);
- The waiting cost for each truck is $\epsilon_i = 260$ SEK per hour (~ 25 Eruo);
- All the route information of each truck is obtained from *OpenStreetMap.*

5.5. Evaluation

This section provides the simulation results and the performance evaluation. By compared to the traditional single-fleet platooning strategy, we demonstrate the advantages of the multi-fleet platoon coordination method from different perspectives.

5.5.1. Utility

The total utility of each type of fleet in single-fleet and multi-fleet platoon coordination method are shown in Figure 42, where the bars without a pattern represent the simulation results in multi-fleet platoon coordination method. The figure shows that the total utility of each type of fleet increases significantly when applying the multi-fleet platooning approach. In comparison with the single-fleet coordination, the increased benefit for small, medium, large fleets are 359, 17, 3 times, respectively.

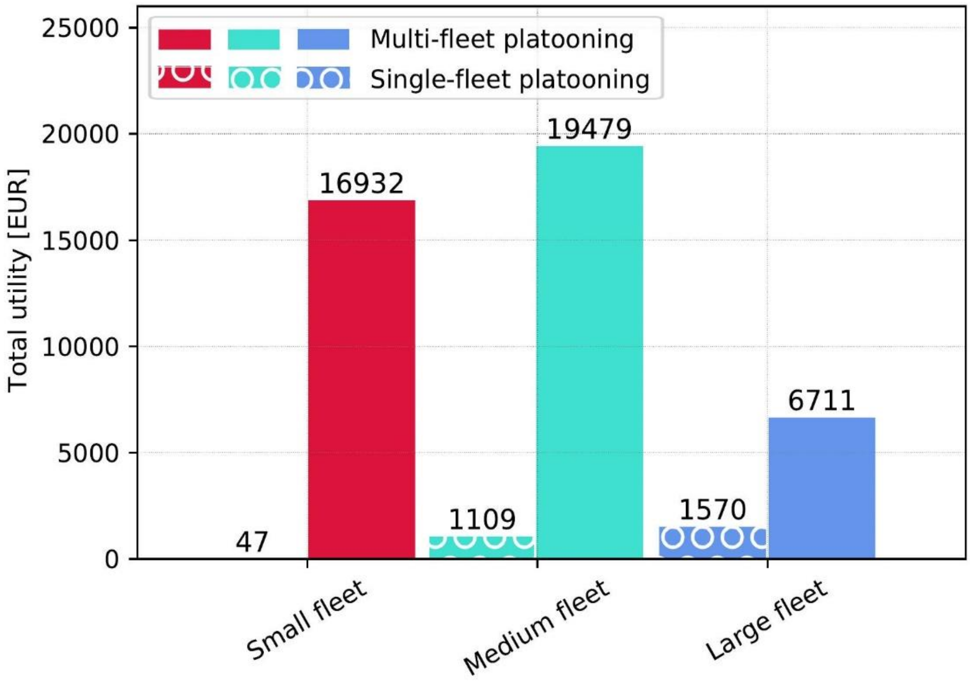


Figure 42: The total utility of each type of fleet

Among the 855 fleets, 767 fleets are small fleets (the fleet index is 1-767), 84 fleets are medium fleets (the fleet index is 768-851), and 4 fleets are large fleets (the fleet index is 852-855). The average utility of per truck in each type of fleet is given in Figure 43. As we can see, the average utility of a single truck in the large fleet is higher than in other two types of fleets when using the single-fleet platoon coordination method. In multi-fleet platooning scheme, the average real utility of per truck in each type of fleet increases appreciably. Additionally, the average real utility of each truck for the tree types of fleets is approximately the same.

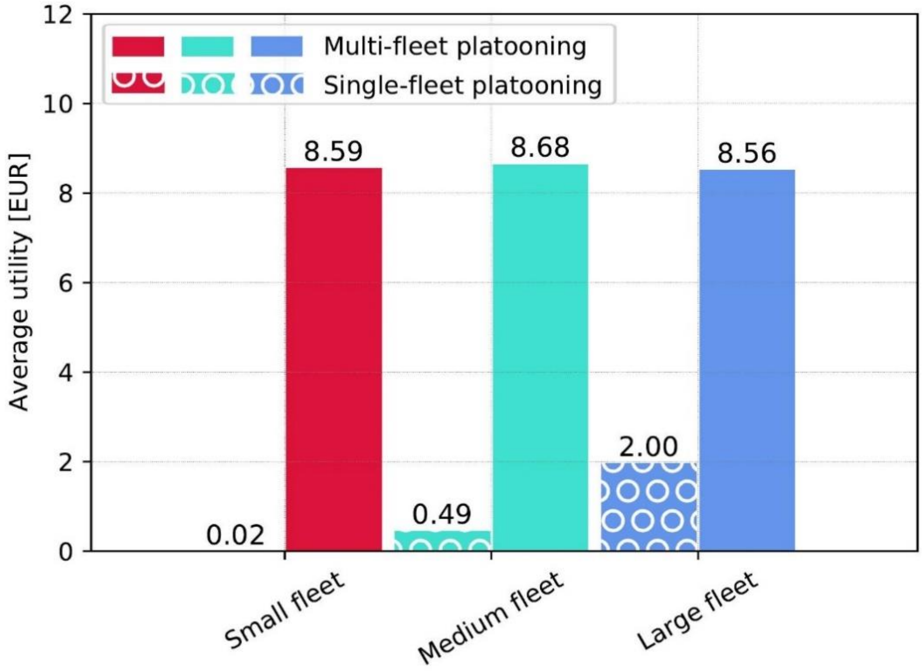


Figure 43: The average utility of trucks in each type of fleet

Figure 44 to Figure 46 are used to show the total utility of every fleet in single-fleet and multi-fleet platoon coordination method. Specifically, Figure 44 gives the total utility of each small fleet where the fleet indexes are sorted according to their utilities. As introduced in the table in section 5.4.2, each small fleet indexed from 1 to 325 contains 1 truck, each small fleet indexed from 326-687 has 3 trucks, and each small fleet indexed from 688-767 includes 7 trucks. It is seen in Figure 44 that only very few trucks have some reward from truck platooning in single-fleet coordination scheme.

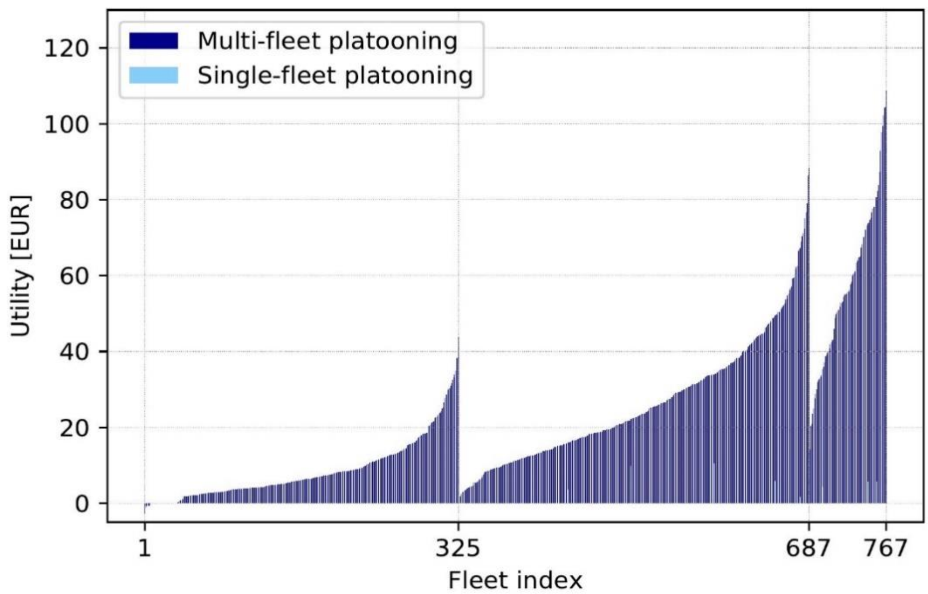


Figure 44: The total utility of small fleets

The total utility of each medium fleet and each large fleet are given in Figure 45 and Figure 46, respectively.

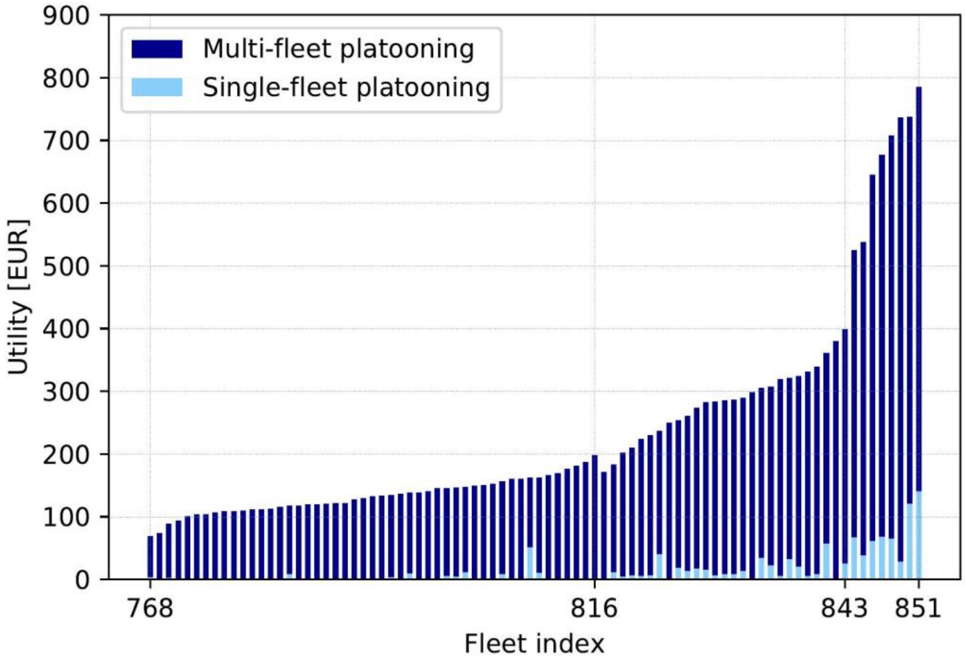


Figure 45: The total utility of medium fleets

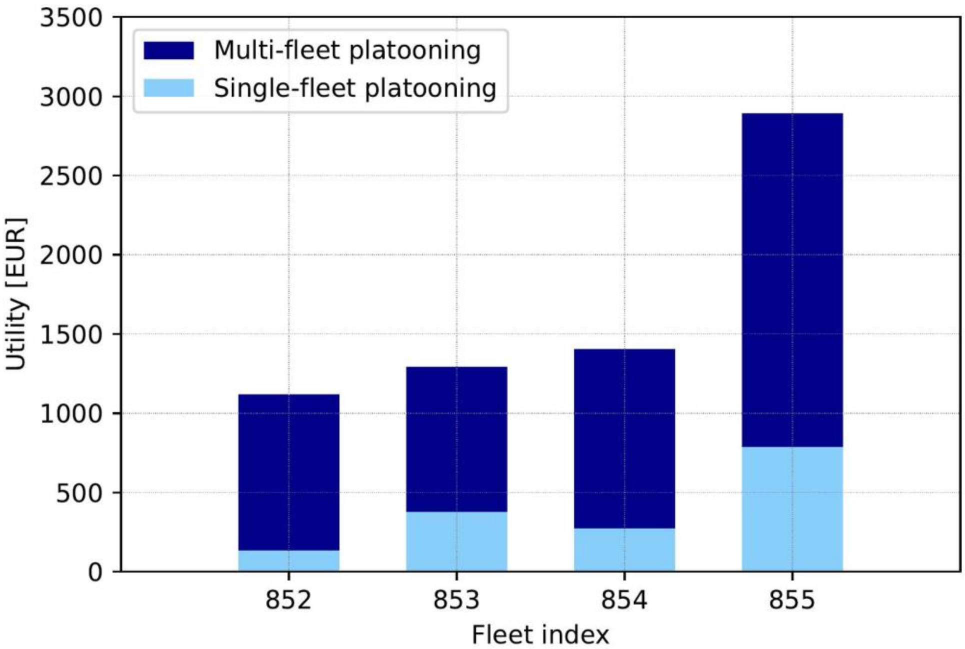


Figure 46: The total utility of large fleets

The number of trucks involved in each fleet can be found in section 5.4.2. Through the comparison and analysis of the result, we can see that the developed multi-fleet platoon coordination method contributes to increasing the utility of each single fleet. Although a medium or large fleet has many platoon chances without considering the cooperation with other fleets due to the large amount of trucks within the fleet itself, the multi-fleet platooning scheme plays an important role in further raising the fleet's utility. The increased benefit is much more than the single-fleet platooning result.

5.5.2. Waiting time

The maximized allowed waiting time and the actual waiting time of all trucks in single-fleet platoon coordination method are shown in Figure 47. The truck indexes are sorted according to their real waiting times. This figure shows that the upper bound for the waiting time is 60 minutes as the longest travel time is 10 hours and the allowed waiting time is less than 10% of the total travel time of each trip. From the result we know that, most of the trucks do not choose to wait in single-fleet platooning scheme.

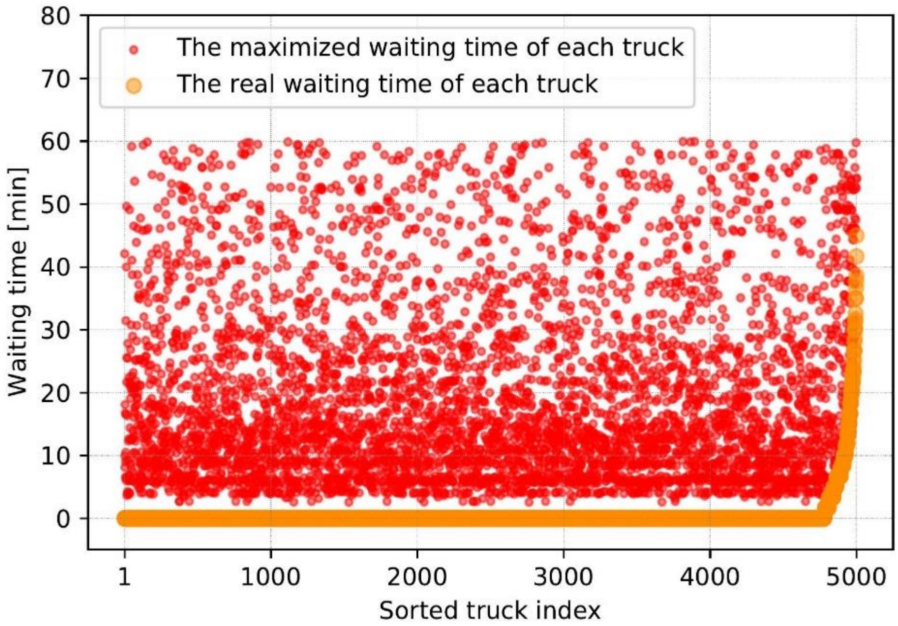


Figure 47: Total waiting time of trucks in single-fleet platoon coordination

For comparison, the waiting time of trucks in multi-fleet platoon coordination method is provided in Figure 48. As is shown, every truck's real waiting time is within their bounds and more than 2000 trucks' waiting times are non-zeros. This indicates that more trucks find proper chances to form platoons with other trucks in multi-fleet platooning scheme.

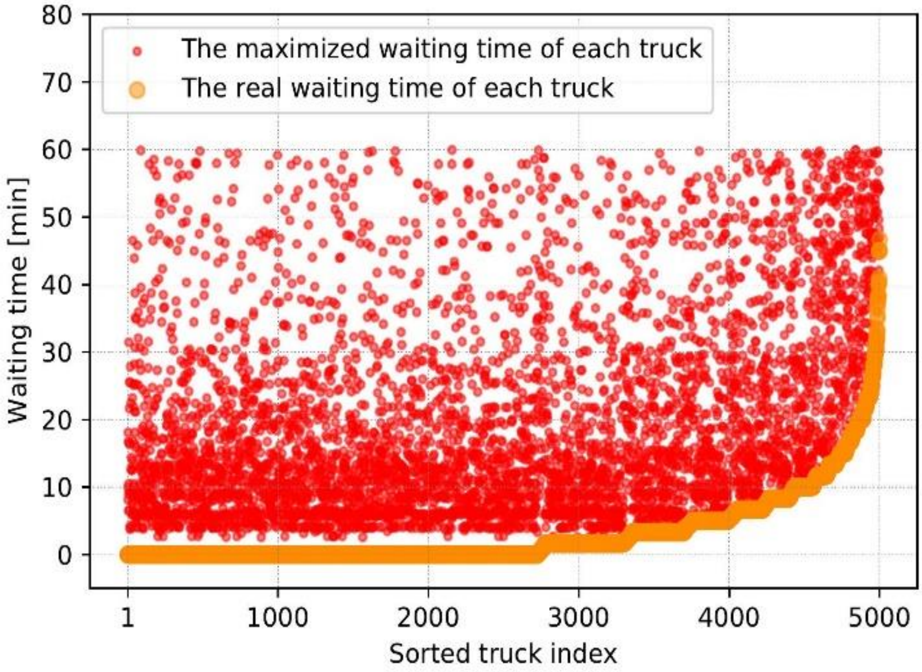


Figure 48: Total waiting time of trucks in multi-fleet platoon coordination

5.5.3. Travel times

Figure 49 shows the total travel time of each truck in the whole transport network and the travel time in a platoon when considering single-fleet platoon coordination method. The x-axis represents the truck index which is sorted in line with the trucks' total travel times in a platoon. More precisely, the trucks with the index between 1-1971, 1972-4216, and 4217-5000 are from small, medium and large fleet, respectively. From the figure we can see, in single-fleet platooning scheme, most of the trucks travel alone in their whole trip with few trucks experiencing a period of time traveling in platoons.

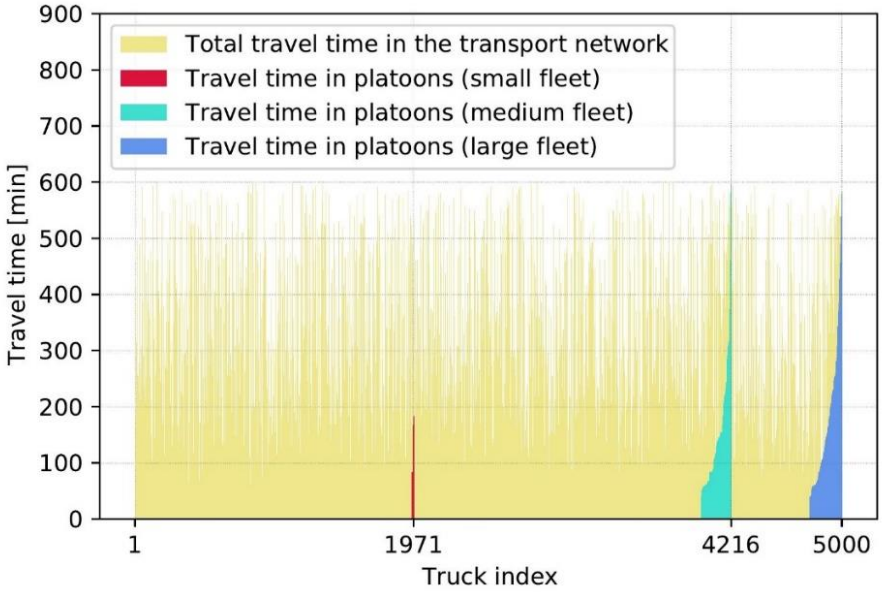


Figure 49: Total travel time of trucks in single-fleet platoon coordination

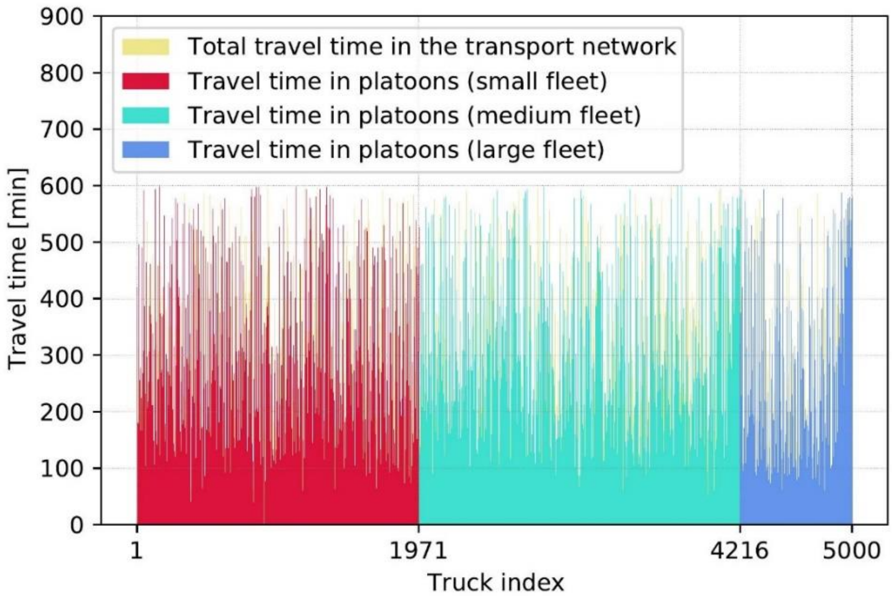


Figure 50: Total travel time of trucks in multi-fleet platoon coordination

In multi-fleet platoon coordination method, the total travel time of trucks in the network and in the platoons are shown in Figure 50, where the truck index is exactly the same with that in Figure 15. By comparing Figure 50 and Figure 49, it can be readily seen that the trucks' travel times in platoons increase phenomenally, which goes for the trucks in each type of the fleet.

5.5.4. Platooning rate

In order to evaluate the platoon coordination efficiency of each method, every truck's time as alone driving is compared with its time as a platoon member, and we define the platooning rate for each truck i as the form of

$$\boldsymbol{r}_i = \frac{\text{Total travel time of truck } i \text{ in platoons}}{\text{Total travel time of truck } i \text{ in the network}}.$$

Using the same order of the truck index in Figure 49, the platooning rate of every truck in single-fleet and multi-fleet platoon coordination method are provided in Figure 51 and Figure 52. Figure 51 shows that in single-fleet platooning scheme, the average platooning rate of the trucks in large fleet is higher than that of medium fleet and small fleet, where the trucks' average platooning rates for the three types of fleet are around 0.21, 0.06, 0, respectively. In Figure 52, it shows that the platooning rates of individual trucks are increased significantly. Meanwhile, the average platooning rate for the trucks in each type of fleet is approximately the same with an average value of 0.8.

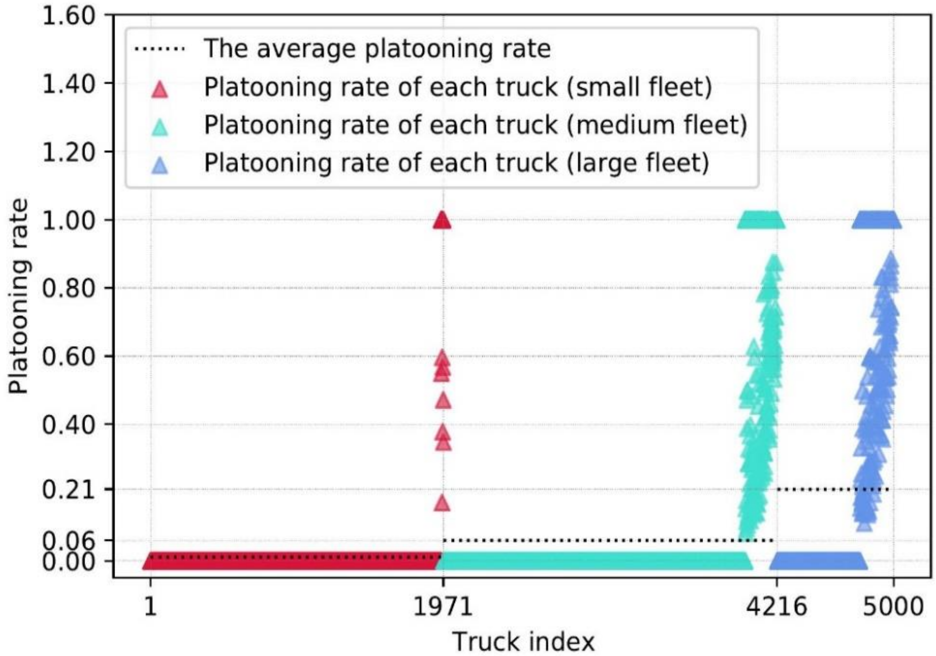


Figure 51: The platooning rate of trucks in single-fleet platoon coordination

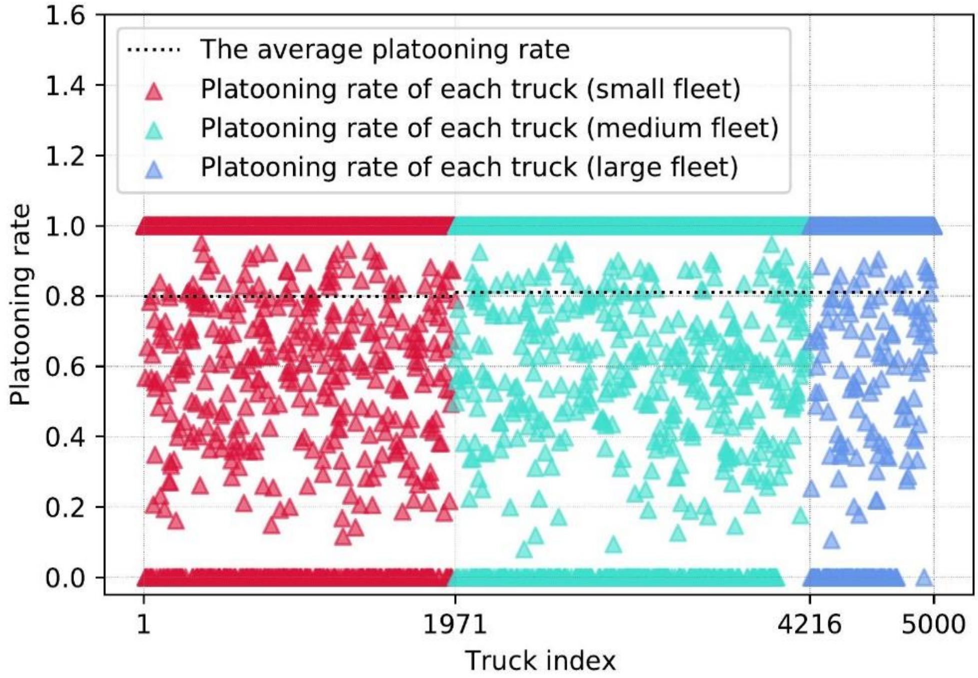
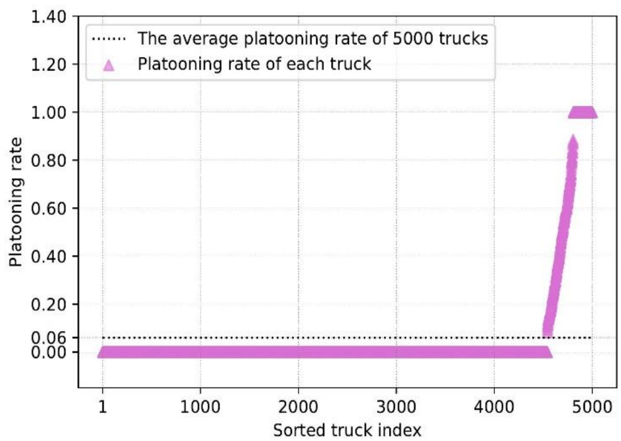
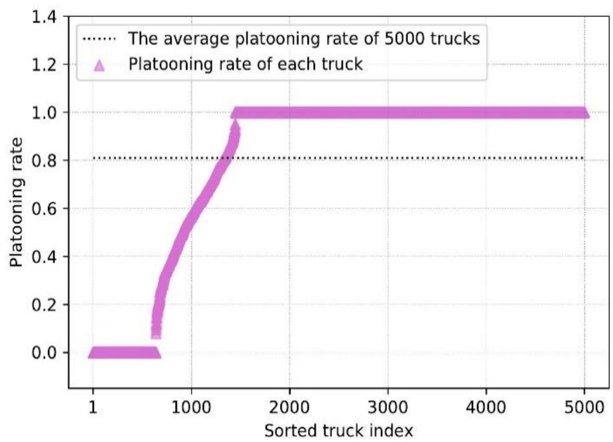


Figure 52: The platooning rate of trucks in multi-fleet platoon coordination

From the perspective of the whole transport system, the platooning rates of all trucks are shown in Figure 53, where the truck indexes are sorted according to the trucks' platooning rates. As we can see, the average platooning rate of all trucks in single-fleet platooning scheme is 0.06 while that in multi-fleet platooning scheme is 0.8. Moreover, by applying the multi-fleet platoon coordination method, more than 80% of the trucks achieve a platooning rate higher than 0 and about 75% of the trucks have a platooning rate of 1. By comparison, only 10% of the trucks have a non-zero platooning rate in single-fleet platoon coordination method.



(a). Single-fleet platoon coordination



(b). Multi-fleet platoon coordination

Figure 53: Sorted platooning rates of trucks in single-fleet and multi-fleet platoon coordination

5.5.5. Fuel savings

The comparison to the fuel consumptions of each type of fleet in single-fleet and multi-fleet platoon coordination method is given in Figure 54, where the consumed fuel without adopting any platooning technique is 100 percentage and is illustrated by the red line. The bars with patterns representing the fuel consumption in single-fleet platoon coordination method indicate that large fleet saves more fuel than small fleet and the maximized saved fuel is 1.4%. This also goes for multi-fleet platoon coordination with the difference that the fuel consumption for each type of fleet is decreased and the average fuel saving is about 5.4%. Thus, the developed multi-fleet platoon coordination approach leads to less fuel consumption and CO_2 emission to the environment.

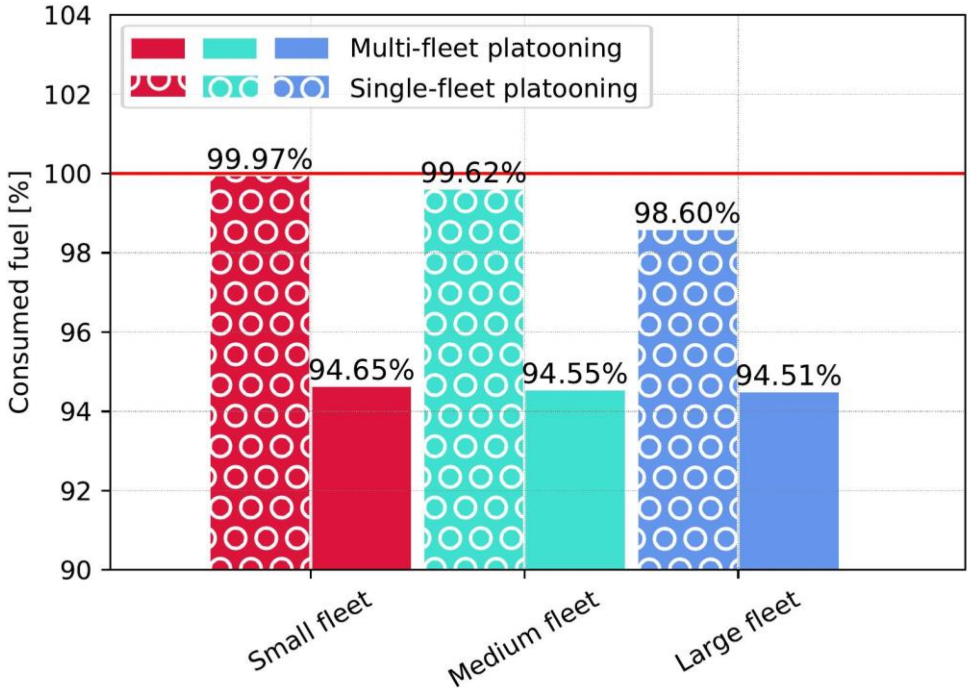


Figure 54: Fuel consumption in single-fleet and multi-fleet platoon coordination

5.5.6. Computational efficiency

Eventually, the computation efficiency of the DP based multi-fleet platoon coordination method is given in Figure 55 and Figure 56, where the truck index in x-axis is exactly the same with Figure 49. As the results in Figure 55 (in single-fleet platoon coordination) and Figure 56 (in multi-fleet platoon coordination) show, the average computation time of every truck for addressing the distributed MPC problem at per hub is within 30 seconds, which indicates a high efficiency of the proposed real-time coordination algorithm. For single-fleet platooning coordination scheme, because each truck has fewer predicted platoon partners at a hub, the time needed to find the optimal decision for a truck by DP is less than that of required in solving the problem in multi-fleet platoon coordination scheme.

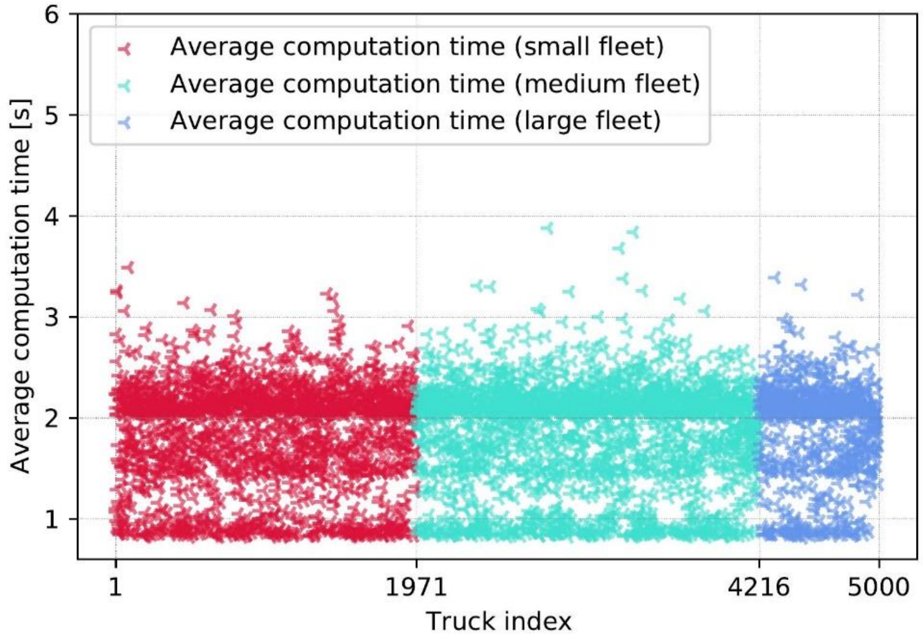


Figure 55: Computation time of trucks in single-fleet platoon coordination

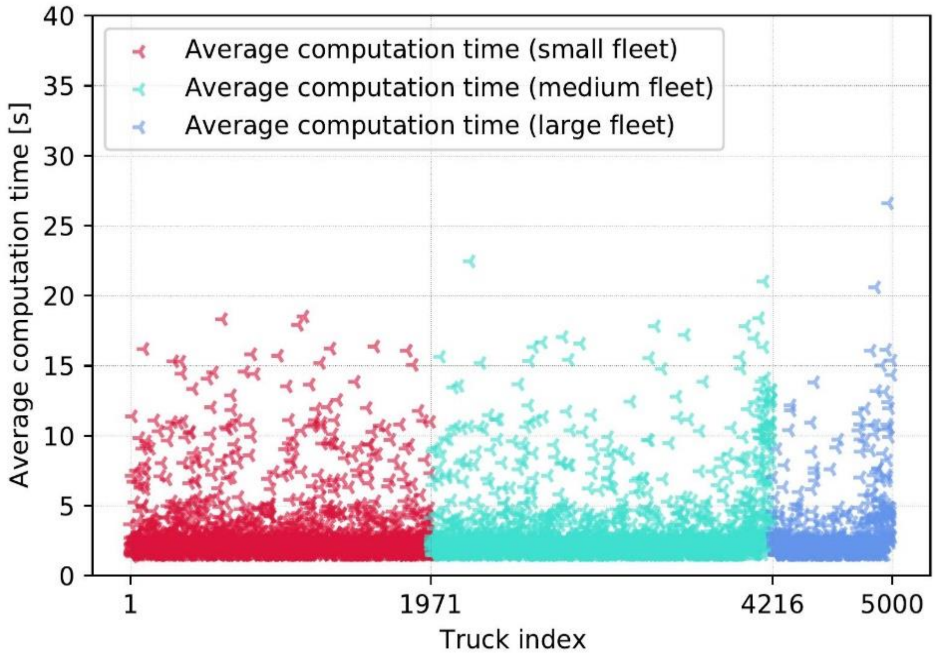


Figure 56: Computation time of trucks in multi-fleet platoon coordination

5.6. Summary and Conclusion

This section developed an MPC-based platoon coordination method that schedules waiting times of trucks in real-time and accounts for the fact that trucks belong to different fleets interested in optimizing their own profits. The platoon coordination method is evaluated in a realistic simulation study where fleets cooperate in forming platoons is compared to a case where only single-fleet platoons are formed.

The results from the simulation study suggests that **multi-fleet platooning is essential to get significant economic and environmental benefits** considering that the majority of trucks belong to smaller fleets. The simulation study showed that compared to single-fleet platooning, multi-fleet platooning achieves 359, 17, and 3 times higher monetary profit for small, medium and large fleets, respectively. Although large fleets achieve less increased benefit compared to small fleets, they also have an incentive to cooperate with other fleets due to their substantial increase in benefit.

Moreover, **compared to a system without any platooning, the multi-fleet platooning system and the single-fleet platooning system reduces the CO_2 emissions from trucks by $\mathbf{5.4}\%$ and $\mathbf{1.4}\%$, respectively**. In the simulation study it was also demonstrated that a coordination solution at a single decision-making instance took at most 4 seconds to compute, making the proposed coordination method suitable to use in real-time transport planning.

6. THE IMPACT OF MULTI-BRAND PLATOONING ON FUEL CONSUMPTION AND EMISSIONS

Authors:

- *Robin Vermeulen, TNO*
- *Nico Deschle, TNO*

In this chapter the task to determine impact of platooning on fuel consumption, CO_2 and pollutant emissions is described. The chapter deals with the method, mostly consisting of test track and open road testing, the results and conclusions.

6.1. Key performance indicators

Fuel consumption (FC) data for mono-brand platooning is readily available. Various studies reported the impact of platooning on fuel consumption mostly compared to solo driving.

Multi-brand platooning has not been tested to date. Mainly short platoons were tested with two or in a single case three vehicles. In Ensemble multi-brand platooning functionality (Platooning Support Function – PSF and Platooning Autonomous Function – PAF) is developed which would allow longer strings of vehicles from multiple brands. The impact on FC and emissions of a string of vehicles of various brands using the multi-brand platooning functionality shall thus be tested on the open road and in real-world driving conditions.
For fuel consumption and emission measurement the following KPI (Key Performance Indicators) have been defined:

- The effect on FC, CO_2 and pollutant emissions of PSF (gap of approximately 1.5 s) and PAF (gap of approximately 0.8 s or shorter) versus solo driving on a test track under optimal conditions. Underlying motivations for testing are: Impact on FC for 3rd, 4th, 5th etc. and trailing vehicle also keeping an eye on string stability of a longer string.
- The effect on FC, CO_2 and pollutant emissions and vehicle dynamic behaviour of the PSF versus solo driving under normal open road driving conditions. Study platoon string stability under normal driving conditions on the open road. Driving at time gap of 0.8 s is not allowed on the open road.

6.2. Measurement method

6.2.1. Method: test track

Measurement of fuel consumption (FC) of the engine, vehicle parameters, including V2X parameters to determine platoon lateral string stability.

Measure FC in a base case, solo driving, and when platooning on an oval test track under controlled conditions. The full lap was 7.5 km and the north straight slope is -0.3 %. The south straight slope is +0.3 %.
Determine achievable effect of multi-brand platooning under controlled conditions on a test track in an A-B-C-D-A schedule;
Base case A – platooning cases B to D – base case A, following the guidelines of SAE J1321-2012-02. Since SAE 1321 is to determine absolute FC and for platooning only relative effects are to be determined, the SAE does not need to be strictly followed on all aspects.
The configuration of the test track is illustrated by Figure 57: test track.

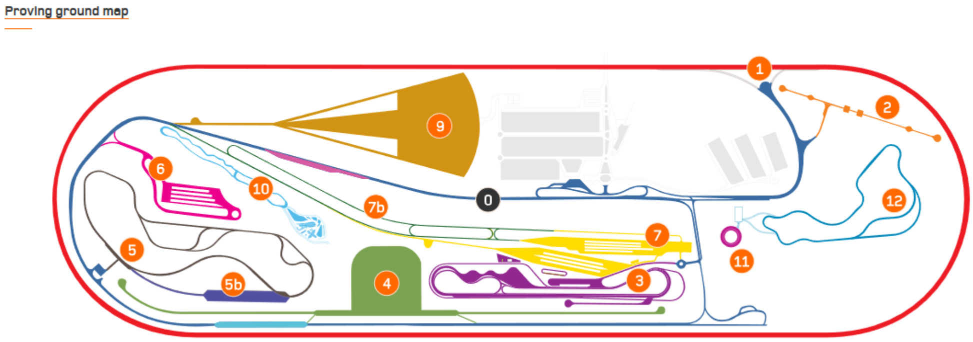


Figure 57: test track at IDIADA.

Test cases:

- Base case solo driving: large gap with no interference at 85 km/h
- Base case solo driving trailing: 2.0 s time gap at 85 km/h
- Platooning support level: 1.5 s time gap at 85 km/h (minimum ACC distance). This represents a distance of 35.4 m at a speed of 85 km/h.
    - ACC was used to drive at minimum ACC distance (1.4 - 1.5 s).
- Platooning autonomous level: 0.8 s time gap at 85 km/h.
    - Cancelled due to lack of safety measures.

For each case, to have a statistically accurate determination of the average with a low uncertainty, a minimum of six successful laps are needed. One additional lap is added for the vehicle to stabilize to the new condition and to manage to arrive into the new testing condition. E.g. vehicles need to form a platoon in this lap.

Table 4: overview of tests ordered.

Time, test nr.	Velocity [km/h]	Gap [s, m]		Remarks
Conditioning	85		60 minutes	7 vehicles, same order
Base case	85	>>>	6 laps	7 vehicles, same order
	85	2.0 s	1+6 laps	7 vehicles, same order
	85	1.4 s	1+6 laps	7 vehicles, same order
Base case	85	>>>	1+6 laps	7 vehicles, same order

Fuel

- Empty tank before arrival at IDIADA as much as possible. Max. 20% fuel left.
- Fuel topping up at local gas station.

Pre driving checks

- Cold tire pressures measured and inflated to vehicle or tire manufacturer standard.
- Proper wheel alignment (once).
- Brake adjustment (no dragging) (once).
- OBD/MI check: no emissions or safety related DTC (once).
- All other checks by IDIADA: oil, brakes, leaks, … (once).

Conditioning

- Forced Diesel Particulate Filter (DPF) regeneration, ensure regeneration up front of testing or even before arrival at IDIADA.
- Warm up, conditioning: according SAE J 1321 minimum of 1h.
- Stabilization of speed (Companion used 200m): recommended 1 lap (7.5km).
- Repetitions: Amount of repetitions on straights in both directions (5 for Companion).
- Recommended 6-7 laps.

Conditions

Ambient

- Pressure: >82.5 kPa, (Test: 100.1 kPa)
- Wind: <3 m/s, gusts up to 8 m/s (Test: average 1.2, max 2.5 m/s)
- Temperature: 10-30 ºC (Test: ~28 ºC)
- Precipitation: Dry, no precipitation (Test: no precipitation)

Vehicle

- Heater off, windows up, normal running lights.
- No regeneration during test. -> trigger regeneration before arrival at IDIADA, during tests force disable and monitor regeneration. Decision valid/invalid test data.

6.2.2. Method: Open road

The vehicles drive a predefined route on the public road encountering normal representative driving, road and traffic conditions. Vehicles do this one time solo, driving normally, using a safe defensive professional driving style, using the commonly used ADAS if available on the vehicle and one time in a string with PSF enabled.

Fuel consumption, engine and vehicle parameters, GPS location and V2X platooning data are recorded to be able to analyse the data with regard to platoon string stability under influence of real world conditions such as other traffic, grades, curves, tunnels etc.

6.2.3. Overview, specification of all required instruments and outputs

This section describes the instruments and sources and, for each of them, the signals obtained, together with their unit, sample frequency, and accuracy (Table 5).

Table 5: overview of required signals and specifications.

Instrument/source	Signal	Unit	Frequency [Hz]	Accuracy/resolution
Vehicle OBD	Fuel rate	l/h	1	+/- 5%, 0.1 l/h
	% engine torque	%	1	Calculation of engine work +/- 5%
	% friction torque	%	1	Calculation of engine work +/- 5%
	Engine speed	rpm	1	Calculation of engine work +/- 5%
	Coolant, oil temps	K	0.1-1	+/- 2K
	DPF regen status	0, 1	1	n.a.
	Exhaust temp	K	1	+/- 5K
NOx and NH3 sensor	NO_x+NH3 concentration	ppm	1	+/- 10pm
GPS	GPS pos, velocity, alt	Lat, lon, km/h, m	1	+/- 0.5 km/h
Local Weather station	Temp, p, RH, wind speed direction	ºC, kPa, %, m/s	Minimum 0.1 Hz	
V2X	Gap distance, position in platoon, etc	m, -,	1	
Scale	Vehicle weight	kg	Before test	+/- 100kg
Pressure gauge	Tire pressure	kPa	Before test-after test	

SEMS (Smart Emissions Measurement System) is a sensor-based system developed by TNO and is used to measure and analyse the tail-pipe NO_x emissions during daily operation and a range of vehicle/engine parameters to be able to characterize the typical operation of the vehicles. The SEMS uses a calibrated automotive NO_x sensor, an ammonia sensor, GPS and a data-acquisition system to record the sensor data and data from the vehicle and engine at a sample rate of 1 Hz. The system can operate autonomously and wakes up at ignition/key-on of the vehicle. The system can be stowed away so that normal operation is not hindered by the measurement. The recorded data is sent hourly to a central data server.

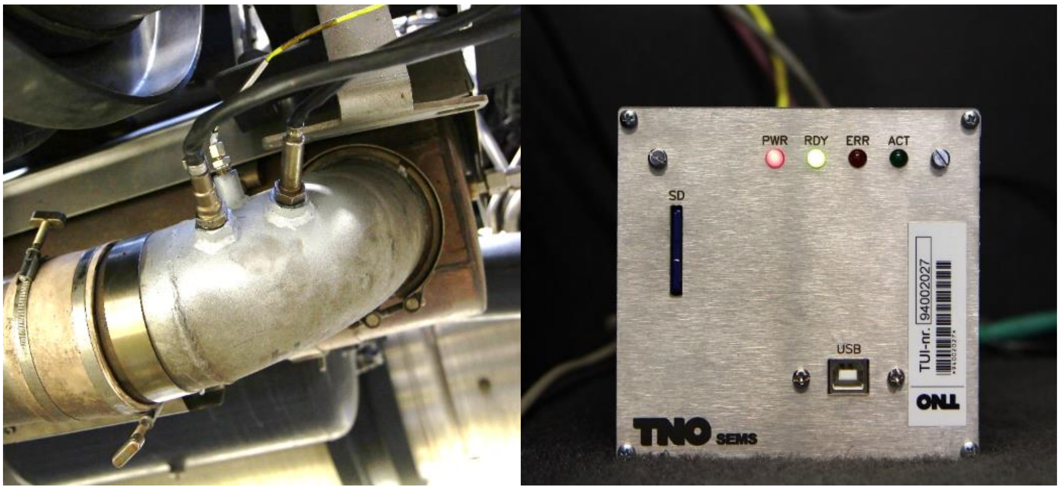


Figure 58: SEMS. Left: calibrated NO_x-O_2 sensor, NH_3 sensor and temperature sensor mounted in the tail-pipe. Right: autonomously running data recording unit with hourly data transmission to a central server via a cellular network.

The raw data on the central server is post-processed automatically to filter and check the data. Sensor output is corrected using sensor specific calibration values.

Mass-emissions and instantaneous engine power are calculated combining sensor data and engine and vehicle data such as manifold-air flow, fuel rate, engine torque, engine speed and sensor O_2 concentration where possible.

6.2.4. Test vehicles

In Table 6 and overview is given of the test vehicles and their specifications.

Table 6: Specifications of the vehicles that participated in the tests.

	Vehicle DAF	Vehicle Iveco	Vehicle MAN	Vehicle Mercedes	Vehicle Renault	Vehicle Scania	Vehicle Volvo
Type	Tractor semi-trailer	Tractor semi-trailer	Tractor semi-trailer	Tractor semi-trailer	Tractor semi-trailer	Tractor semi-trailer	Tractor semi-trailer
Cabin	Day, sleeper cab	Sleeper cab	Sleeper cab	Sleeper cab	High sleeper cab		High sleeper cab
Axle config tractor, semi-trailer	4x2, 3	4x2, 3	4x2, 3	4x2, 3	4x2, 3	6x2, 3	4x2, 3

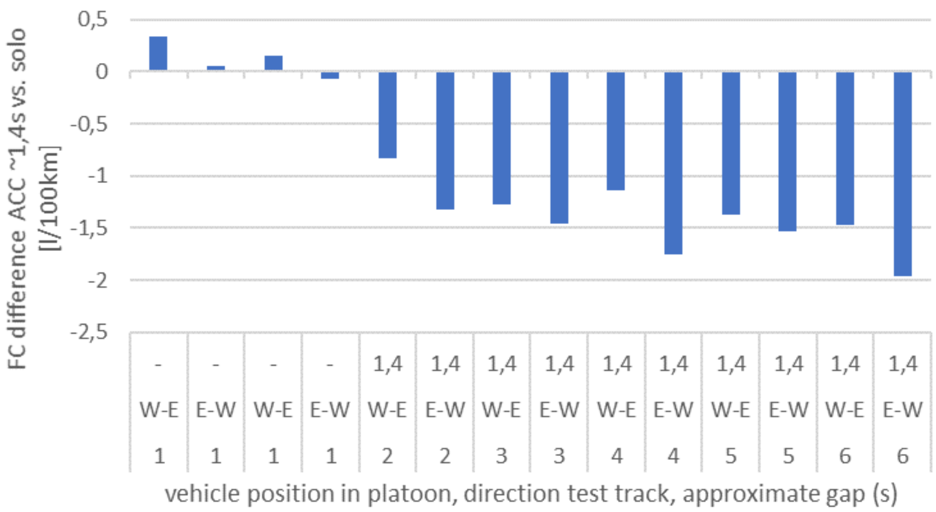
(Semi-) trailer type	Box	Curtain side	Curtain side	Curtain side + skirts	Box	Box	Box
Engine power [kW]	350-400	350-400	350-400	350-400	350-400	350-400	500-600
Vehicle combination test mass weighted [kg]	36.105	33.156	32.813	26.958	37.379	35.962	37.665
Aero package	Cabin side skirts and roof spoiler	Cabin side skirts and roof spoiler	Cabin side skirts and roof spoiler deflectors	Side skirts on trailer Cabin side skirts and roof spoiler and deflectors Side mirror cam	Cabin side skirts and roof spoiler	Cabin side skirts and roof spoiler	Cabin side skirts and roof spoiler

6.3. Results of the fuel consumption and emissions tests

6.3.1. Test track

During the test track tests wind speed was low around 1 bft, i.e. 1.5 m/s, with light gusts up to 2.5 m/s. Direction on average Southerly but changing. Asphalt temperature was around 40 ºC and ambient temperature was 28 ºC, barometric pressure was 1004 mbar with good visibility with no precipitation. Driving at cruising speed is necessary to bring the trucks drivelines and tires at a stable working temperature. Test track tests were preceded by extensive driving on the track allowing sufficient warm up time. The oval test track has two large curves and straight sections with ascending and descending and wind direction relative to the vehicle changes. That means that the required power output from the truck engine to maintain a given speed setting and the speed and engine power will need to stabilize after the transition from the curve to the straight section of the oval test track. A margin of 200 m is used, meaning that 200 m of data after a curve is removed to allow stabilisation.

In Figure 59 the absolute and relative difference in fuel consumption are given between the tests driving at an inter-vehicular gap of approximately 1.4 s at cruising speed of 85 km/h compared to solo driving with gaps of approximately 1 km. For the leading vehicle the difference is not significant. For the flowing vehicles there is a consistent lower fuel consumption when driving at gaps of approximately 1.4 s. The measured difference is about -1 to -2 l/100km and on average -1.4 l/100km. In general, the difference is about 0.5 l/100km larger for the E-W direction on the test track. The difference seems to increase for vehicles towards the end of the platoon. The relative difference is on average -7 % and higher for the W-E direction because in that case the fuel consumption was clearly lower than for driving in the E-W direction on the test track.



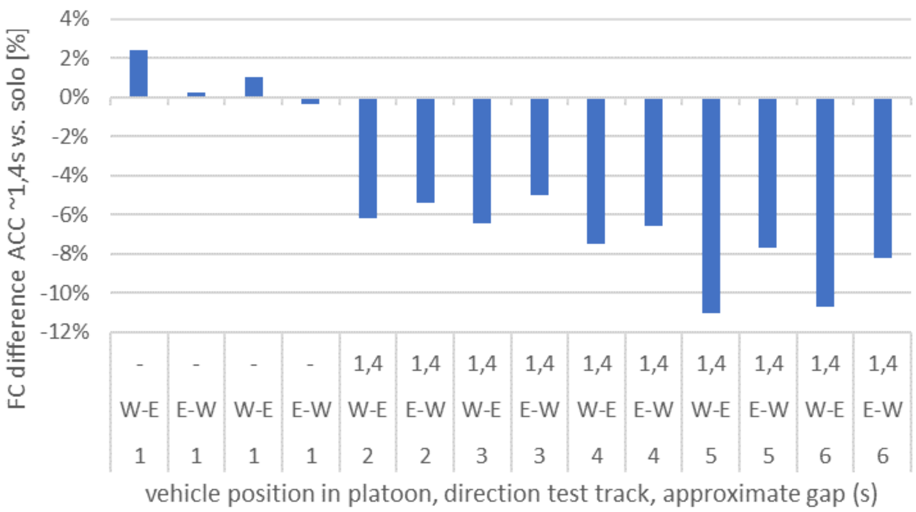


Figure 59: Absolute (upper graph) and relative (lower graph) difference in Fuel Consumption between the tests driving at an inter-vehicular gap of approximately 1.4 s at cruising speed of 85 km/h compared to solo driving with gaps of approximately 1 km.

For the difference in NOx emissions between the two cases, see Figure 60, there is no clear trend. Figure 61 shows the difference in average speed between the tests driving at an inter-vehicular gap of approximately 1.4 s at cruising speed of 85 km/h compared to solo driving with gaps of approximately 1 km. Finally, Figure 62 to Figure 64 show the results for driving at an inter-vehicular gap of approximately 2 s.

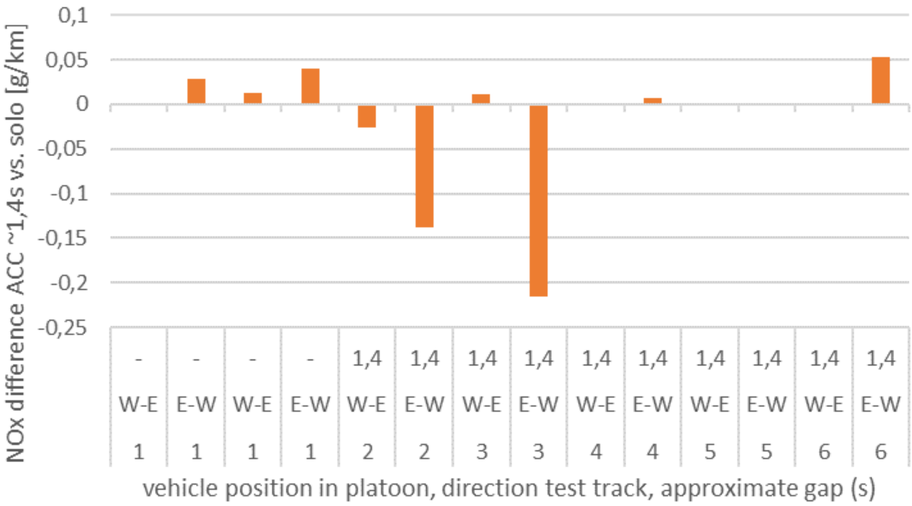


Figure 60: Difference in NO_x emissions between the tests driving at an inter-vehicular gap of approximately 1.4 s at cruising speed of 85 km/h compared to solo driving with gaps of approximately 1 km.

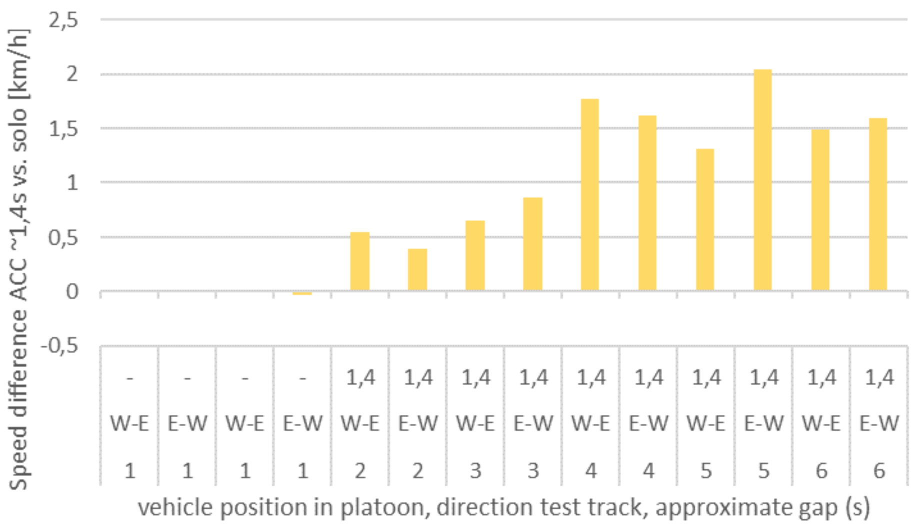
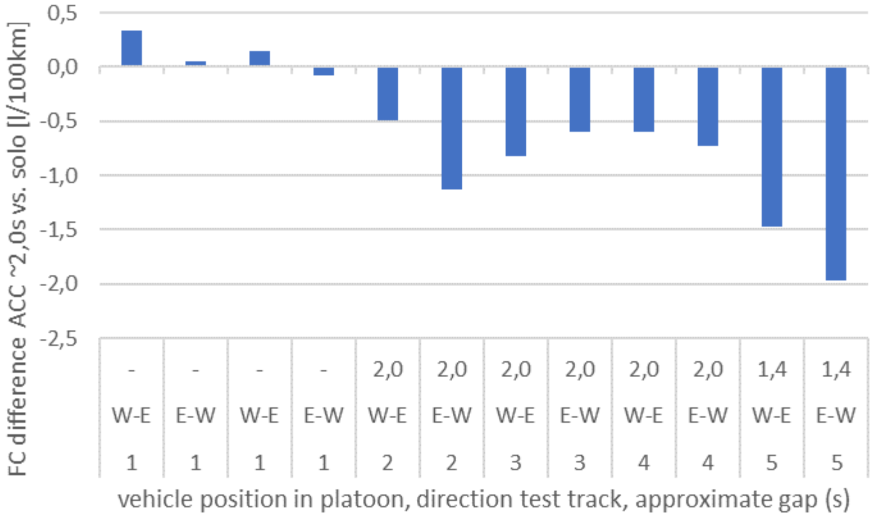


Figure 61: Difference in average speed between the tests driving at an inter-vehicular gap of approximately 1.4 s at cruising speed of 85 km/h compared to solo driving with gaps of approximately 1 km.



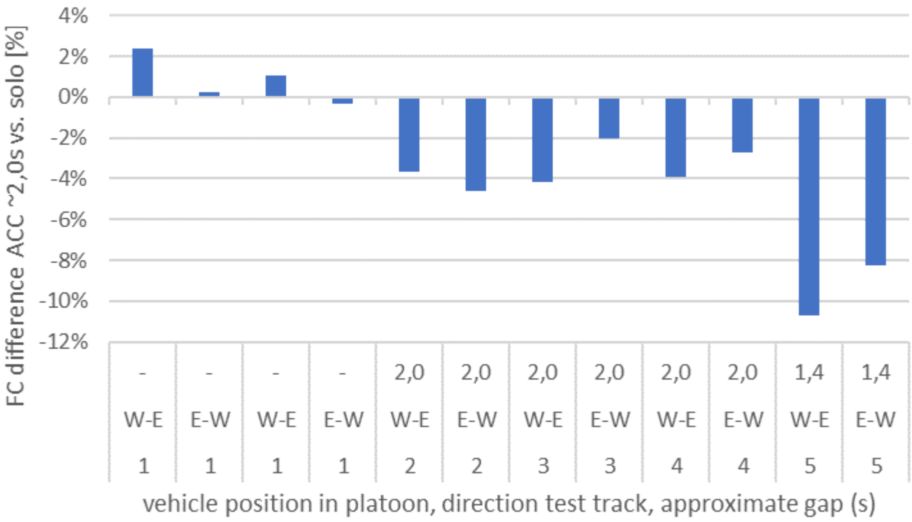


Figure 62: Absolute and relative difference in Fuel Consumption between the tests driving at an inter-vehicular gap of approximately 2.0 s at cruising speed of 85 km/h compared to solo driving with gaps of approximately 1 km.

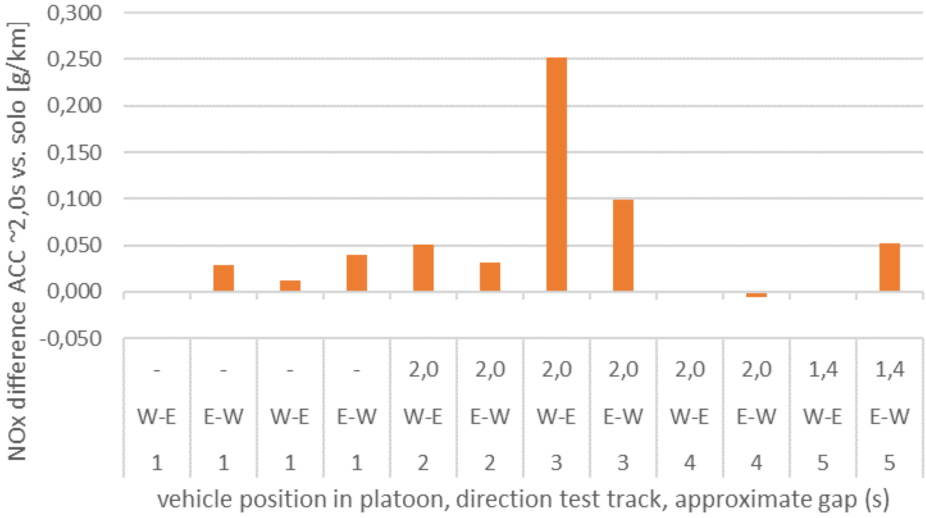


Figure 63: Difference in NO_x emissions between the tests driving at an inter-vehicular gap of approximately 2.0 s at cruising speed of 85 km/h compared to solo driving with gaps of approximately 1 km.

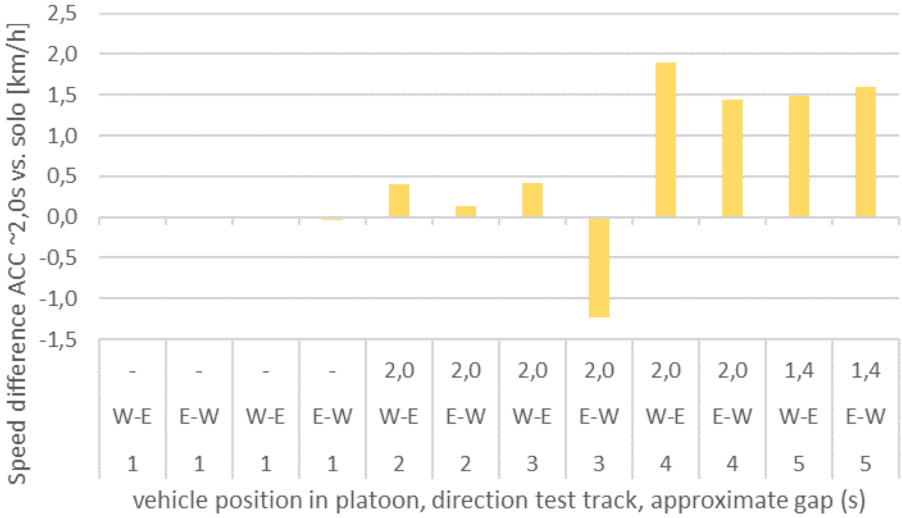


Figure 64: Difference in average speed between the tests driving at an inter-vehicular gap of approximately 2.0 s at cruising speed of 85 km/h compared to solo driving with gaps of approximately 1 km.

For the test track measurements the following was observed:

- There is no significant effect on FC (and CO_2) for the lead vehicle.
- For the following vehicles the fuel consumption and CO_2 emission was on average about 1.4 l/100km and 7 % lower at about 85 km/h and a 1.4 s gap compared to driving solo at a large gap of approximately 1 km.
- For the gap of 2.0 s, driving about 85 km/h, this difference was smaller at an average for all following vehicles of about 1.0 l/100km and 5 % respectively.
- Effects of the position of the following vehicles could not be observed due to variation in the measurements but for the 1.4 s gap there seems to be a trend with lower absolute and relative fuel consumption compared to solo driving towards the tail of the platoon.
- Solo driving was executed at a consistently lower speed compared to the platooning cases of 1.4 and 2.0 s. This probably influences the difference between FC from solo driving and platooning because at a lower speed the fuel consumption will be lower. We reason that in the case the vehicles would have driven at the same speed this would result in a 1-2 % larger difference between solo driving and platooning at a 1.4 s and 2.0 s gap and 85 km/h.
- This would be roughly in line with recent literature (Veldhuizen, 2019) for the1.4 s gap which gives a decrease of about 9%, although payload isn't known for that study.
- For tail-pipe NO_x emissions we observed small increases and some larger decreases between the two cases for two vehicles for the East-West direction of the test track for 1.4 s vs. solo. For the 2.0 s case there are more increases but most are very small. The vehicle showing the larger decrease at the 1.4 s gap showed a larger increase at a gap of 2.0 s. Probably this vehicle was less stable in terms of NO_x emissions. Overall there is no clear trend for NO_x emissions.
- A large consistent difference was observed between FC (CO_2) in the two directions of the test track (east-west was about 7-11 l/100km higher than west-east). There was little wind at approximately 1 m/s which on average was Southerly and thus perpendicular to the test track. The test house IDIADA explained that the two straight sections have grades of 0.3 % inclination and declination. This total difference of 0.6 % can explain the consistent difference in FC between the two straights sections.
- A consistent larger absolute difference of Fuel Consumption was found between for East-West compared to West-East. The relative difference of Fuel Consumption showed the opposite. This can be explained by the fact that the fuel consumption was higher when driving East-West on the +0.3 % incline.

6.3.2. Open road

For the open road test all the vehicles drove a route of about 90 km back and forth from IDIADA El Vendrel to Lleida. Not all the vehicles managed to log the whole trajectory without interruptions. Also note that for one vehicle the data for the solo route was not recorded.

To make a clear and fair analysis we identified the longest part of the route with continuous data recording during both the platoon and solo case. The final route was trimmed from about 180 km to about 127 km in total, for all the vehicles as similar as possible, as shown in Figure 65 and Figure 66. Figure 67 shows the altitude profile of the trip.

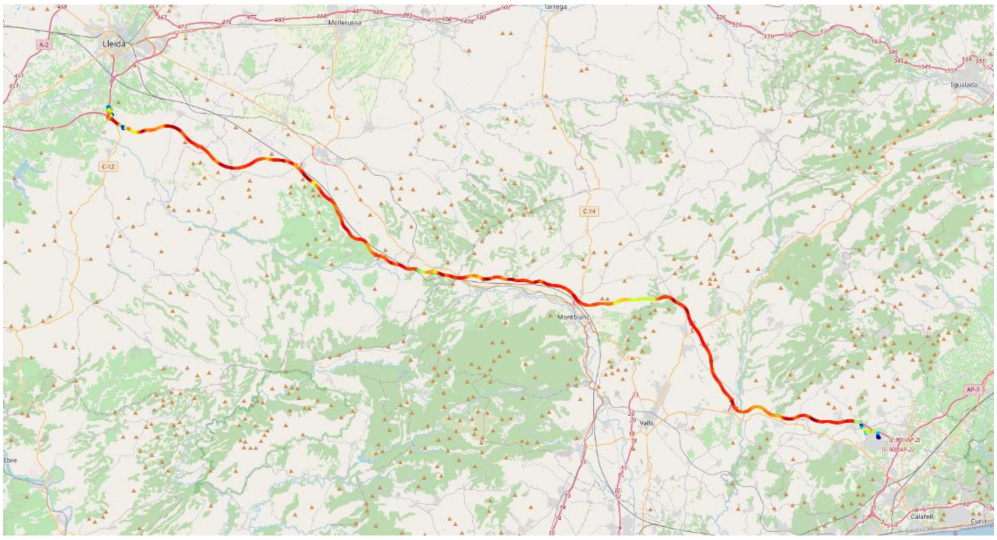


Figure 65: Complete open road test route.

Figure 66: Trimmed route used in the analysis. This is the subsection of the total route from the experiment that is shared over all the vehicles and both experiments.

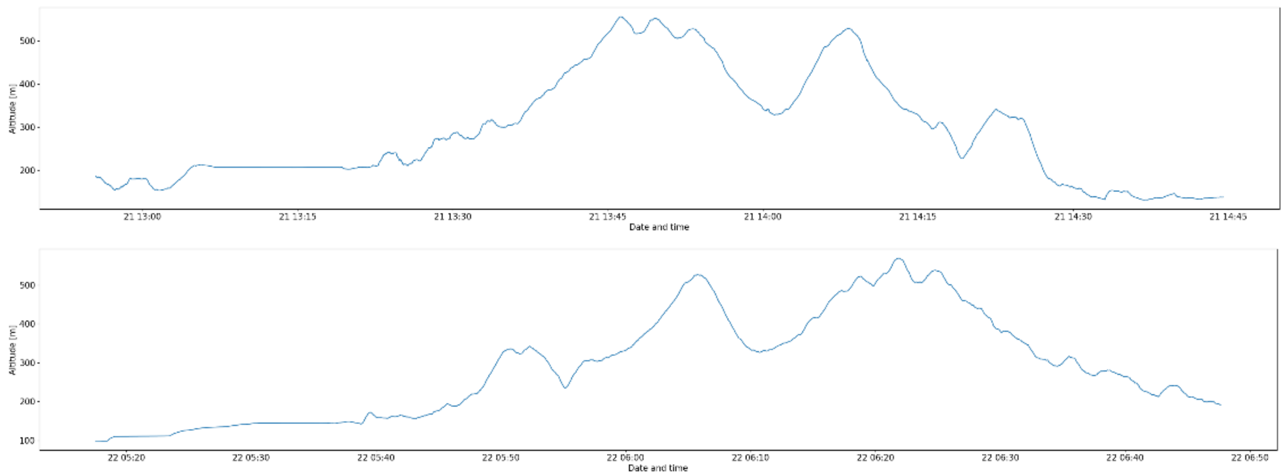


Figure 67: altitude profiles of the outbound and inbound parts of the test route. Large part of the route contains grades, ascending or descending.

Following, we studied the average speed (Figure 68) and the speed distribution for the different routes for both cases. The first thing that can be observed is that naturally, the mean velocities of the vehicles in the platoon case are very similar to each other. They have larger dispersion however. Furthermore, the average speed for the vehicles for the platooning case is slower than the vehicles driving solo. It was reported by the drivers that to maintain a joined platoon on grades the platoon needed to slow down because the vehicles with lower power-to-mass ratio couldn't keep up.

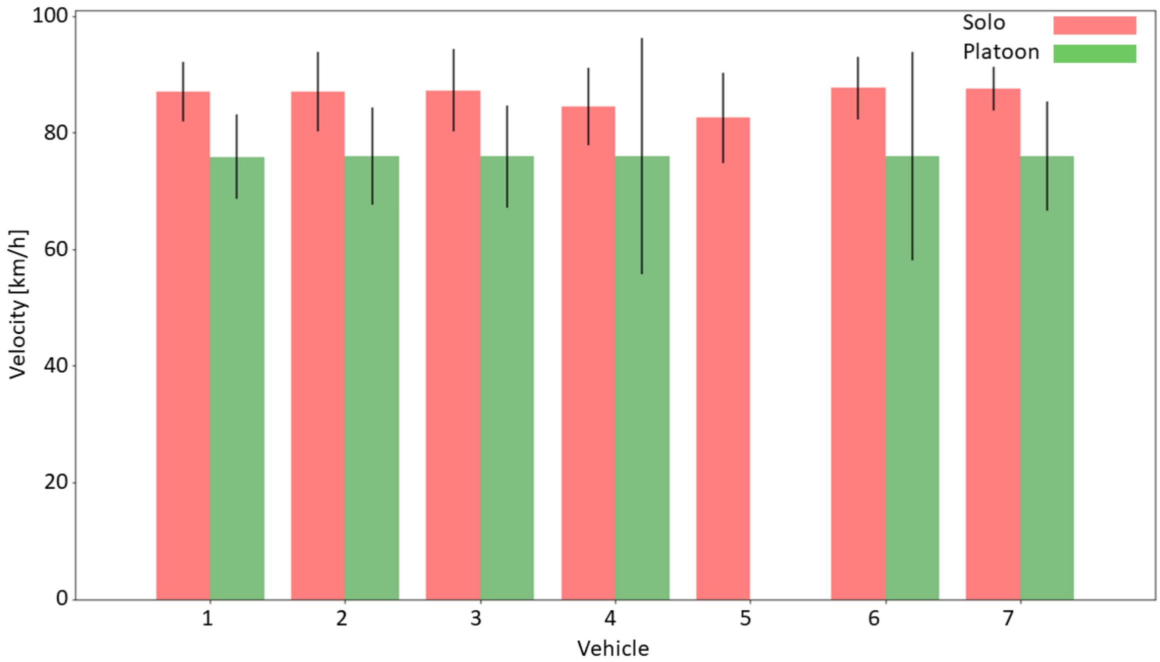


Figure 68: Mean velocities computed from the GPS data for all the vehicles from the selected part of the test route. It can be observed that for platooning the speed is slower and speed variance is larger compared to solo driving.

To have an initial better understanding of the speed behaviour, we can observe the speed distribution for each of the vehicles on both experiments, this is shown in Figure 69. Clearly the overall variation of speed is larger for all measured vehicles in the platooning case. The effort to establish and maintain a stable platoon on grades caused the platoon to drive at a lower average speed than when each vehicle is driving solo. This probably also caused the larger speed variation for the platoon case versus solo case, at least over the part of the trip for which continuous, uninterrupted data is available.

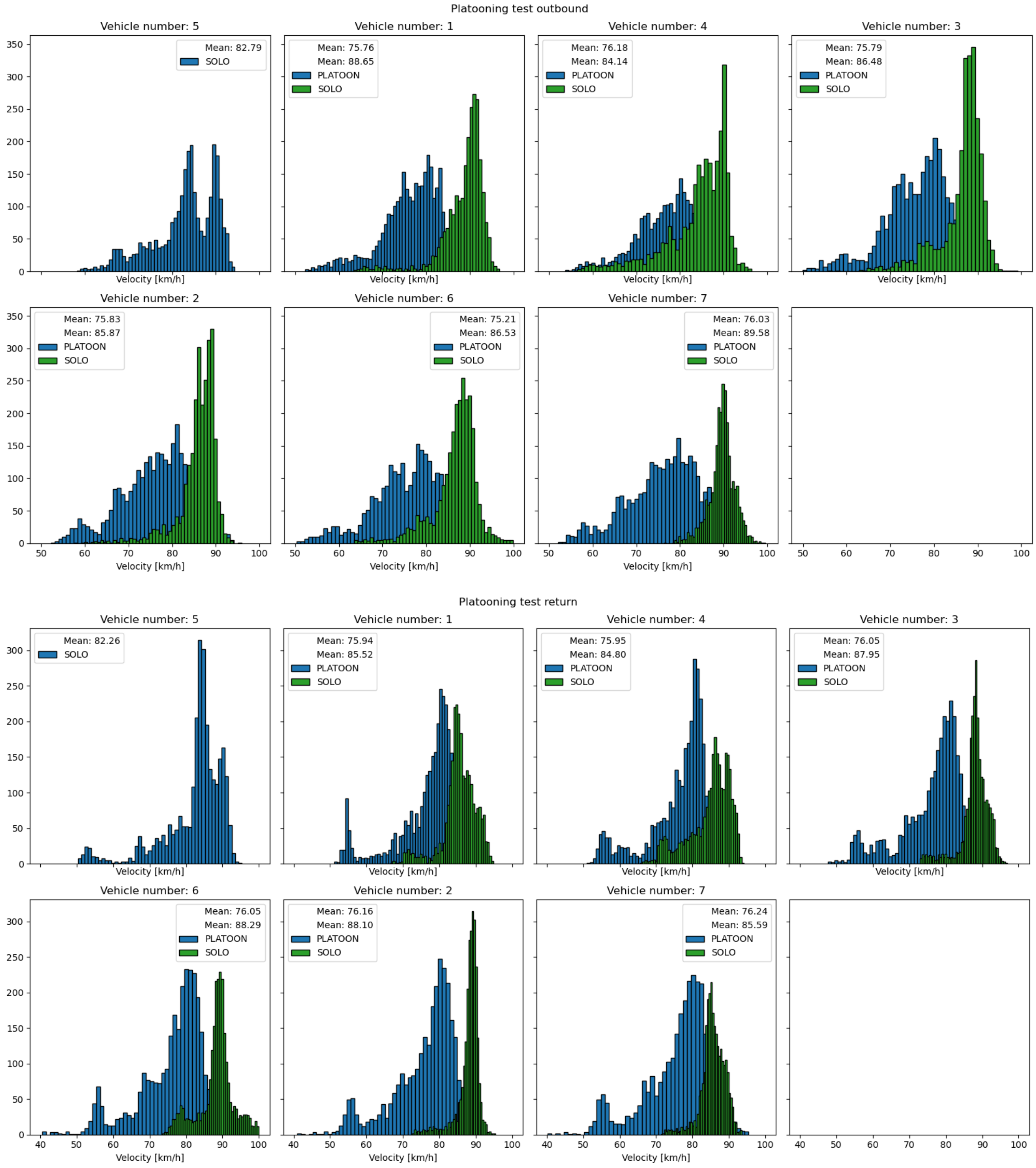


Figure 69: Speed distributions for the different vehicles and the different experiments solo versus platooning for the outbound trip (upper plots) versus inbound part (bottom plots) of the whole trip. As predicted by the previous figure, the dispersion of the speeds during platooning is very large, indicating higher accelerations.

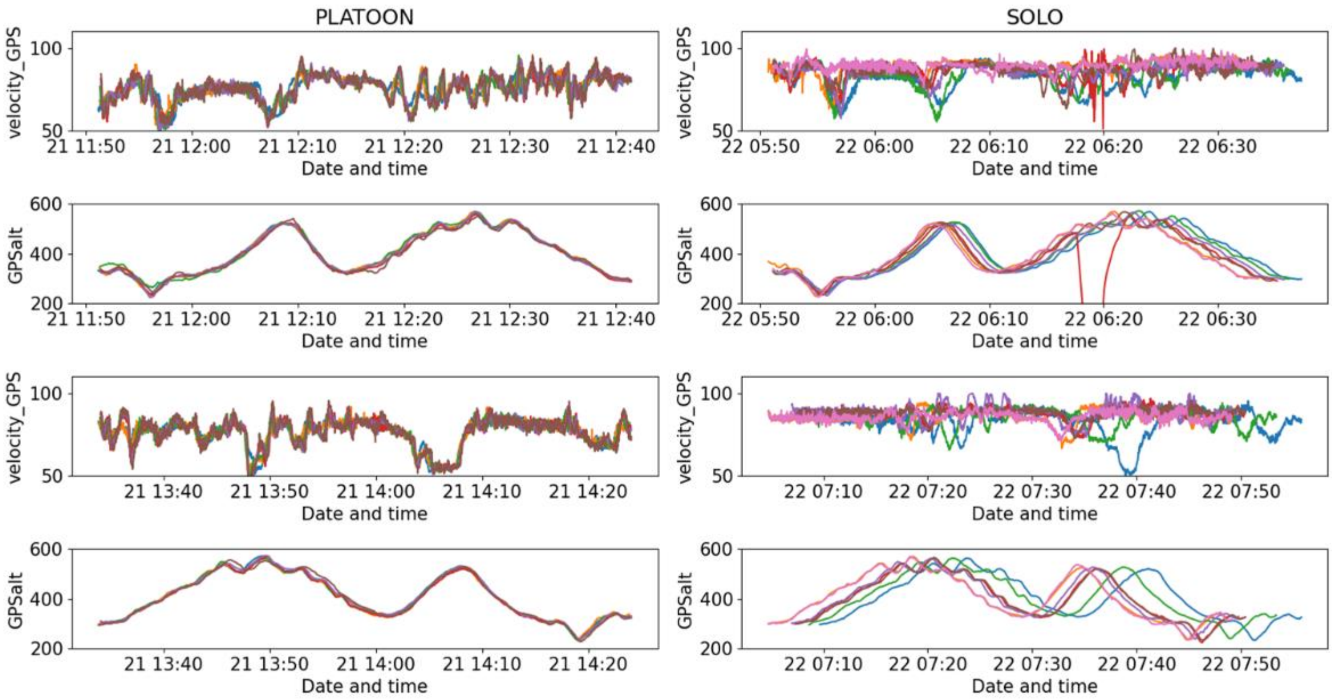


Figure 70: time plots of GPS vehicle speed [km/h] and GPS altitude [m] of the two cases for the outbound part (upper plots) of the trip and the inbound part (bottom plots) of the trip. The platoon case (left) shows more irregularities for speed and lower speeds as well than the solo case (right).

The fuel consumption was averaged over the selected part of the test route, see Figure 71. For five vehicles, fuel consumption data was available for the two cases of regular solo driving and platooning. A clearly lower fuel consumption is measured for platooning compared to regular driving which varies amongst the vehicles from about -3 to -5 l/100km. As observed, the driving conditions were different between the two cases; the average speed was lower for the platooning case and there were more irregularities (accelerations and decelerations).

It is not clear from this data how much and when the vehicles actually were joined and drove in a stable platoon. To investigate platooning in detail, parts of data could be selected for which the platoon was actually joined. This information is essential for the analyses as at least it needs to be determined if vehicles drove in platooning mode at all. This can be investigated by analysing the platoon join parameter from the V2X data. A first analyses using V2X data showed that the V2X data contains inconsistencies. An example is that vehicles broadcast a different amount of vehicles in the platoon although they drive in the same platoon. The data inconsistency has also been described in Ensemble Deliverable 2.5. The data from the inter-vehicular gap shows quite some noise making it hard to determine the actual distance.

Because the driving conditions were different between the two cases and disrupted by platoon formation and maintain issues, it is not possible to derive the sole effect of mature platooning. The reduced fuel consumption for platooning might partly have been caused by the lower speeds.

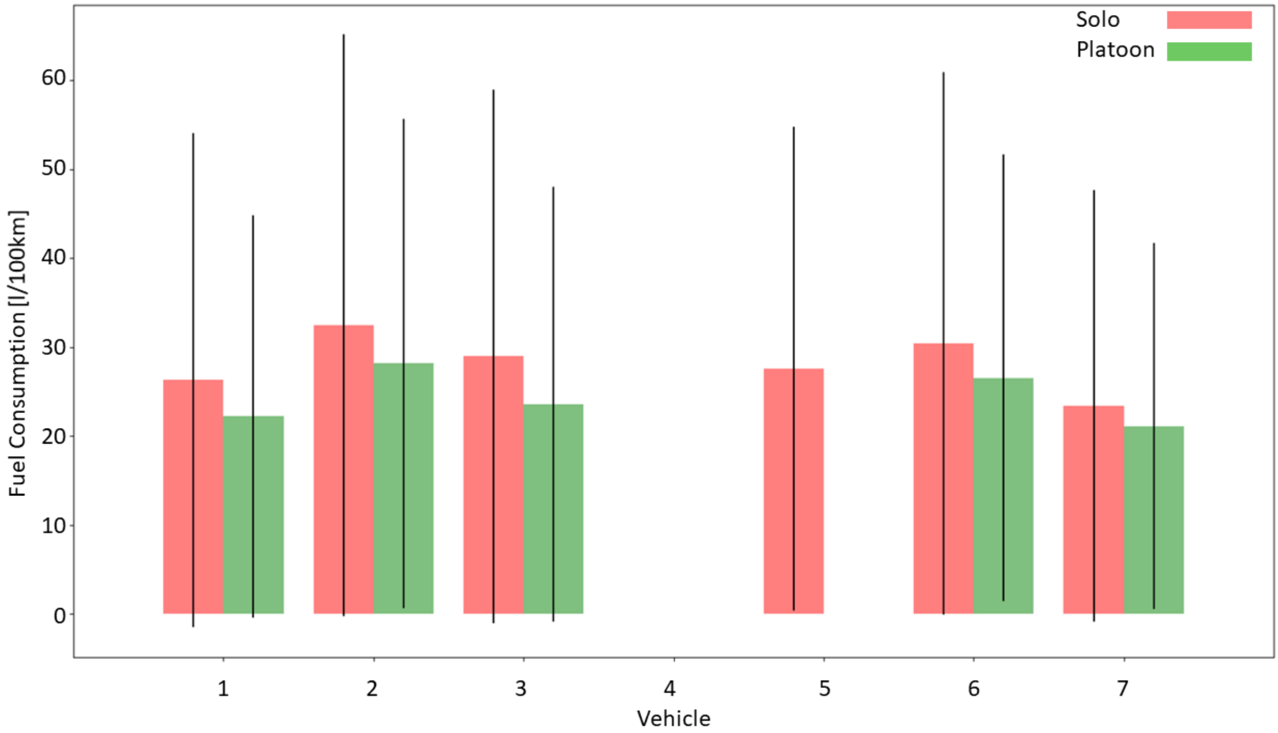


Figure 71: mean fuel consumption for the vehicles for the solo and platooning case for the selected part of the test route. Note that the platooning case contains driving with platoon formation and maintain issues and the overall speed of the platoon needed to be reduced on grades to match the speed of the slowest vehicles (lowest power-to-mass ratio).

6.4. Status quo effects on fuel consumption of trucks in platoons

Research on truck platooning and emission measurements is mostly operationalized through measuring fuel consumption in two distinct modes, driving 100% solo and driving (100%) with a specific inter vehicular gap, see Table 7 for an overview of investigations were the impact of platooning was tested. Relative figures thus represent effects between these two modes. In the real world, the base case already constitutes certain inter-vehicular distances distribution where spontaneous convoying is happening (2020, Vooronderzoek truck platooning). Various studies have been performed and these show varying results as the graph illustrates. Average fuel savings are reported in most instances, only the magnitude of these savings varies, depending on conditions and the type of study. We summarized the conditions of the various studies. It can be seen that there is quite some variation among the studies, with respect to:

- Testing protocols - ranging from no clear protocol (PATH, ITS) to test-track SAE J1321 Type II fuel economy protocol (a.o. Veldhuizen et al., 2019; Peleton, 2017) and real-world monitoring (ACC Integrator Connected Truck Trials, 2021).
- Number of vehicles. 2 or 3 truck platoons;
- Vehicle driving speed – 80-105 km/h
- Miscellaneous - Weather conditions, load, type of trucks used

Table 7: overview of programs where the fuel consumption of platooning was measured.

Project/ Research	Test protocol	Speed (km/h)	Gap distance (m)	Truck platoon # of trucks	Truck characterisation	Load	Average fuel savings
Auburn Peleton (2017)	SAE J1321 Type II fuel economy protocol	105	9,12,15, 23,45.	2	Articulated tractor-trailer	30t / truck-trailer	8.7% (9m/45m.)-10.2% (15m)
CHAUFFEUR/ PROMOTE (2000-2003)	By flow measurement (3% reliability)	80	8,10,12, 14	2	No wind deflectors on tractors	Lead truck 14.5t; following truck 28t following truck 40t	6% (10m) 21% (10m) Est. 17% (10m)
COMPANION (2016)		80	12, 15, 20	2, 3	Tractor-trailer		8.5% (12m) 7.8% (15m) 8.6% (20m)

Project/ Research	Test protocol	Speed (km/h)	Gap distance (m)	Truck platoon # of trucks	Truck characterisation	Load	Average fuel savings
EDDI (2019)	Real-world	80	15	2		Dummy and actual goods (from sept.)	1.3% leading 4% following
ITS (2013)	No clear protocol	80	5,10,15, 20	3	Rigid truck	Empty-loaded	12% (20m) to 22.5% (5m)
NRC (2017)	SAE J1321 Type II, modified	89, 105	17-43m	3 CACC, 1 control vehicle	Tractor trailer, standard and aerodynamic trailer.	Empty (14t) and loaded (29.4t)	Following: 22-43m: 5.2% Leading: >26m, 0%. 17m, 1% Trailing vehicle 3% less FC than 2nd vehicle Empty: 1.6% less than loaded.
PATH (2004)	No clear SAE protocol mentioned	80, 89	3,4,6, 8,10.	2	Articulated tractor-trailer	Empty-loaded. 14-28 t / truck-trailer	8% (10m) – 11% (4m)
SARTRE (2013)	Extensive description (not SAE)	85	5, 12, 20, 25.	2	Rigid body	Unknown	8% (25m) to 12% (5m)
Veldhuizen et al. (2019)	SAE J1321 Type II fuel economy protocol	85	10,20,30, 40,50,70.	2 ACC	EU truck over cab	Unknown	9.0+-2.8% (50-20 m):
Integrator Connected Truck Trials, ACC (Kempen et al., 2021)	Real-world (naturalistic driving, field operational test)	80	33, 50	2 truck ACC convoy	EU truck over cab	Loaded, mean weight 38t	ACC3 (50m): 4% (1.2 l/100km) ACC1 (33m): 6% (0.8 l/100km)

Relative fuel savings vary among the studies. And within the studies savings also vary. Usually research relates this to vehicle characteristics (roof spoilers) or local conditions such as the weather (wind yaw angle) and test repeatability. Clear effect is that the following/ trailing vehicle generally saves more fuel (see Veldhuizen et al., 2019) than the leading vehicle. The leading vehicle saves fuel at short distances as of <17m.

Figure 72, Figure 73 and Figure 74 show the average fuel savings of the leading and following vehicles in a truck-platoon, derived in earlier studies (dots). The majority of the work listed here is conducted at gap distances 5-20 m (CHAUFFEUR, COMPANION, SARTRE, ITS). In these studies fuel savings of respectively 8.1 % (SARTRE; gap distance 12 m.) – 22.5 % (ITS; gap distance 5 m) and 10.6 +/- 31 % at 10 m (Veldhuizen et al., 2019) are reported.

Studies focusing on larger gap distances give the following results:
For 30 m: 9.0+-2.8 % - there was no significant difference with 50 m (Veldhuizen et al., 2019); 6 % (Van Kempen et al., 2021). For 50 m: 9.0+-2.8 % (Veldhuizen et al., 2019); 4 % (Kempen et al., 2021). For 70 m: 8.3+-4.2 %, (Veldhuizen et al., 2019).

COMPANION reported different relative fuel savings for the second vehicle in a two and three vehicle platoon, but tested at short gaps of 12 to 20 m. The second vehicle would yield a larger fuel saving in the three vehicle platoon than in the two vehicle platoon, additional savings are highest at the short gap (1.4 %) and are tested lower at the 20 m gap (0.4 %)

Another effect that isn't often considered for calculating the impact of FC is the effect of the vehicle mass. With a low payload, the relative effect (delta) is larger as in that case the aerodynamic drag represents a larger share in total driving resistances (forces acting in the opposite of the driving direction). The absolute effect (delta) will probably be more or less the same for the given conditions. Tests done without payload will show larger relative effects on FC than tests done with for instance full payload, as was reported by the NRC study (McAuliffe et al., 2017). The fuel saving was 1.6 % higher for the empty vehicle compared to the loaded vehicle.

All in all, it is very difficult to claim that there is one number that represents fuel savings as a result of platooning versus solo driving.

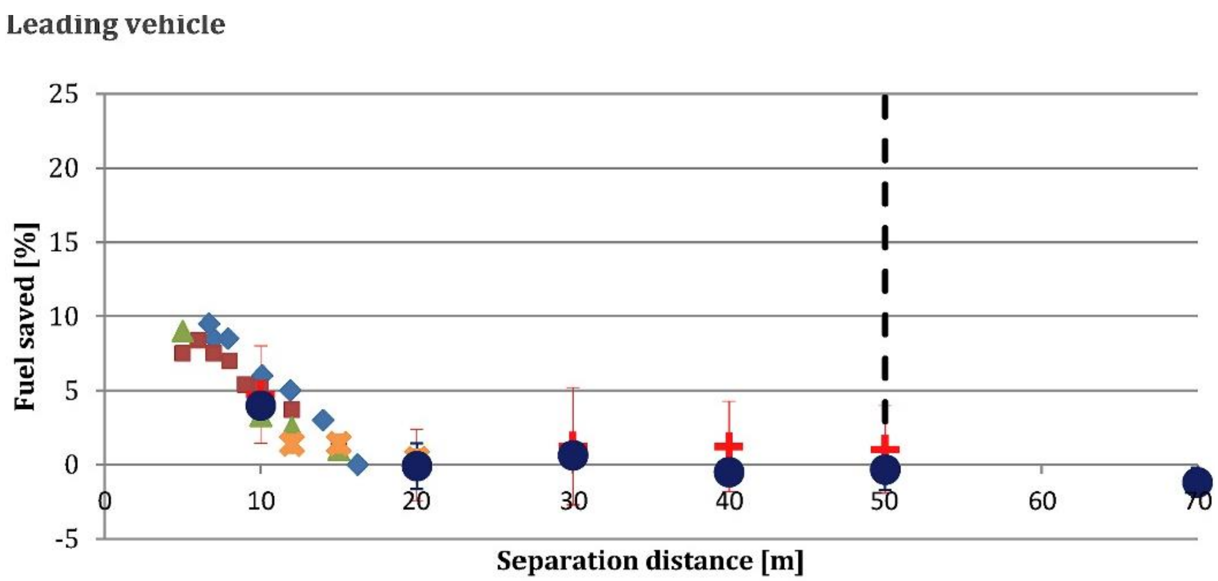


Figure 72: relative effects of platooning of the leading vehicle in the platoon versus solo driving for various studies.

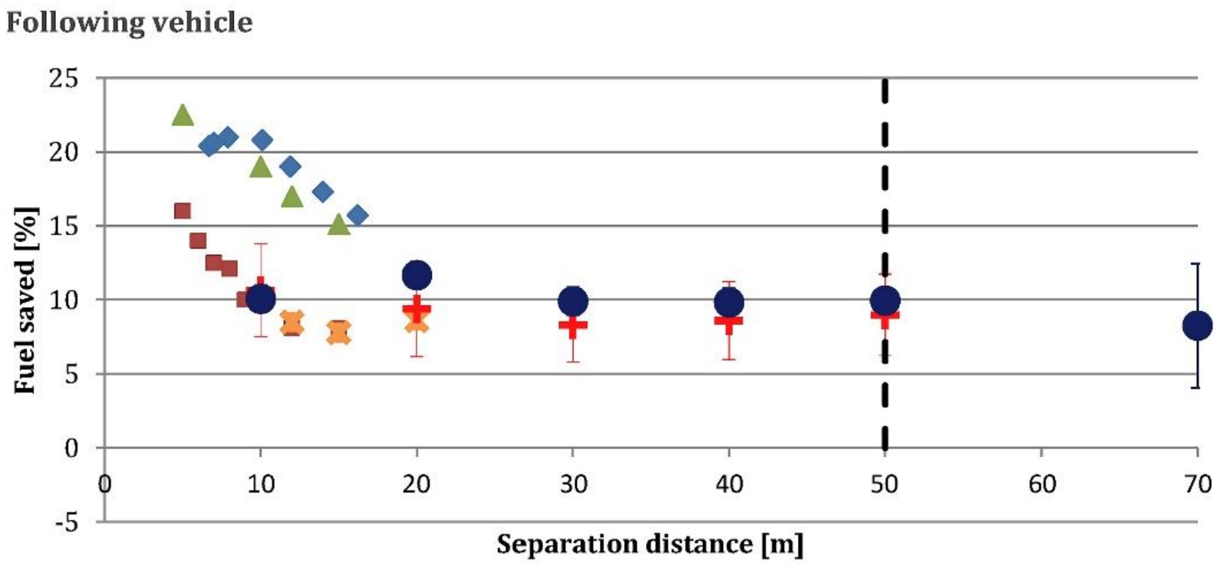


Figure 73: relative effects of platooning of the following vehicle in the platoon versus solo driving for various studies.

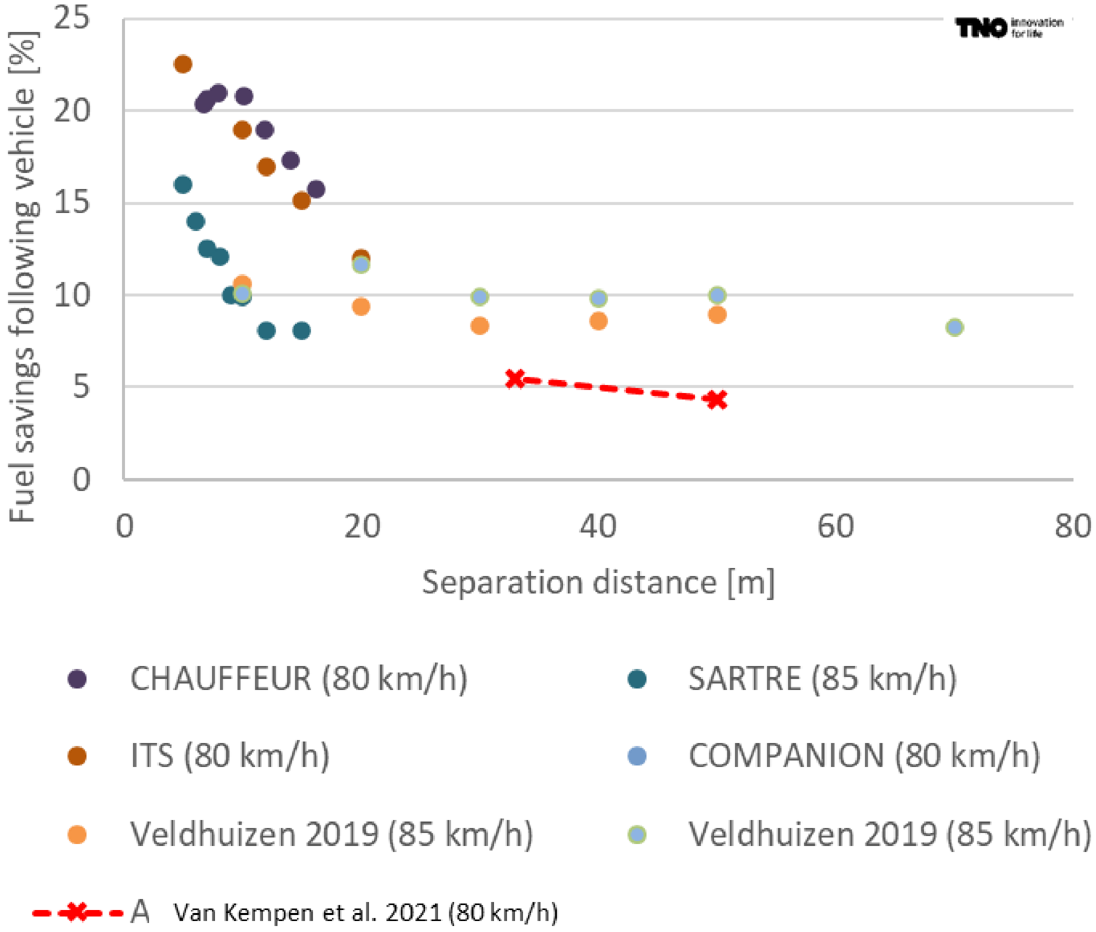


Figure 74: relative effects of platooning of the following vehicle in the platoon versus solo driving for various studies. In this figure the results found by van Kempen 2021 are also included (for ACC in real world usage).

Reported fuel savings mostly represent solo driving versus driving in a platoon at certain gap distances. The definition of solo driving of a test as well as the actual gaps (distributions) in normal traffic need to be considered if real world impacts are to be calculated. Often, in normal traffic, vehicles already drive at certain distance to the vehicle before in spontaneous convoys. Veldhuizen et al., 2019 reported that following vehicles already have a lower FC compared to solo driving at larger distance gaps tested until 70 m. For larger distances no tests are known to date.

The actual distances in real traffic may depend on traffic and road conditions and on driver preference. (Dicke-Ogenia et al., 2020) reported gap distance distributions of heavy-duty vehicles on a few motorway locations in the Netherlands and counted the number of spontaneous convoys and the number of vehicles in the convoy. For the definition of a convoy, a gap time of 0 to 4 s was used (94 m at a vehicle speed of 85 km/h).

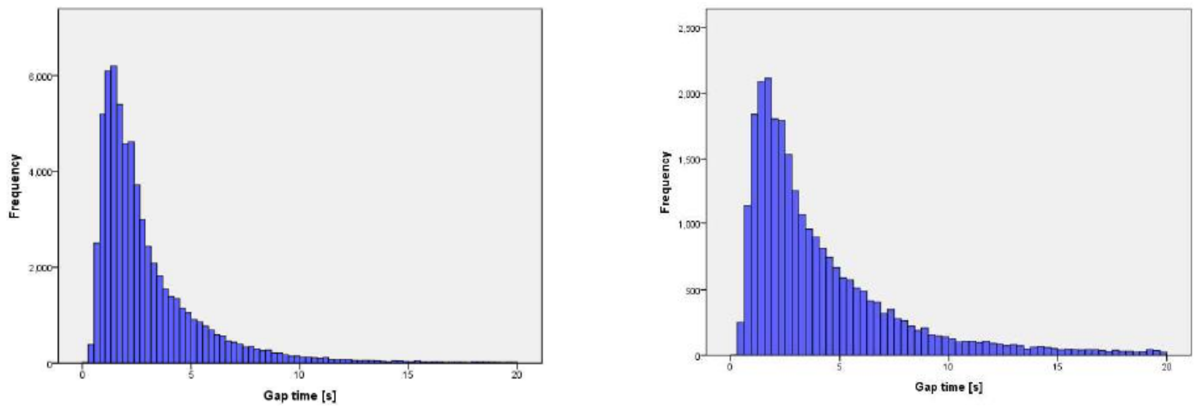


Figure 75: gap times measured in two directions for a Dutch motorway. (Dicke-Ogenia et al., 2020)

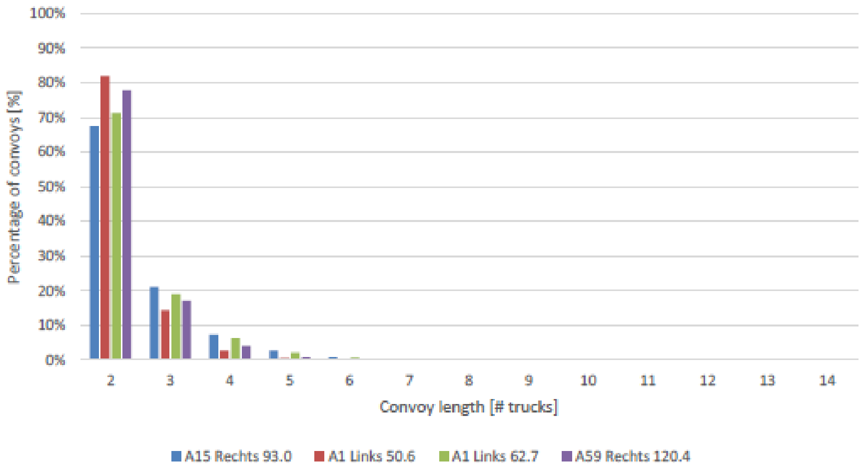


Figure 76: Convoys by number of vehicles in the convoy (gap times <4s define a convoy) (Dicke-Ogenia et al., 2020).

6.4.1. Considerations for the determination of the impact of platooning on FC and CO_2 emissions

In the ENSEMBLE platooning project, we define platooning as a group of following trucks with automated, cooperative functions using vehicle to vehicle communication. We distinguish two platooning functions or levels:

- Platooning Support Function (PSF). The driver is responsible for the task of driving. The inter-vehicular distance when cruising can be maintained at around 35 m at around 1.4-1.5 seconds (@85 km/h).
- Platooning Autonomous Function (PAF). The following vehicle(s) in a platoon now conducts the driving task within an operational design domain. The inter-vehicular distance when cruising can be maintained at closer gaps than for PSF of shorter than 1 seconds (@85 km/h).

Taking account of the status quo from past studies and the measurements performed in the framework of Ensemble, the following items need to be considered when impact of platooning on FC and CO_2 emissions would be determined in case studies.

- Reported fuel savings of test track testing represent 100% solo driving versus 100% driving in a platoon at certain gap distances.
- On a test track, the leading vehicle in a convoy or platoon only yields a (small) FC reduction compared to solo driving at a inter vehicular distance well below 20 m and the reduction is significantly smaller than for the following vehicle. For the leading vehicle the platooning support function (PSF) for Ensemble (gap ~1.5 s or 35 m) thus entails a 0% reduction compared to solo driving. This was confirmed by the measurements in Ensemble.
- On a test track, the following vehicle yields a reduction of fuel consumption at 70 m that seems to increase more rapidly below 20 m. The PSF entails a reduction of the fuel consumption of about 9 % compared to solo driving. This is confirmed by the measurements on the test track in Ensemble.
- According literature, reporting effects on Fuel Consumption of closer gaps, PAF (Platooning Autonomous Function) could bring about a further reduction of the fuel consumption of a few percent compared to PSF when inter-vehicular gaps can decrease below 20 m, but the magnitude is not very certain as studies show varying results.
- One study concluded that there is a small additional benefit for the 2nd vehicle when the platoon has three vehicles, but the benefit is only significant at short distances, shorter than 20 m.
- The relative effect of platooning on fuel consumption also depends on the total vehicle mass. Driving without payload for instance results in a higher relative effect on fuel consumption than when driving with full payload. This means that it matters for the relative result what the mass was during a test or that a case study should account for different relative impacts if mass deviates from the test mass.
- The relative effects also showed to depend on grade of the road with a lower relative effect on a climb and vice versa.
- Test data is compared at straight sections not taking account of aerodynamic changes when vehicles drive a curve.
- The momentary reduction of fuel consumption depends on the wind yaw angle and strength. For instance, at perpendicular wind there is less/no reduction of the fuel consumption at inter-vehicular distances 20-10m.
- The reduction of fuel consumption depends on the vehicle shape (spoilers etc., aero-dynamic trailers).
- In current traffic, a significant share of trucks already drives in convoys which brings about a reduction of fuel consumption and emissions compared to solo driving. The actual gaps (distributions) in normal traffic need to be considered if real world impacts are to be calculated.

- Platooning can mainly be done at steady motorway driving or driving at cruising speed. For other conditions, platooning isn't possible or desirable such as on roads with lower speeds, like urban roads, roads with sharp curves, at intersections, etc.
- Secondary effects such as on other road traffic aren't considered.
- At roads with grades, a platoon may need to break up or slow down to match the speed of the slowest vehicle (lowest power-to-mass ratio). Slowing down to match platoon speed may also be the case for vehicles with different maximum speeds on flat roads or when vehicles need to keep the right lane. A lower cruising speed over longer trajectories generally results in lower fuel consumption and could be a side effect of platooning.
- Modern heavy-duty vehicles have ACC. ACC already facilitates driving at an inter vehicular gap of about 1.5 s. Compared to solo driving in real traffic a reduction of fuel consumption is observed of 4 to 6 % [Kempen et al., 2021]. For platooning support function driving at 1.5 s this means that compared to driving with ACC there is probably a negligible reduction of the fuel consumption.
- The measured impact of platooning on fuel consumption represents effects for individual vehicles, not taking account of effects of possible logistical choices. If platooning leads to changes in logistical schedules that impact number of drives, routes or payload this needs to be taken into account.

6.4.2. Impact on pollutant emissions

Road vehicles emit air pollutants such as PM (particulate matter), NO_x and NEE (Non exhaust Emissions such as from brake and tyre wear). Driving conditions may affect the emissions level of these pollutants and therefore for the Ensemble project it is necessary to investigate whether possible changes in driving conditions caused by multi-brand platooning can change the level of the emission. CO_2 as a greenhouse gas is investigated together with the possible impact on fuel consumption in the section about economic analyses.

At present, there is no comparative data of exhaust emissions or NEE representing normal driving and multi-brand platooning of trucks. Without actual test data a theoretical approach is needed. A qualitative assessment could reveal if possible changes in driving conditions associated with platooning compared to normal baseline driving could affect emissions levels of pollutants. Pollutants to be considered are exhaust emission NO_x, NO_2 and PM given the majority of HDV use diesel engines. Additionally, NEE shall be considered because changes in driving conditions (hard braking, accelerations, speed changes) can potentially have an effect on the level of NEE. Therefore, a theoretical exercise is needed identifying possible paths as to if and how platooning can affect emissions. The approach is to make an inventory of what driving conditions are affected by platooning and if these could potentially change the pollutant emissions to what extent.

A number of air pollutants are emitted by road vehicles. These pollutants can harm human health, the environment and/or cultural heritage (e.g. by damaging buildings, monuments and materials). The relationship between emissions of air pollutants, their concentrations in the air and their subsequent impacts is complex. Road transport remains an important source of harmful pollutants as emissions often occur in areas where people live and work, such as cities and towns. Road transport is responsible for significant contributions to emissions of nitrogen oxides (NO_x) and particulate matter (PM). For road vehicles in the EU, pollutant emissions from the exhaust are regulated. The EU standards comprise type-approval tests, conformity and diagnostic procedures with the aim to reduce pollutants to levels defined in the standard, often referred to as ‘Euro standard’. The Euro VI standard was introduced by Regulation 595/2009 followed by a number of comitology packages and amendments.

Nitrogen oxides (NO_x) are produced when fuel is combusted in the engine in the presence of air. NO_x comprises a mixture of nitric oxide (NO) and nitrogen dioxide (NO_2). NO is not harmful to health at the concentrations typically found in the atmosphere. However, in contrast, NO_2 is associated with a range of environmental and health problems.
PM emissions of road vehicles may origin from different sources: exhaust, tyres, brakes, clutch and corrosion. PM from the exhaust is produced when fuel is not completely combusted in the engine. Diesel engines as currently used in most HDV are known to produce significant amounts of PM.
PM emissions from road vehicles that do not origin from the exhausts are often referred to as NEE (Non Exhaust Emissions). NEE are produced by wear and corrosion of components, such as brake pads, brake discs, clutch, tyre abrasion and rust. NEE are not regulated in the EU but there is a growing awareness that NEE from road vehicles also significantly contribute to harmful PM emissions to the air.
Other pollutant emission sources from vehicles are from evaporation and ventilation.

Most HDV are equipped with diesel engines. These engines are known to produce harmful NO_x and PM. EU emissions regulation for diesel engines especially aims to reduce the emission levels of these two pollutants and the newest Euro VI standard requires the application of efficient emission control systems.

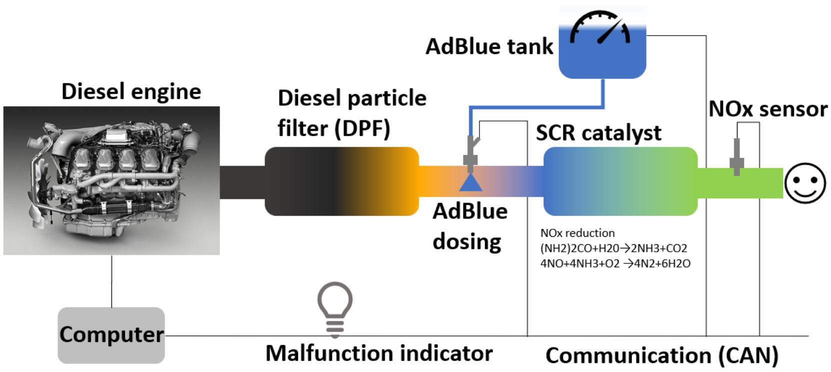


Figure 77: Schematic showing the typical set-up of exhaust gas aftertreatment for Euro VI certified heavy-duty diesel engines.

Selective Catalytic Reduction is commonly used to reduce the diesels engines NO_x emissions. In the selective catalytic reduction (SCR) process, NO_x reacts with ammonia, which is injected in an

aqueous solution (reagent: AdBlue) into the exhaust gas stream before the catalyst. SCR is often complemented by the use of exhaust gas recirculation (EGR) which reduces the combustion temperature and thus NO_x formation in the engine. Closed loop control using NO_x sensors in the tail pipe allows more accurate control of urea dosage.
NO_x abatement using SCR and EGR and closed loop control can reduce the diesel engines NO_x emissions with high efficiencies more than 90-95% for the current generation of systems. SCR works most optimal, i.e. reduce NO_x with the highest efficiency, at steady motorway driving at medium engine loads. Current SCR systems tend to work less efficient or not at all, at low speeds and after idling because under these conditions the SCR can cool down below it's working temperature[50] causing increased emissions of NO_x at the tail-pipe. At very high engine loads the NO_x mass from the engine and the catalyst temperature increase. At high temperatures and loads the SCR catalyst generally becomes somewhat less efficient resulting in less reduction of the high NO_x mass from the engine.

To reduce PM of heavy-duty diesel engines highly efficient wall-flow Diesel Particle Filters are used. The filter traps most particulate matter which is either regenerated passively by means of oxidation during normal use or by means of an active regeneration process when the filters soot load increases above a certain threshold. Heat for active regeneration can be supplied by engine management or upstream fuel injection. Diesel particulate filters for heavy-duty diesel engines filter the mass of particulate matter with efficiencies higher than 95% for the fraction of elemental carbon, but with lower efficiencies for the organic fraction (50-95%). The frequency of passive regeneration depends largely on the DPF temperature. Active regenerations mainly happen after reaching predicted soot accumulation load in the DPF or measured high back pressure due to a high soot load. Active regenerations are known to temporarily raise emissions, but these regenerations generally happen at low frequencies, after hundreds of kilometres driven.

When platooning is compared with driving solo, due to the short inter-vehicular distance, the aerodynamic drag reduces and as a result engine load (torque) reduces at given speed. The lower engine load in turn results in lower fuel consumption and CO_2 emissions. These effects are reported in multiple studies based on data obtained from test track testing. A change in load (torque) for a heavy-duty diesel engine, generally results in lower combustion temperatures and a higher air-to-fuel ratio. This means that NO_x and PM formation in the combustion chamber are affected and will probably change as a result[51]. Engine control settings, such as injection timing, variable turbo, EGR rate may change and have an effect on combustion as well.
The measured effects on fuel consumption indicates the change of engine load. Roughly, load and fuel consumption of a diesel engine relate closely, a reduction of fuel consumption of 10 % is the result of a change in engine load of the same level, in this case 10 %. When driving at normal, intermediate engine loads and speed (~30 % as happens most of the times at cruising speeds (80-

[50] Vermeulen et al., Dutch In-service emissions testing programme 2015 - 2018 for heavy-duty vehicles: status quo Euro VI NO_x emissions, TNO report TNO 2019 R10519, 10 April 2019
[51] https://dieselnet.com/tech/diesel_emiform.php (emission formation in diesel engines)

90 km/h) we expect no large changes in engine NO_x and PM formation due to this slight reduction in load.

The SCR system reduces a large portion of the formed NO_x by means of closed loop-controlled urea (AdBlue) dosage.[52] This means that when NO_x emissions out of the engine are higher, more reagent is dosed and vice versa when NO_x emissions out of the engine are lower, less reagent is dosed to achieve a certain NO_x emissions level. NO_x emissions out of the engine are significantly reduced with more than 90 % meaning that small changes in engine out NO_x probably result in only minor, negligible changes of the NO_x emissions at the tail pipe. The test data confirm this, see paragraph 6.3.
For PM a change in load and engine PM emission may result in a change of soot built up in the DPF and thus the frequency of regeneration. We expect the change in engine PM emission also to be only small and consequently hardly impact the tail pipe emissions levels and frequency of regenerations.

6.5. Conclusions on fuel consumption and emissions

Fuel savings in steady-state platooning are mainly caused by aerodynamic drag reduction. Generally, the smaller the time gap is to the preceding truck, the larger the reduction is, but the curve is highly nonlinear, meaning that reduction is relatively higher at small gaps. For safety reasons, the platooning support function is limited to a time gap of 1.4 s. This time gap can also be already achieved with current ACC systems, although at a lower safety level. Consequently, it is concluded that the platooning support function does not lead to an improvement in fuel consumption and CO_2 emissions compared to ACC operating at the small time gap setting of 1.4 s. Tests on a test track confirmed that a time gap of 1.4 s results in lower fuel consumption compared to completely driving solo, which means that individual vehicles currently driving at large following distances can still benefit from using a platooning support function or ACC.

The tests on the open road also showed a reduction in fuel consumption, but also the average speed of platooning was considerably lower than that of solo driving and for the platooning trip it couldn't be derived from inconsistent data from the vehicles how much of the trip vehicles actually drove in a stable platoon. This makes it impossible to solely relate this reduction to platooning. Possible explanations for the lower speed are mainly the road elevation, which caused trucks to slow down to keep the platoon together, as trucks were not able to keep the maximum speed due to the slope of the road and their (different) power-to-mass ratios. It must however be said that conditions are road and route dependent. On roads with less elevation differences, these effects are probably smaller and vice versa. Furthermore, longitudinal control systems of trucks could be improved to optimise between advantages of aerodynamic drag reduction, or the 'advantages' the road elevation offers when driving downhill, e.g. rolling out when driving down hill and start doing this at the right

[52] https://dieselnet.com/tech/cat_scr_diesel_control.php

moment for the ego vehicle. Such behaviour could lead to temporarily increasing time gaps, or (temporarily) leaving the platoon.

In a qualitative assessment a negligible impact was found on pollutant emissions from the exhaust for Euro VI and up due to application of emissions abatement, which works very efficiently at cruising speeds. For tail pipe NO_x emissions this was confirmed by measurements on the test track. In the assessment, a negligible impact was found on NEE as well (non-exhaust emissions) because no large changes in driving dynamics and speeds are expected.

According to the relation between time gap and fuel consumption found in literature, smaller time gaps than 1 second could lead to a reduction of fuel consumption and CO_2 emissions compared to the current lowest ACC setting of 1.4 s.

7. LIFE CYCLE ANALYSIS

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7.1. Introduction

Environmental problems such as climate change, fossil resource depletion, and air pollution have become global concerns (IPCC, 2018). The transport sector is an important source of environmental emissions, and its dependence on fossil fuels is a major driver of CO_2 emissions and air pollution. In 2018, direct CO_2 emissions from global transport reached 8.2 Gt CO_2-eq and were responsible for about 24% of energy-related CO_2 emissions (IEA, 2020). Tailpipe emissions from heavy-duty vehicles (HDV) contributed 1770 Mt of CO_2, representing 5% of total energy-related CO_2 emissions in 2018 (IEA, 2019). Since 2000, CO_2 emissions from HDV have increased at an annual rate of 2.6% (IEA, 2020); this could be linked to increased economic activities and demand for goods. HDV operating in the European Union (EU) is currently responsible for 25% of transport CO_2 emissions and 6% of the EU total CO_2 emissions (European Commission, 2019). Additionally, HDV contributes to combustion pollutants, such as particulate matter (PM) and nitrogen oxides (NO_x), among others (Winkler et al., 2018). In this light, the transport sector is deploying technologies that can reduce its overall environmental impacts, such as vehicle electrification and automation (Meyer, 2016).

Platooning technologies, such as cooperative adaptive cruise control (CACC), enable truck platooning by linking two or more heavy-duty trucks (HDT) in convoy driving at a close inter-vehicle distance. HDV platooning, often called truck platooning, is among the technologies supporting sustainable transport systems. Truck platooning has been shown to increase road-network capacity, improve road safety, and reduce fuel consumption and greenhouse gas (GHG) emissions (van Ark et al., 2017; Zhang et al., 2020).

Given its potential benefits on road transport, the European H2020 project ENSEMBLE is addressing the way to adopt multi-brand truck platooning in Europe. The project is a joint action of several vehicle manufacturers, research institutions, and original equipment manufacturers (OEM). It aims to harmonise multi-brand specifications and realise a multi-brand vehicle-to-vehicle (V2V) communication protocol that supports all platooning levels.

An objective of the project is to understand the life cycle environmental impacts of truck platooning. Thus, this report aims to conduct an environmental life cycle assessment (LCA) of truck platooning. The analysis will focus on the impact of manufacturing, well-to-tank emissions, and tailpipe emissions of HDT travelling in platoons.

7.2. Literature review

Several studies have assessed the impact of vehicle platooning on fuel consumption and CO_2 emissions. For example, Tsugawa (2013) presented the findings of the Energy ITS project (Tsugawa, 2013). The truck platoon formed in this study included three fully automated HDT and a light-duty truck (LDT) travelling at 80 km/h with an inter-vehicle distance of 4 m and 10 m. The author found an 18% and 13% reduction in fuel consumption for empty trucks with inter-vehicle distances of 4 m and 10 m, respectively. A platoon of loaded trucks realised 15% and 8% fuel savings (Tsugawa, 2013), resulting in a 4.8% and 2.1% decrease in CO_2 emissions for 4 m and 10 m inter-vehicle distances; this was based on a simulation considering 40% penetration of HDT in a platoon.

Al Alam et al. (Al Alam et al., 2010) conducted an experimental study on the fuel-saving potential of HDT platooning. Authors based their analysis on a commercial control strategy of two HDT, with the mass of the lead HDT varied by 10t to examine its influence on fuel savings. The HDTs were driven at 70 km/h with various inter-vehicle distances. Authors found that fuel savings can range from 4.7 to 7.7 % depending on the distance between vehicles (inter-vehicle distance). A lead truck, which is 10t heavier, realised 4.3– 6.9% fuel reduction while a lead truck, which is 10t lighter, realised 3.8–7.4% fuel reduction. The authors proposed that more energy savings could be achieved for a platoon of more than two trucks due to likely additional reduction in air drag. Likewise, smaller inter-vehicle distances between trucks are suggested as an essential factor for truck platooning to reach its maximum energy reduction potential. Additionally, the mass of the lead truck was found to influence the effectiveness of fuel savings.

Bonnet and Fritz used an electronic tow bar to demonstrate truck platooning in two HDT at 6 – 16 m inter-vehicle distance (Bonnet and Fritz, 2000). The lead truck was driven manually, and the trailing truck followed the lead truck automatically using a vehicle controller. The experiment was done on a test track with the trucks driven at 80 km/h at 10 m inter-vehicle distance. Authors found 7% and 21% fuel savings for the lead truck and trail truck, respectively. Additionally, at smaller inter-vehicle distances, the authors found an increase in fuel savings. However, no significant reduction in fuel use was noted at inter-vehicle distances below 10 m.

Lammert et al. (Lammert et al., 2014) examined the effect of speed, inter-vehicle distance, and mass on fuel consumption for HDT platooning. The trucks weighed about 29.5 and 36.3 tonnes and were driven at steady-state speeds ranging from 88.5 to 112.6 km/h, with inter-vehicle distances of 6.1 m and 22.8 m. The authors found that the average fuel consumption of the lead truck reduced as the inter-vehicle distances were decreased; this resulted in fuel savings of 2.7 to 5.3% with a truck mass of 29.5 tonnes. Similarly, fuel savings in the trailing vehicle ranged from 2.8 to 9.7% with the engine cooling fan turned on, while 8.4 to 9.7% fuel savings was found when the engine cooling fan was turned off. The combined average fuel savings of the two HDT ranged from 3.7 to 6.4% at 88.53 km/h. The best-combined result was found at 88.53 km/h, 9.14 m inter-vehicle distance, and a gross truck mass of 29.5 tonnes.

LCA studies of truck platooning and autonomous platooning technologies are limited. Most studies are focused on the operation or energy implications of autonomous technologies for vehicle application. Little has been done on the LCA of platooning. Gawron et al. (Gawron et al., 2018) conducted an LCA of Level 4 connected and automated vehicle (CAV) sensing and computing technologies integrated into passenger cars. Although uncertain, the authors found that CAV technologies could increase primary energy consumption and GHG emissions in cars by 3 to 20% due to the added burden for CAV manufacture.

An increase in energy use, weight, wind drag, and processes for data transmission due to CAV technologies were also significant contributors to energy use and GHG emissions. However, when the authors assumed 14% reduction in fuel use due to the expected benefit of CAV application (e.g. eco-driving and platooning), they found 9% reduction in total energy and GHG emissions compared to non-CAV integrated cars. Likewise, Kemp et al. (Kemp et al., 2020) assessed the life cycle impact of CAV technologies on the overall GHG emissions and energy use of electric sport utility vehicles (SUV) and conventional diesel vans. They found that current CAV technologies do not reduce vehicle GHG emissions but increase them due to the added burden for CAV manufacturing and high-power demand during operation. The impact of integrating CAV technologies outweighed the potential benefits of 14% in fuel savings from platooning and eco-driving. Their baseline case, modelled with a grid carbon intensity of 0.15 kgCO_2-eq/MJ, 500 W of computing power demand, and 45% highway driving, showed a respective increase in GHG and primary energy use of 2.7% and 1.1% for battery-electric SUV and 2.7% and 1.3% for conventional diesel vans compared to their non-CAV counterparts. However, a sensitivity analysis found that CAV integrated with battery-electric SUV showed a 31% reduction in GHG emissions when powered with low carbon electricity of 0.08 kgCO_2-eq/kWh. A CAV integrated battery-electric SUV with high energy demand for computing (4000 W) showed a 34% increase in GHG emissions compared to the base case.

Overall, all the referenced studies suggested that truck platooning can significantly reduce fuel consumption and improve traffic safety. In addition to this, the fuel savings potential of HDT platooning is greatly dependent on the inter-vehicle distance, speed, and mass of the leading truck. However, the impact of CAV technologies on the overall environmental benefit is inconclusive (Gawron et al., 2018; Kemp et al., 2020). What is apparent is that the carbon content of the charging electricity mix and power requirement of the CAV system are the main drivers of GHG emissions and energy use in passenger vehicles. The lack of consensus on the environmental benefits of vehicles integrated with CAV technologies indicates the need for this study.

7.3. Material and methods

LCA is a fact-based analysis of a product's life cycle environmental impact. It has been used in several studies to identify hotspots for improving the environmental performance of products, and its application to transport technologies is widely accepted (Del Duce et al., 2013; Nordelöf et al., 2014; Peters et al., 2017). LCA is standardised by ISO 14040:2006 and ISO 14044 (ISO, 2006a, 2006b). It is an iterative methodology consisting of four phases, as shown in Figure 78: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation. Due to its iterative nature, the different stages can influence each other, and modification can be made iteratively throughout the assessment as more data become available. In subsections 4.1 to 4.4, these phases are addressed in context of truck platooning as a case study.

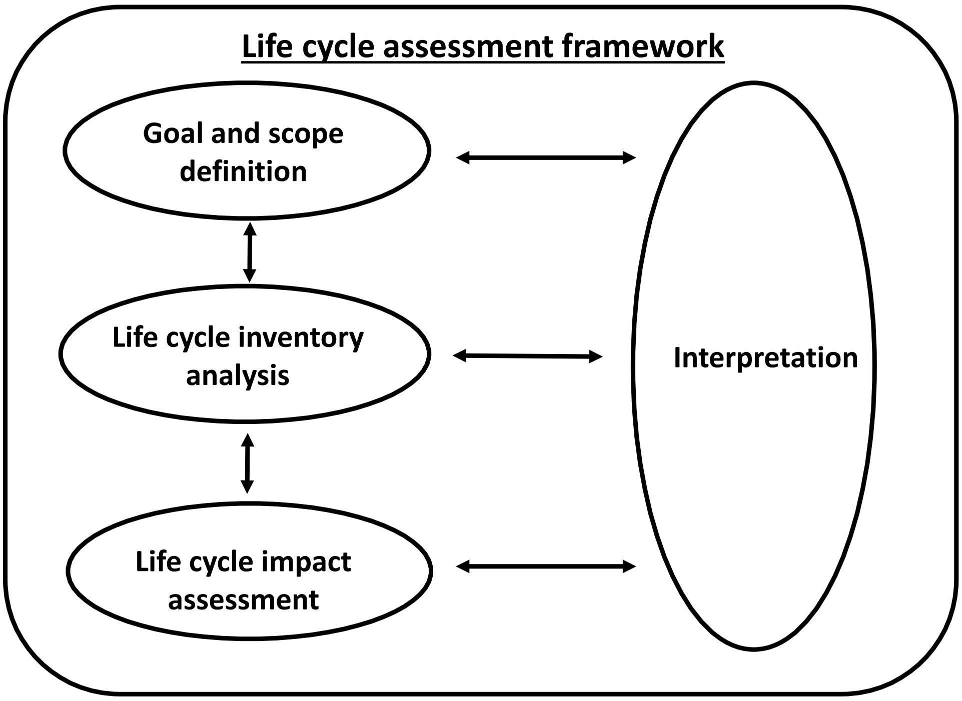

Figure 78. Life cycle assessment framework. Source: adapted from ISO standard (ISO, 2006a, 2006b)**.**

7.3.1. Goal and scope definition

The goal and scope definition is the first step in every LCA. This stage addresses the study's objectives, intended audience, context, system boundaries, the functional unit (FU), and the modelling choices. In this work, the goal was to estimate the environmental impacts of seven HDT driving in platoons. The study was in Europe and analysed level 4 CAV technologies integrated into conventional HDT travelling in a platoon. The level 4 CAV technologies used to enable platooning in this work include: cameras, sonar, radar, LiDAR (small and large), Global Positioning System (GPS), and Computer and Dedicated Short Range Communication (DSRC).

The FU is the quantified performance of the product system under study and serves as the reference unit to which all the inventory and impact assessments are reported (ISO, 2006a, 2006b). In other words, it is the quantity of function delivered by the product or system under study and for which the potential environmental impacts are estimated. The FU is defined as the transportation of 1-tonne cargo over 1 km in a HDT with a lifetime mileage of 800,000 km. The lifetime mileage of HDT was chosen arbitrarily by the authors based on the literature average, thus a sensitivity test was performed on this parameter.

The LCA is conducted from the cradle to the grave (Figure 79). The system boundaries include the production, use, and end-of-life (EoL) stages of the HDT and the CAV components. In addition, tailpipe emissions, the effect of the tyre, brake, road abrasion, well-to-tank emissions, vehicle and CAV manufacturing, and the net impact of CAV technology at the vehicle level are also included.

The foreground system for this study comprises the manufacture of truck and CAV components, their size and mass, energy consumption, maintenance, and end of life treatment. The supply of energy, raw materials, and services needed to support the different life cycle stages of the trucks are part of the background system.

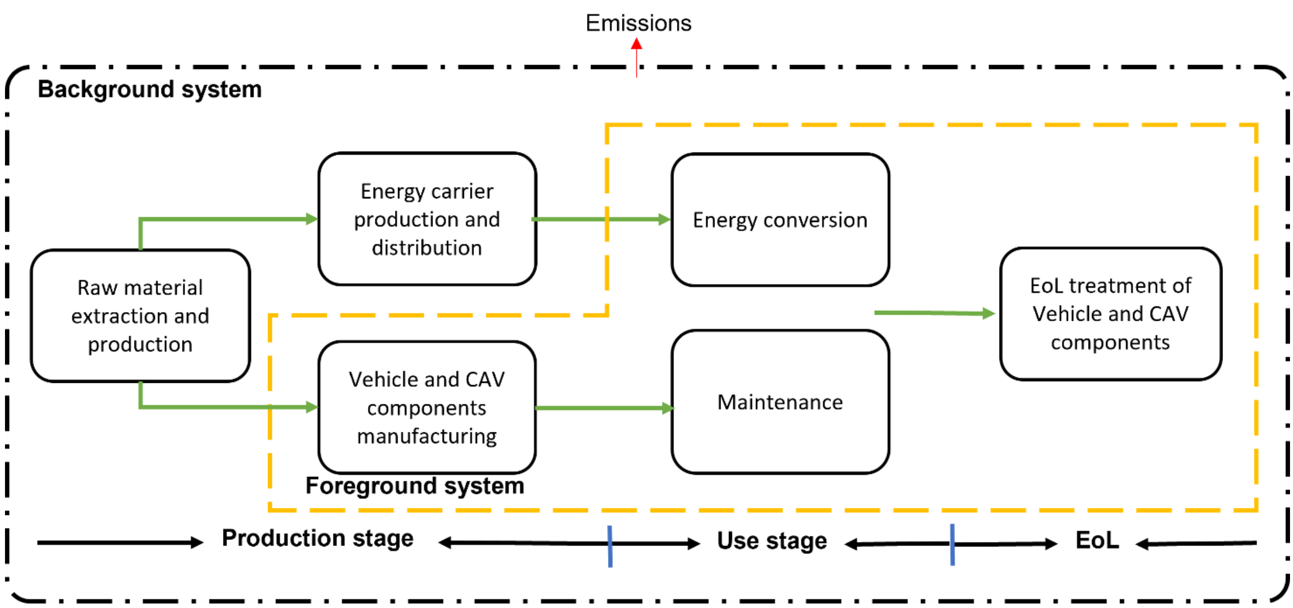

Figure 79. System boundary, showing background and foreground (yellow dotted lines) systems as applied in this study. Legend: EoL = End-of-life

7.3.2. Definition of scenarios

Based on the defined system boundaries, four scenarios were assessed, divided into the following groups:

- **No platoon:** this group comprises one scenario where it is assumed that the trucks are equipped with platooning technology, but their platooning features are switched off during operation. In this context, the trucks are considered to operate like conventional trucks. This scenario is used to compare the platooning scenarios.

- **Platooning**: this group assumed that the trucks are equipped with platooning technology and their platooning features are turned on during operation. It is further divided into three sub-scenarios: reference, moderate, and optimistic.

Several technological and operational factors have been shown to influence the potential of truck platooning – such as traffic volume and market penetration rate (MPR), among others (Song et al., 2021). For instance, traffic volume and MPR directly influence truck platoon formation probability. MPR can directly affect the traffic volume levels of trucks equipped with platooning technology, which determines the opportunity for trucks to form a platoon. This relationship suggests that high (or low) traffic volume levels of trucks equipped with platooning technology will increase (or decrease) the chances of truck platoon formation. These parameters can affect the percentage of the trucks' lifetime mileage driven in a platoon. Therefore, a direct relationship was assumed between the MPR and the trucks' lifetime mileage driven in a platoon (Table 8).

All scenarios assessed a platoon length of seven trucks as proposed in ENSEMBLE Project. With this background, the sub-scenarios are defined as follows:

- Reference scenario assumed 10% MPR; it depicts truck platooning at its early stage and represents the near-future scenario.
- Moderate scenario: assumed 40% MPR and defined future cases where more trucks are equipped with platooning technology.
- Optimistic scenario: assumed 70% MPR, described future instances in which most trucks are equipped with platoon technology and implemented large-scale adoption of truck platooning. Thus, the trucks were assumed to be in platoon formation for 70% of their lifetime mileage.

Table 8: Scenarios in terms of market penetration and lifetime mileage.

Platoon scenario	Market penetration rate (%)	Lifetime mileage in a platoon (%)
Reference	10	10
Moderate	40	40
Optimistic	70	70

The freight activity is an essential aspect of the defined functional unit (tonne-km). The freight activity is calculated as the product of lifetime mileage by the average shipment weight. The average shipment weight was calculated via equation 1 (Facanha and Horvath, 2006):

$$\mathcal{W} = V_c \times V_u \times (1 - M_e) \quad (1)$$

Where:

$\mathcal{W}$ = Average shipment weight (tons)

V_c = Vehicle capacity (tons)

V_u = Vehicle utilisation (%)

M_e = Empty Miles

The proposed shipment weight (payload) for the test trucks in the ENSEMBLE project was 19t, which from equation 1 gives an average vehicle utilisation of 77% at 25% empty miles. However, statistical data shows lower values for average payload mass in real life, in the order of 14t (about 57% vehicle utilisation rate) in the case of a regular tractor semi-trailer (4x2 + 3 axle) with a max GVW of 40t (Source: NEA). Therefore, a sensitivity check was performed on these parameters considering 55% - 90% average vehicle utilisation and 10% - 40% average empty miles.

7.3.3. Life cycle inventory

The LCI stage described and quantified the material and energy flows within the system boundary. During the LCI phase, valuable data are collected to model the defined system. An essential step in the LCI is collecting foreground and background systems data. The foreground data were mainly sourced from the literature and from the Ecoinvent database v3.6 (Wernet et al., 2016). However, expert knowledge was sought when necessary to confirm their consistency with the requirements from the ENSEMBLE project.

Truck characteristics

LCI data for HDT were derived from available technical data sheets of truck models based on the DAF XF series (DAF, 2020; PACCAR, 2020). All truck options were modelled based on the same data for glider, drivetrain, trailer, and CAV subsystem using equivalent processes in the ecoinvent database. The CAV subsystem was assumed at the Platooning Support Function level, as defined by the ENSEMBLE consortium (Willemsen et al., 2022; Konstantinopoulou et al., 2019). The internal combustion engine performs following Euro 6 standards. Table 9 shows the characteristics of the HDT in this study.

Table 9: Characteristics of reference truck.

Characteristic	Model: DAF XF	Reference
Gross tractor weight (kg)	18000	(DAF, 2020)
Gross combination weight (kg)	40000	(DAF, 2020)
Maximum payload load (kg)	24756	Authors estimate
Maximum engine power (kW)	355	(PACCAR, 2020)
Maximum engine torque (Nm)	2500 at 900-1125 rpm	(PACCAR, 2020)
Euro class	Euro 6	
Tractor kerb weight (kg)	7665	(DAF, 2020)
Semi-trailer weight (kg)	7471	
Fuel type	Diesel	

Truck manufacturing

Truck manufacturing was modelled based on a modular approach; the main modules were divided into the glider, CAV subsystem, and powertrain, as shown in Table 10. The glider consists of all vehicle components except its powertrain and energy sources. The powertrain generally includes the internal combustion engine (ICE) and all drivetrain components: transmission, clutch, differential, and suspension. The CAV subsystem includes all components that enable truck platooning (connectivity and automation) into the conventional HDT platform. These include a camera, sonar, radar, LiDAR, Global Positioning System (GPS)/Inertial Navigation System (INS), computer, wire harness, Dedicated Short Range Communication (DSRC) and antenna carriers (structure).

Table 10: Components masses for HDT and CAV technologies in this study

Module	Components	Mass (kg)	Quantity	Reference
Glider (including trailer)	Cabin	1253	1	
	Frame	3439	1	
	Suspension	2756	1	
	Braking system	884	1	
	Tires & Wheels	1422	1	
	Others	2800	1	
Drivetrain	IC engine	1042	1	
	Exhaust system	220	1	
	Diesel tank	80	1	
	Transmission system	558	1	
	Retarder	82	1	
	Lead-Acid battery	90	1	
	Lubrication system	140	1	
CAV subsystem	Camera	0.164	1	
	Radar	0.36	1	
	GPS/INS	0.64	1	
	DSRC	2.654	1	
	CPU/computer	5.075	3	
	Structure	1.416	2	
	Harness	1	1	

Use stage

The average fuel consumption of the test trucks was 31L/100km. It is assumed that the trucks were driven at an inter-vehicle distance of 4 to10 meters with a fuel savings potential of 5 and 10% in the lead and trailing trucks, respectively (Zhang et al., 2020). Except for CO_2 emissions, the potential reduction in the tailpipe and non-exhaust emissions was assumed unchanged due to a lack of reliable data.

Several factors were considered to assess the use phase of the CAV subsystem; these include an increase in fuel consumption due to CAV weight and power requirements for CAV subsystem operation, such as sensing, computing, and data transmission. A possible increase in fuel consumption is also considered due to increased drag for externally mounted CAV components. However, it was assumed that the fuel consumption data measured on-site for test trucks includes these factors, except for data transmission over the 4G LTE network. This parameter's energy consumption was assumed to be 1.25 MJ/GB, covering energy use at the base station, telecommunications networks, and data centres (CEET, 2013; Gawron et al., 2018). Based on data requirements for map applications, it was assumed that 0.87 MB of data was needed per km of truck platooning, considering no storage and reuse of data is required (Gawron et al., 2018). Thus, total lifetime data transmitted was computed as the product of lifetime mileage in platoon and data requirement per km. Finally, the 2019 average electricity grid mix for Europe from the Ecoinvent database v3.6 was used to estimate the impacts associated with this parameter.

End of life

The end-of-life (EoL) model covers all trucks and CAV system components, including parts replaced during the maintenance stage. In short, it covers resource use and emissions during the different EoL treatment processing, such as dismantling of trucks and CAV components and material separation for recycling.

The model was performed according to the ecoinvent cut-off allocation method [27], [28]. This allocation method allows no credit from recycled materials at the trucks EoL, considering that recycled materials in upstream production processes of the truck and CAV manufacturing were modelled burden-free (Wernet et al., 2016). The EoL processes for Truck and CAV system EOL were based on used trucks and electronic components in the Ecoinvent v3.6 database (Wernet et al., 2016).

7.3.4. Life cycle impact assessment and sensitivity analysis

This stage uses data obtained from the LCI phase to characterise potential impacts, translating them into environmental impact categories. Additionally, sensitivity and scenario analyses were performed to examine the influence of specific parameters on the accuracy of the overall results. The ReCiPe 2016 [29] LCIA method was used in this study. However, only the climate change (CC) impact category was discussed in detail due to its relative importance for this case study.

A sensitivity analysis was conducted to assess the robustness of the results to the adopted parameters. The parameters selected for sensitivity analysis are shown in Table 11.

Table 11: Selected parameters for sensitivity analysis

Parameter or assumption	Explanation
Truck's lifetime mileage	Main study = 800,000 km; sensitivity test: 600,000 km and 1,000,000 km
Fuel savings	Main study = 5% in lead truck and 10% in trail trucks Sensitivity test: lower values (-3% in Leader, -6% in Follower) and higher values (-7% in Leader, -14% in Follower)
Average vehicle utilisation	Main study = 77%; sensitivity test: 55% and 90%
Average empty miles	Main study = 25%; sensitivity test: 10% and 40%
Electricity mix used to power data transmission systems	Baseline case = 2019 EU electricity mix; sensitivity test: Norwegian (highly renewable) and Poland (highly fossil)

7.4. LCA Results and discussion

Figure 80 shows the CC impacts of 7 HDT driving in different scenarios. The results are relative to the no platoon scenario with an average payload of 19 tons per truck. The optimistic scenario accounted for a 5% reduction in CC impacts, followed by 3% in the moderate scenario and less than 1% in the reference scenario. The primary driver for the decrease in CC impacts is fuel consumption savings due to truck platooning. However, the truck platoon rate (i.e., their average lifetime mileage in a platoon) is responsible for the reduced CC impacts across the scenarios. The trucks' average mileage in a platoon is synonymous with the MPR of HDT capable of forming platoons. Consequently, as the MPR increases, the chances for HDT to travel in a platoon will increase, contributing to higher reductions in CC impacts in the optimistic scenario.

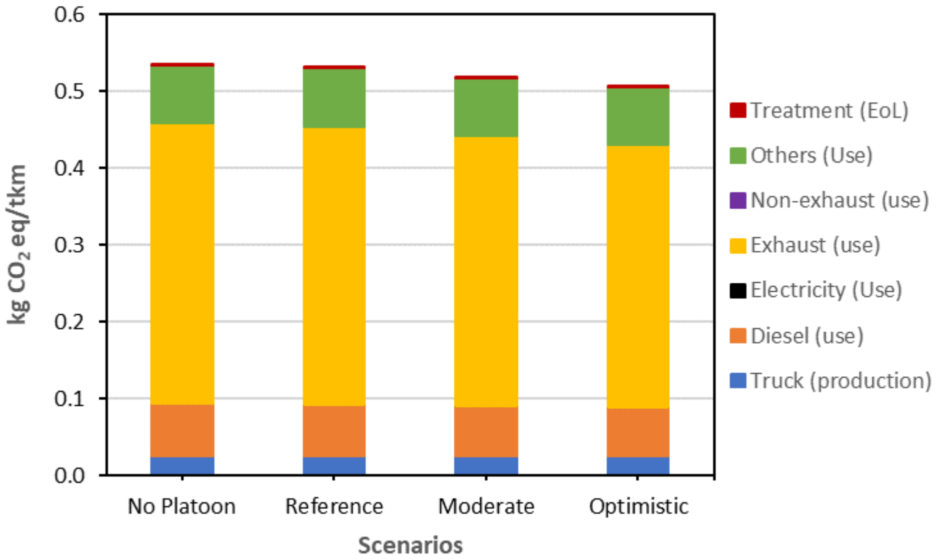

Figure 80: Climate change impacts of 7 heavy duty trucks under different scenarios. Legend: (Use) = Use stage; (production) = Production stage; (EoL) = End of life; Others(use) =Truck maintenance + road construction and maintenance; Diesel(use) = diesel production and distribution

Exhaust emissions from diesel combustion contributed the most to CC impacts ranging from 69% in the no platoon scenario to 67% in the optimistic scenario. Impacts from others (use) (roughly 14%) and diesel (use) (approximately 14%) were significant across all scenarios. These results suggest that truck platooning can reduce the climate impacts of HDT, and its potential strongly depends on the MPR and the fuel consumption savings. Alternatively, battery-electric trucks (BET) have no tailpipe emissions (Sacchi et al., 2021), which implies that installing them with platoon technologies will significantly reduce the climate impacts of road freight transportation compared to conventional HDT. However, further studies are needed to clarify the potential of BET in platoon since the climate impact of their manufacturing stage is significantly higher than the traditional HDT (Wolff et al., 2020).

Figure 81 shows the influence of the following critical parameters: empty miles, electricity source, fuel consumption, lifetime mileage, and vehicle utilisation on the lifetime CC impacts of 7 HDT. Vehicle utilisation and empty miles have the most variability in the results. Varying the vehicle utilisation from 77% in the main study to 55% and 90% showed approximately 27% increase and 9% decrease in the lifetime CC impacts of the 7 trucks, respectively. Similarly, changing the percentage of empty miles from 25% in the main study to 10% and 40% resulted in 11% reduction and 14% increase in the lifetime climate impacts of the trucks, respectively. The influence of these parameters on the lifetime CC of HDT demonstrates their importance in managing road freight operations. Therefore, trucking companies should prioritise increasing the efficiency of freight operations to improve the CC impacts of HDT per tonne of transported goods. Likewise, LCA practitioners should provide quality data for these parameters to guarantee robust LCA outcomes.

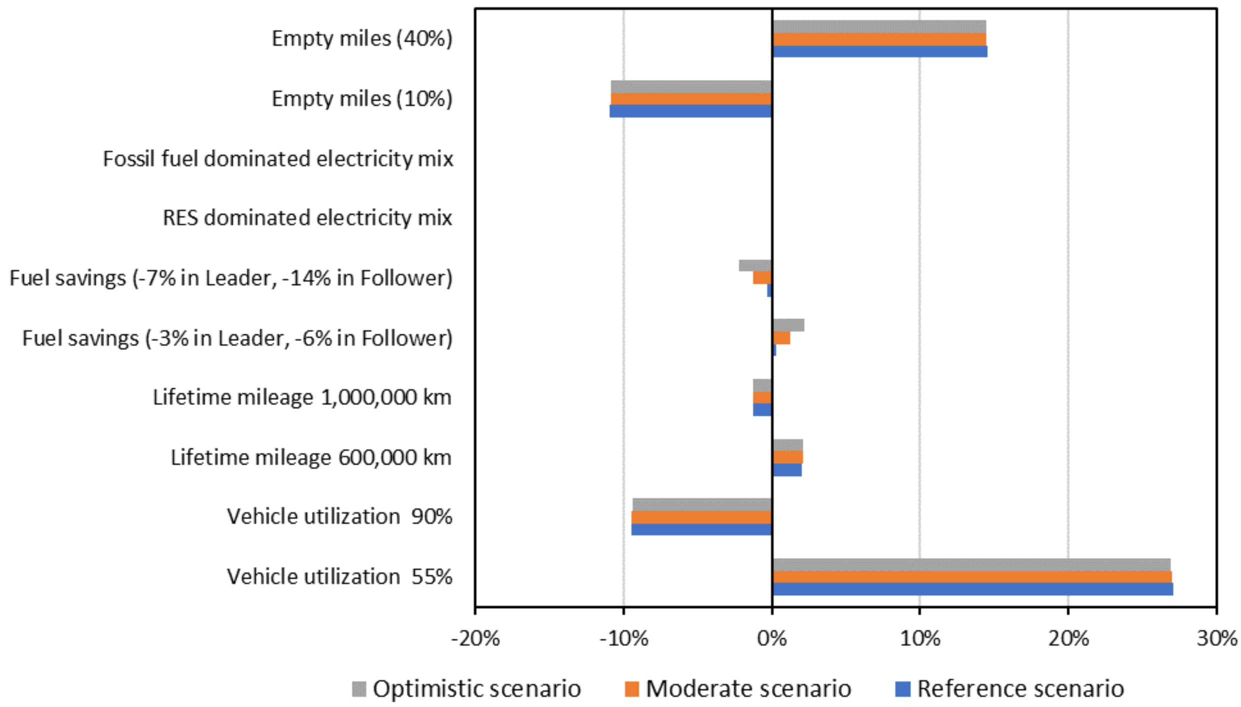

Figure 81: Sensitivity of lifetime climate change impacts of 7 heavy-duty trucks to critical parameters. The 0% line represents the main study for each scenario, whereas the bars demonstrate the variation associated with the following changes in parameters listed at the left-hand side of the figure.

The influence of fuel savings ($\pm1\%$) and lifetime mileage ($\pm1\%$) is marginal compared to vehicle utilisation and empty miles. However, the effect of these parameters on CC impacts could become vital from a nation's trucking fleet perspective. Similarly, the impact of electricity source for data transmission over the 4G LTE network during the use phase of the CAV subsystem is almost zero since their electricity consumption is relatively small.

8. SUMMARY AND CONCLUSION

The objective of this deliverable is to analyse the economic and environmental impacts of platooning, as specified in the framework of the H2020 project ENSEMBLE. To do so, the business case of platooning was analysed with a combination of approaches.

8.1. Value chain and market structure

First, a qualitative analysis makes it possible to extricate the complex interdependencies underlying the issue of the market uptake of platooning. Indeed, a substantially varied set of stakeholders are concerned, more or less directly, with platooning. The most important category is that of carriers: at the core of the business case of platooning, carriers use trucks to produce freight transportation. **For platooning to have a business case without a legal obligation, it has to produce added value to carriers, either as improved productivity, or improved level of service for shippers, or a suitable combination of both**. In particular, if level of service is deteriorated, improved productivity must compensate that in the forms of consistently reduced prices for shippers. OEMs are also core stakeholders of platooning, as they produce and sell trucks, and they must provide the platooning technology with a level of efficiency, and prices, such that carriers will find platooning profitable. An additional stakeholder category is that of Platooning Service Providers, which are required for platoon formation to be possible at a wide scale and efficient way. Other stakeholders such as governments, insurance companies or infrastructure managers, are relevant to the business case of platooning, but in a less direct way.

The first main result of the analysis is that **for platooning to have a business case, it must bring direct benefits for carriers**. Other stakeholders can amplify those benefits, but they will not create a business case out of nowhere if there are no direct benefits for stakeholders. The second main result is that **platooning is a two layers market**, where one should consider the lower-level decision of carriers to have their platoon-enabled vehicles form platoons; and the higher-level decision of carriers to acquire platoon-enabled vehicles, or not. The third main result is that **the platooning market exhibits strong network externalities**. The fourth main result is that **the business case of platooning relies very strongly on the geography of freight flows**. This geography should be understood in a wide sense: it encompasses both the road network configuration, but also the economic life-cycle of vehicles (including their routes during their lifetimes).

8.2. Market uptake and expected benefits

Second, a quantitative micro-economic model is elaborated, in order to quantify the possibilities in terms of platooning market uptake. The model makes explicit the bi-level nature of the market, and the strategic interactions between the carriers at both levels. By design, the model accounts for the network externalities. It is also able to compute the dynamics of market uptake for a variety of assumptions. The main conclusions of this quantitative work are the following ones. First, platooning equipment is a trade-off between the benefits of platooning and the associated costs. The benefits of platooning depend on the amount of opportunities to form platoons and on the distances platoons will cover before dissolution. The costs of platooning are, on the one hand, the fixed investment cost of buying a platoon enabled truck, and on the other hand the cost of forming a platoon, which is due each time two trucks coordinate their trips in order to get close enough to one another for a platoon to be formed.

The balance between both costs and the benefits of platooning can be such that there will be no market for platooning. In particular, **with the assumption that the leader vehicle's fuel consumption is unchanged when it's in a platoon, and that the follower vehicle consumes 5% less fuel in the same situation** (a theoretical assumption consistent with the Platooning Support Function as specified in ENSEMBLE)**, there is no business case for platooning. With the more optimistic assumption that the follower vehicle would safe 10% on fuel consumption** (or obtain a monetary benefit of equivalent scale from platooning through another channel, such as, theoretically, reduced workforce costs) **then market uptake seems possible** under reasonable economic assumptions. In that case, the theoretical maximal gross gains of platooning are about 5% of fuel costs in the model, where only two-vehicle platoons are allowed; this maximal value could approach 10% with longer platoons, i.e. a total cost decrease of about 3%. Net of platooning costs, these gains would substantially decrease, around 1.5%-2%, under very optimistic assumptions.

Market uptake is highly sensitive to a host of variables, due to the network externalities, which can act both as a positive reinforcement loop or a negative reinforcement loop, depending on the circumstances. **In particular, a favourable network configuration, a lower waiting speed, a higher maximal legal speed, a decreased cost of the platooning equipment all improve the prospects of a market uptake.** Note that when market uptake happens, it typically waits for a number of years before it kicks off, and then the fleet progressively gets completely equipped at the speed of fleet renewal (retrofit is not assumed to be possible). The variables which were found to have the most impact on the business case were, on the one hand, fuel prices, and on the other hand, the share of early adopters. More precisely, **if fuel prices are assumed to increase continuously, for example due to an increase fiscal pressure, then the business case of platooning would improve spectacularly**. Regarding early adopters, **increasing the number of platoon-enabled trucks from start, either from the initiative of OEMs, or through subsidies, can accelerate very strongly market uptake**. However, that will not create a market if there is none.

8.3. Single-fleet platooning vs multi-fleet platooning

In the ENSEMBLE project, strong emphasis was put on making platooning completely interoperable. Due to the network externalities of the platooning market, this decision has a critical impact on the business case of platooning. There are several ways to demonstrate that statement. One is to simulate the case of a set of carriers, each with their own fleets, all platoon-enabled, optimizing their vehicles' routes so as to minimize their own costs; and compare the results when platooning isn't possible between two vehicles of different carriers, with when it is.

The approach taken in this deliverable is to elaborate an algorithm of platooning formation strategies for a large number of carriers with a large number of trucks moving in various directions over a realistic road network. Platooning can be formed by adapting the routes of different vehicles so that they pass through the same location at virtually the exact same time. However, adapting routes causes delays, which are costly. The algorithm designed in this deliverable, based on Dynamic Programming, compares the results of allowing platoons between any set of vehicles and allowing it only for two vehicles owned by the same carriers. The results show that **the benefits of platooning are orders of magnitude larger in the former case, confirming and quantifying the intuition according to which platooning benefits from maximum interoperability.**

8.4. Environmental impacts

It is concluded that the platooning support function does not lead to an improvement in fuel consumption and CO_2 emissions because a time gap of 1.4 s can also be achieved by using ACC, albeit at a lower safety level. Tests on a test track confirmed that a time gap of 1.4 s results in lower fuel consumption compared to completely driving solo, which means that individual vehicles currently driving at large following distances can still benefit from using a platooning support function or ACC.

In a qualitative assessment a negligible impact was found on pollutant emissions from the exhaust for Euro VI and up due to application of emissions abatement which works very efficiently at cruising speeds. For tail pipe NOx emissions this was confirmed by measurements on the test track. In the assessment, a negligible impact was found on NEE (non-exhaust emissions) as well, because no large changes in driving dynamics and speeds are expected.

According to the relation between headway and fuel consumption found in literature, smaller time gaps than 1 second could lead to a reduction of fuel consumption and CO_2 emissions compared to the current lowest ACC setting.

8.5. Life-cycle analysis

The LCA study has shown that truck platoons can improve climate change, impacts of heavy duty trucks and the trucking sector. However, the potential reduction in climate change impacts depends on the expected fuel saving of truck platoons, which strongly depends on the platoon configuration. From a trucking fleet perspective, the market penetration rate of platoon technology will strongly influence the potential for trucks to travel in platoons and consequently drive the expected reduction in CC. Therefore, the deployment of truck platoons in the European Union would significantly reduce the trucking industry’s fuel consumption and climate change impacts. Due to data constraints, only the implications of fuel savings and exhaust emissions of truck platooning were assessed. Future work may determine the effects of truck platooning on non-exhaust emissions from brake, road and tyre wear.

9. BIBLIOGRAPHY

Ark, E.J.van, Duijnisveld, M., van Eijk, E., Janssen, R., van Ommeren, C., Soekroella, A., 2017. Value Case Truck Platooning - an early exploration of the value of large-scale deployment of truck platooning, Tno.

Al Alam, A., Gattami, A., Johansson, K.H., 2010. An experimental study on the fuel reduction potential of heavy duty vehicle platooning. IEEE Conf. Intell. Transp. Syst. Proceedings, ITSC 306–311. https://doi.org/10.1109/ITSC.2010.5625054.

Abate, M., and de Jong, G. (2014). The optimal shipment size and truck size choice–The allocation of trucks across hauls. Transportation Research Part A: Policy and Practice, 59, 262-277.

Anderson, S. P., De Palma, A., and Thisse, J. F. (1992). Discrete choice theory of product differentiation. MIT press.

Bakermans, B. A. (2016) Truck platooning – Enablers, barriers, potential and impacts. Transport, infrastructure and logistics Master Thesis, TU Delft.

Baumol, W. J. and Vinod, H. D. (1970). An inventory theoretic model of freight transport demand. Management science, 16(7), 413-421.

Bellman, R. (1966). Dynamic programming. Science, 153(3731): 34-37.

Bertsekas, D. (2019). Reinforcement learning and optimal control. Athena Scientific.

Bonnet, C., Fritz, H., 2000. Fuel consumption reduction in a platoon: Experimental results with two electronically coupled trucks at close spacing. SAE Tech. Pap. https://doi.org/10.4271/2000-01-3056

Brealey, R. A., Myers, S. C. and Allen, F. (2013) Principles of corporate finance. Ed. McGraw-Hill Education.

Brian R. McAuliffe, Mark Croken, Mojtaba Ahmadi-Baloutaki, Arash Raees, (2017) National Research Council Canada, Fuel-Economy Testing of a Three-Vehicle Truck Platooning System, LTR-AL-2017-0008 April 22, 2017

Buchanan, J. M. (1965). An economic theory of clubs. Economica, 32(125), 1-14.

CEET, 2013. The Power of Wireless Cloud. Melbourne.

Combes, F. and Tavasszy, L. A. (2016). Inventory theory, mode choice and network structure in freight transport. European journal of transport and infrastructure research, 16(1).

Combes, F., and Leurent, F. (2013). Improving road-side surveys for a better knowledge of road freight transport. European Transport Research Review, 5(1), 41-51.

Comité National Routier (2021). https://www.cnr.fr/espace-standard/2 (accessed 17th of May, 2021)

Council of Supply Chain Management Professionals. (2013). Supply Chain Management Terms and Glossary.

DAF, 2020. Specification sheet: XF 450, FT 4X2 Tractor. Schmierungstechnik. URL https://www.daf.co.uk/en-gb/trucks/specsheets-search-page?VehicleSerie=XF&Page=1 (accessed 9.22.20).

Del Duce, A., Egede, P., Öhlschläger, G., Dettmer, T., Althaus, H.-J., Bütler, T., Szczechowicz, E., 2013. E-Mobility Life Cycle Assessment Recommendations. Guidelines for the LCA of electric vehicles.

Dullaert, W. and Zamparini, L. (2013). The impact of lead time reliability in freight transport: A logistics assessment of transport economics findings. Transportation Research Part E: Logistics and Transportation Review, 49(1), 190-200.

European Commission, 2019. Reducing CO2 emissions from heavy-duty vehicles | Climate Action [WWW Document]. URL https://ec.europa.eu/clima/policies/transport/vehicles/heavy_en (accessed 8.14.20).

Facanha, C., Horvath, A., 2006. Input-Output Analysis (Subject Editor : Sangwon Suh) Environmental Assessment of Freight Transportation in the U . S . Int. J. Life Cycle Assess. 11, 229–239. https://doi.org/http://dx.doi.org/10.1065/lca2006.02.244

Felton, J. R. (1981). The impact of rate regulation upon ICC-regulated truck back hauls. Journal of Transport Economics and Policy, 253-267.

Feo-Valero, M., García-Menéndez, L. and Garrido-Hidalgo, R. (2011). Valuing freight transport time using transport demand modelling: a bibliographical review. Transport Reviews, 31(5), 625-651.

Gawron, J.H., Keoleian, G.A., De Kleine, R.D., Wallington, T.J., Kim, H.C., 2018. Life Cycle Assessment of Connected and Automated Vehicles: Sensing and Computing Subsystem and Vehicle Level Effects. Environ. Sci. Technol. 52, 3249–3256. https://doi.org/10.1021/acs.est.7b04576

van de Hoef, S., Johansson, K. H. and Dimarogonas, D. V. (2018). Fuel-efficient en route formation of truck platoons. IEEE Transactions on Intelligent Transportation Systems, 19(1), 102-112.

IEA, 2020. Tracking Transport 2020 . Paris.

IEA, 2019. Global Energy & CO2 Status Report 2019. Paris.

IPCC, 2018. Global Warming of 1.5 ºC - an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial level, Report. Geneva.

ISO, 2006a. 140 44 Environmental management -- Life cycle assessment -- Requirements and guidelines. Geneva.

ISO, 2006b. 14040 Environmental management - life cycle assessment - principles and framework. Geneva.

Johansson, A., Nekouei, E., Johansoon, K. H. and Mårtensson, J. (2018). Multi-fleet platoon matching: a game-theoretic approach. 21st IEEE International Conference on Intelligent Transportation Systems, Hawaii, USA.

Johansson, A., Nekouei, E., Johansson, K. H., Mårtensson, J.(2021a). Strategic hub-based platoon coordination under uncertain travel times. IEEE Transactions on Intelligent Transportation Systems.

Johansson, A., Mårtensson J., Sun, X., Yin, Y. (2021b). Real-time cross-fleet Pareto-improving truck platoon coordination. IEEE International Intelligent Transportation Systems Conference (ITSC): 996-1003.

Katz, M. L. and Shapiro, C. (1985). Network externalities, competition, and compatibility. The American economic review, 75(3), 424-440.

Kemp, N.J., Keoleian, G.A., He, X., Kasliwal, A., 2020. Life cycle greenhouse gas impacts of a connected and automated SUV and van. Transp. Res. Part D Transp. Environ. 83, 102375. https://doi.org/10.1016/j.trd.2020.102375

Kempen, E. van, J. De Ruiter, J. Souman, E. van Ark, N. Deschle, L. Oudenes, M. Geurts, R. van der Horst, R. Janssen (2021). “Real-world impacts of truck driving with Adaptive Cruise Control on fuel consumption, driver behaviour and logistics results from a hybrid field operational test and naturalistic driving study in the Netherlands.” TNO report, 2021

Kempen, Elisah van et al., (2021) Catalyst living lab, TNO 2021 P10081, Maart 2021.

Konstantinopoulou, L., Coda, A., Schmidt, F., 2019. Specifications for Multi-Brand Truck Platooning, in: ICWIM8, 8th International Conference on Weigh-In-Motion. https://doi.org/https://hal.archives-ouvertes.fr/hal-02465190

Lammert, M.P., Duran, A., Diez, J., Burton, K., Nicholson, A., 2014. Effect of Platooning on Fuel Consumption of Class 8 Vehicles Over a Range of Speeds, Following Distances, and Mass. SAE Int. J. Commer. Veh. 7, 626–639. https://doi.org/10.4271/2014-01-2438

Lancaster, K. J. (1966), A new approach to consumer theory. The Journal of Political Economy, 74(2), 132-157.

Liang, K. Y., Mårtensson, J. and Johansson, K. H. (2016). Heavy-duty vehicle platoon formation for fuel efficiency. IEEE Transactions on Intelligent Transportation Systems, 17(4), 1051-1061.

Matthijs Dicke-Ogenia, Mariska van Essen, Guido Sluijsmans, Pavlo Bazilinskyy, Maurice Taams, (2020) Vooronderzoek truck platooning, Eindrapportage, report nr. 004333.20200529.R2.07, 29 May 2020.

Meyer, G., 2016. Synergies of Connectivity, Automation and Electrification of Road Vehicles, in: Meyer, G, Beiker, S. (Eds.), Road Vehicle Automation 3: Lecture Notes in Mobility. Springer, Cham, pp. 187–191. https://doi.org/10.1007/978-3-319-40503-2_14

Mohring, H. (1972). Optimization and scale economies in urban bus transportation. The American Economic Review, 62(4), 591-604.

Nordelöf, A., Messagie, M., Tillman, A.M., Ljunggren Söderman, M., Van Mierlo, J., 2014. Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles — what can we learn from life cycle assessment? Int. J. Life Cycle Assess. 19, 1866–1890. https://doi.org/10.1007/s11367-014-0788-0

OECD-ITF (2017). Managing the Transition to Driverless Road Freight Transport. Case-Specific Policy Analysis Report.

PACCAR, 2020. PACCAR MX-13 engines: Technical information sheet [WWW Document]. URL https://www.daf.co.uk/en-gb/trucks/daf-xf/daf-xf-driveline (accessed 9.22.20).

Peters, J.F., Baumann, M., Zimmermann, B., Braun, J., Weil, M., 2017. The environmental impact of Li-Ion batteries and the role of key parameters – A review. Renew. Sustain. Energy Rev. 67, 419–506. https://doi.org/10.1016/j.rser.2016.08.039

Rushton, A., Croucher, P. and Baker, P. (2014). The handbook of logistics and distribution management: Understanding the supply chain. Kogan Page Publishers.

Sacchi, R., Bauer, C., Cox, B.L., 2021. Does Size Matter? The Influence of Size, Load Factor, Range Autonomy, and Application Type on the Life Cycle Assessment of Current and Future Medium? The Heavy-Duty Vehicles. Environ. Sci. Technol. 55, 5224–5235. https://doi.org/10.1021/acs.est.0c07773

Scotchmer, S. (1985). Profit-maximizing clubs. Journal of Public Economics, 27(1), 25-45.

Shy, O. (2001). The economics of network industries. Cambridge university press.

Song, L., Fan, W., Liu, P., 2021. Exploring the effects of connected and automated vehicles at fixed and actuated signalized intersections with different market penetration rates. Transp. Plan. Technol. 44, 577–593. https://doi.org/10.1080/03081060.2021.1943129

Tavasszy, L. and de Jong, G. (2013). Modelling freight transport. Elsevier.

Tsugawa, S., 2013. An overview on an automated truck platoon within the energy ITS project, IFAC Proceedings Volumes (IFAC-PapersOnline). IFAC. https://doi.org/10.3182/20130904-4-JP-2042.00110

Vargo, S. L. and Lusch, R. F. (2008). Service-dominant logic: continuing the evolution. Journal of the Academy of marketing Science, 36 (1), 1–10.

Varian, H. R. (2014). Intermediate microeconomics with calculus: a modern approach. WW Norton & Company.

Veldhuizen, R., G. Van Raemdonck en J. Van der Krieke, (2019) Fuel economy improvement by means of two European tractor semi-trailer combinations in a platooning formation,” Journal of Wind Engineering and Industrial Aerodynamics, vol. 188, pp. 217-234, 2019.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., Zah, R., Wernet

wernet, G., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Willemsen, D., Schmeitz, A. et al., (2022). *V2 Platooning use cases, scenario definition and Platooning Levels*. D2.3 of H2020 project ENSEMBLE

Winkler, S.L., Anderson, J.E., Garza, L., Ruona, W.C., Vogt, R., Wallington, T.J., 2018. Vehicle criteria pollutant (PM, NOx, CO, HCs) emissions: how low should we go? npj Clim. Atmos. Sci. 1. https://doi.org/10.1038/s41612-018-0037-5

Wolff, S., Seidenfus, M., Gordon, K., Álvarez, S., Kalt, S., Lienkamp, M., 2020. Scalable life-cycle inventory for heavy-duty vehicle production. Sustain. 12. https://doi.org/10.3390/su12135396

Zhang, L., Chen, F., Ma, X., Pan, X., 2020. Fuel Economy in Truck Platooning: A Literature Overview and Directions for Future Research. J. Adv. Transp. 2020. https://doi.org/10.1155/2020/2604012

Zeng, Y. (2020). Distributed coordination for multi-fleet truck platooning. Master thesis.

10. APPENDIX A. GLOSSARY AND ACRONYMS

10.1.Glossary

Term	Definition
Convoy	A truck platoon may be defined as trucks that travel together in convoy formation at a fixed gap distance typically less than 1 second apart up to 0.3 seconds. The vehicles closely follow each other using wireless vehicle-to-vehicle (V2V) communication and advanced driver assistance systems
Cut-in	A lane change manoeuvre performed by vehicles from the adjacent lane to the ego vehicle's lane, at a distance close enough (i.e., shorter than desired inter vehicle distance) relative to the ego vehicle.
Cut-out	A lane change manoeuvre performed by vehicles from the ego lane to the adjacent lane.
Cut-through	A lane change manoeuvre performed by vehicles from the adjacent lane (e.g. left lane) to ego vehicle's lane, followed by a lane change manoeuvre to the other adjacent lane (e.g. right lane).
Economic Life Cycle	Costs and activity of an asset (e.g. a vehicle) over the whole time it is operated by a given firm (e.g. a carrier). Costs include the ownership or renting costs, and operating costs, net of an eventual residual value.
Ego Vehicle	The vehicle from which the perspective is considered.
Emergency brake	Brake action with an acceleration of <-4 m/s2
Event	An event marks the time instant at which a transition of a state occurs, such that before and after an event, the system is in a different mode.
Following truck	Each truck that is following behind a member of the platoon, being every truck except the leading and the trailing truck, when the system is in platoon mode.
Leading truck	The first truck of a truck platoon
Legal Safe Gap	Minimum allowed elapsed time/distance to be maintained by a standalone truck while driving according to Member States regulation (it could be 2 seconds, 50 meters or not present)
Manoeuvre ("activity")	A particular (dynamic) behaviour which a system can perform (from a driver or other road user perspective) and that is different from standing still, is being considered a manoeuvre.

Term	Definition
ODD (operational design domain)	The ODD should describe the specific conditions under which a given automation function is intended to function. The ODD is the definition of where (such as what roadway types and speeds) and when (under what conditions, such as day/night, weather limits, etc.) an automation function is designed to operate.
Operational layer	The operational layer involves the vehicle actuator control (e.g. accelerating/braking, steering), the execution of the aforementioned manoeuvres, and the control of the individual vehicles in the platoon to automatically perform the platooning task. Here, the main control task is to regulate the inter-vehicle distance or velocity and, depending on the Platooning Level, the lateral position relative to the lane or to the preceding vehicle. Key performance requirements for this layer are vehicle following behaviour and (longitudinal and lateral) string stability of the platoon, where the latter is a necessary requirement to achieve a stable traffic flow and to achieve scalability with respect to platoon length, and the short-range wireless inter-vehicle communication is the key enabling technology.
Platoon	A group of two or more automated cooperative vehicles in line, maintaining a close distance, typically such a distance to reduce fuel consumption by air drag, to increase traffic safety by use of additional ADAS-technology, and to improve traffic throughput because vehicles are driving closer together and take up less space on the road.
Platoon Automation Levels	In analogy with the SAE automation levels subsequent platoon automation levels will incorporate an increasing set of automation functionalities, up to and including full vehicle automation in a multi-brand platoon in real traffic for the highest Platooning Automation Level. The definition of "platooning levels of automation" will comprise elements like e.g. the minimum time gap between the vehicles, whether there is lateral automation available, driving speed range, operational areas like motorways, etc. Three different levels are anticipated; called A, B and C.
Platoon candidate	A truck who intends to engage the platoon either from the front or the back of the platoon.
Platoon cohesion	Platoon cohesion refers to how well the members of the platoon remain within steady state conditions in various scenario conditions (e.g. slopes, speed changes).
Platoon disengaging	The ego-vehicle decides to disengage from the platoon itself or is requested by another member of the platoon to do so. When conditions are met the ego-vehicle starts to increase the gap between the trucks to a safe non-platooning gap. The disengaging is completed when the gap

Term	Definition
	is large enough (e.g. time gap of 1.5 seconds, which is depends on the operational safety based on vehicle dynamics and human reaction times is given). A.k.a. leave platoon
Platoon dissolve	All trucks are disengaging the platoon at the same time. A.k.a. decoupling, a.k.a. disassemble.
Platoon engaging	Using wireless communication (V2V), the Platoon Candidate sends an engaging request. When conditions are met the system starts to decrease the time gap between the trucks to the platooning time gap. A.k.a. join platoon
Platoon formation	Platoon formation is the process before platoon engaging in which it is determined if and in what format (e.g. composition) trucks can/should become part of a new / existing platoon. Platoon formation can be done on the fly, scheduled or a mixture of both. Platoon candidates may receive instructions during platoon formation (e.g. to adapt their velocity, to park at a certain location) to allow the start of the engaging procedure of the platoon.
Platoon split	The platoon is split in 2 new platoons who themselves continue as standalone entities.
Requirements	Description of system properties. Details of how the requirements shall be implemented at system level
Scenario	A scenario is a quantitative description of the ego vehicle, its activities and/or goals, its static environment, and its dynamic environment. From the perspective of the ego vehicle, a scenario contains all relevant events. Scenario is a combination of a manoeuvre (“activity”), ODD and events
Service layer	The service layer represents the platform on which logistical operations and new initiatives can operate.
Specifications	A group of two or more vehicles driving together in the same direction, not necessarily at short inter-vehicle distances and not necessarily using advanced driver assistance systems
Steady state	In systems theory, a system or a process is in a steady state if the variables (called state variables) which define the behaviour of the system or the process are unchanging in time. In the context of platooning this means that the relative velocity and gap between trucks is unchanging within tolerances from the system parameters.

Term	Definition
Strategic layer	The strategic layer is responsible for the high-level decision-making regarding the scheduling of platoons based on vehicle compatibility and Platooning Level, optimisation with respect to fuel consumption, travel times, destination, and impact on highway traffic flow and infrastructure, employing cooperative ITS cloud-based solutions. In addition, the routing of vehicles to allow for platoon forming is included in this layer. The strategic layer is implemented in a centralised fashion in so-called traffic control centres. Long-range wireless communication by existing cellular technology is used between a traffic control centre and vehicles/platoons and their drivers.
Tactical layer	The tactical layer coordinates the actual platoon forming (both from the tail of the platoon and through merging in the platoon) and platoon dissolution. In addition, this layer ensures platoon cohesion on hilly roads, and sets the desired platoon velocity, inter-vehicle distances (e.g. to prevent damaging bridges) and lateral offsets to mitigate road wear. This is implemented through the execution of an interaction protocol using the short-range wireless inter-vehicle communication (i.e. V2X). In fact, the interaction protocol is implemented by message sequences, initiating the manoeuvres that are necessary to form a platoon, to merge into it, or to dissolve it, also taking into account scheduling requirements due to vehicle compatibility.
Target Time Gap	Elapsed time to cover the inter vehicle distance by a truck indicated in seconds, agreed by all the Platoon members; it represents the minimum distance in seconds allowed inside the Platoon.
Time gap	Elapsed time to cover the inter vehicle distance by a truck indicated in seconds.
Trailing truck	The last truck of a truck platoon
Truck Platoon	Description of system properties. Details of how the requirements shall be implemented at system level
Use case	Use-cases describe how a system shall respond under various conditions to interactions from the user of the system or surroundings, e.g. other traffic participants or road conditions. The user is called actor on the system, and is often but not always a human being. In addition, the use-case describes the response of the system towards other traffic participants or environmental conditions. The use-cases are described as a sequence of actions, and the system shall behave according to the specified use-cases. The use-case often represents a desired behaviour or outcome. In the ensemble context a use case is an extension of scenario which add more information regarding specific internal system interactions, specific interactions with the actors (e.g. driver, I2V) and will add different flows (normal &

Term	Definition
	alternative e.g. successful and failed in relation to activation of the system / system elements).

10.2.Acronyms and abbreviations

Acronym / Abbreviation	Meaning
ACC	Adaptive Cruise Control
ADAS	Advanced driver assistance system
AEB	Autonomous Emergency Braking (System, AEBS)
ASIL	Automotive Safety Integrity Level
ASN.1	Abstract Syntax Notation One
BTP	Basic Transport Protocol
C-ACC	Cooperative Adaptive Cruise Control
C-ITS	Cooperative ITS
CA	Cooperative Awareness
CAD	Connected Automated Driving
CAM	Cooperative Awareness Message
CCH	Control Channel
DEN	Decentralized Environmental Notification
DENM	Decentralized Environmental Notification Message
DITL	Driver-In-the-Loop
DOOTL	Driver-Out-Of-the Loop
DP	Dynamic Programming
DSRC	Dedicated Short-Range Communications
ETSI	European Telecommunications Standards Institute
EU	European Union
FCW	Forward Collision Warning
FLC	Forward Looking Camera

Acronym / Abbreviation	Meaning
FSC	Functional Safety Concept
GN	GeoNetworking
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GUI	Graphical User Interface
HARA	Hazard Analysis and Risk Assessment
HDV	Heavy Duty Vehicle
HIL	Hardware-in-the-Loop
HMI	Human Machine Interface
HW	Hardware
I/O	Input/Output
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
ITL	In-The_Loop
ITS	Intelligent Transport System
IVI	Infrastructure to Vehicle Information message
LDWS	Lane Departure Warning System
LKA	Lane Keeping Assist
LCA	Lane Centring Assist
LRR	Long Range Radar
LSG	Legal Safe Gap
MAP	MapData message
MIO	Most Important Object
MPC	Model Predictive Control
MRR	Mid Range Radar
OS	Operating system
ODD	Operational Design Domain

Acronym / Abbreviation	Meaning
OEM	Original Equipment Manufacturer
OOTL	Out-Of The-Loop
PAEB	Platooning Autonomous Emergency Braking
PMC	Platooning Mode Control
PSP	Platooning Service Provider
QM	Quality Management
RSU	Road Side Unit
SA	Situation Awareness
SAE	SAE International, formerly the Society of Automotive Engineers
SCH	Service Channel
SDO	Standard Developing Organisations
SIL	Software-in-the-Loop
SPAT	Signal Phase and Timing message
SRR	Short Range Radar
SW	Software
TC	Technical Committee
TOR	Take-Over Request
TOT	Take-Over Time
TTG	Target Time Gap
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to any (where x equals either vehicle or infrastructure)
VDA	Verband der Automobilindustrie (German Association of the Automotive Industry)
WIFI	Wireless Fidelity
WLAN	Wireless Local Area Network
WP	Work Package