Analysis of the operational and environmental benefits of truck platooning in freight transport: the case study of Luís Simões

Ricardo Pereira[1], Vasco Reis[2], Rosário Macário[3]

[1]ricardo.o.pereira@tecnico.ulisboa.pt, [2]vascoreis@tecnico.ulisboa.pt, [3]rosariomacario@tecnico.ulisboa.pt

Department of Civil Engineering, Architecture and Georesources

Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

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ABSTRACT

Despite the focus of the media is on the latest advances in what concerns to autonomous passenger cars, relevant work has been developed at the level of autonomous vehicles applied in freight transportation and its impacts on the Logistics industry. With road transport being the main responsible for the pollutant emissions from the Transport sector, plus the goals set by the European Commission (EC) with a view to its drastic reduction, more efficient solutions are meant to be found. This work intends to explore the benefits of introducing truck platooning on a set of daily routes across Portugal, of the main portuguese logistics operator Luís Simões (LS). Substantial route segments overlap on the highways, which indicates potential for platooning. Routinely, platooning has been analysed in long routes spanning several hundreds of kilometres. This is not the case of Portugal, where the average length is below 300 kms. To that end, a route optimisation algorithm is being used to determine the route paths that minimise the network transport costs. Through the methodology used, efficiency gains in terms of fuel consumption and pollutant emissions produced along the routes will be quantified, as well as assess the viability of truck platooning over short distances.

Keywords: road transport; autonomous vehicles; truck platooning; vehicle routing problem; route optimization.

1. INTRODUCTION

The transport sector accounts for about one third (Agência Europeia do Ambiente, 2016b) of total energy consumption and about a quarter (Agência Europeia do Ambiente, 2016a) of total pollutant emissions recorded in the 28 European Union (EU) Member States. Nowadays, road transport is responsible for carrying about 75% of all the freight handled in the EU (Eurostat, 2016) and for more than 70% (Comissão Europeia, 2015) of the pollutant emissions produced by the transport sector. In this context, the EC has set as a goal, in its White Paper, a reduction of at least 60% of the pollutant emissions until 2050, in comparison to the levels of 1990, with a significant contribution expected from road transport to this reduction (Comissão Europeia, 2011). To this end, more efficient solutions are meant to be found.

The main objetive of the study presented in this work intends to explore the benefits of introducing truck platooning on a set of daily routes across Portugal, of the main portuguese logistics operator Luís Simões. Specifically, the potential for reducing fuel consumption and CO_2 emissions will be assessed, comparing two scenarios: the current situation, Scenario 1, in which the trucks make the respective routes individually; and Scenario 2, the execution of the same routes using platoons of two trucks, running the optimization model. These scenarios will be compared to a theoretical approach of platooning, corresponding to the maximum level of benefits. The second objective of this work consists on evaluate the potential for the use of truck platooning over shorter distances, as is the case of the portuguese network.

This paper is organized as follows. Section 2 provides a literature review on autonomous vehicles, in particular in what regards to autonomous freight vehicles and truck platooning. In Section 3, the case study is presented, together with the methodology adopted. Section 4 presents the results obtained for the three scenarios, as well as a discussion of them. Finally, Section 5 brings together the main conclusions drawn from this study and an outlook on future research.

2. STATE-OF-THE-ART

2.1. Definition and terminology

There is no consensual definition for the term "autonomous vehicle", often referred to in the literature as "automated", "autonomous" or "driverless". At european level, the EU defines an "autonomous vehicle" as "a fully automated vehicle equipped with the technologies capable to perform all driving functions without any human intervention" (Pillath, 2016).

In what concerns to the automation levels of vehicle systems, in Europe and in line with the international car industry, the EU adopts the taxonomy of the Society of Automotive Engineers (SAE) (Pillath, 2016; Davies, 2016). This classification is made up of six levels of automation, with the first three levels corresponding to states in which the driver monitors the driving environment, while the other levels is the system to assume this role (SAE International, 2014).

2.2. Truck Platooning

The concept of "platoon" refers to a group of trucks that circulate in a coordinated way, cooperating and constantly communicating with each other through WiFi technology (Janssen *et al.*, 2015; Bergenhem *et al.*, 2012). In this type of formation, trucks have the possibility to move safely within a shorter distance since the reaction time of the system in an emergency is much lower than that required for a human driver (Townsend, 2016), around 25 times faster (Mearian, 2016). This is achieved through the use of V2V and V2I communication systems, together with Advanced Driver Assistance Systems (ADAS). Although it is already technologically possible to set up platoons with multiple vehicles, it is expected that, in an initial phase, platoons up to three trucks will be allowed, so that the other infrastructure users can get used to the presence of this type of "trains" on the road and to minimize possible friction in the traffic flow (Janssen *et al.*, 2015).

Most of the projects devoted to the study of autonomous freight vehicles have explored the concept of platooning, given its potential for fuel efficiency, improved traffic flow and road safety, and driver comfort (Van Meldert & De Boeck, 2016; Bergenheim *et al.*, 2012). In Europe, the most important projects in this area were the CHAUFFEUR I and II (1996 and 2003), KONVOI (2005-2009), SARTRE (2009-2012), COMPANION (2013-2016), Distributed Control of a Heavy Duty Vehicle Platoon and iQFleet (2011-2014); in the USA, one can refer the PATH project (1994 and 1998) and, in Japan, the Energy ITS (2008-2012) (Frisoni *et al.*, 2016; Peters & Elston, 2012; Bergenheim *et al.*, 2012). In Europe and the USA, the first demonstrations on public highways begin to take place (Daimler, 2016; Hottentot *et al.*, 2015; DAF & TNO, 2015). The most important event to date in Europe was the Truck Platooning Challenge, organized by the Dutch Ministry of Infrastructure and the Environment with the aim of promoting the advantages of truck platooning and collaboration between Member States, manufacturers, logistics operators, road authorities and boosting the introduction of this technology in Europe. It was the first cross-border event to involve autonomous vehicles (European Union, 2016c).

The introduction of autonomous vehicles, in particular in freight transport, brings with it benefits with impact on two main prisms: for transport companies and logistic operators – by improving working conditions for drivers, improving their productivity, and reducing costs with fuel and with vehicles involved in accidents – and for society – by reducing environmental impact and improving road safety and traffic flow. Especially with truck platooning, efficiency gains are even more significant. As the vehicles can travel at a constant speed and with a smaller gap between them, it leads to a decrease in the aerodynamic resistance felt by the vehicles in the platoon, which translates into a more efficient consumption and reduction of CO_2 emissions (European Union, 2016c; Roland Berger, 2016). In general, the authors report fuel savings in the order of 5-15% (ERTRAC, 2015; Andersen, 2015; SARTRE, 2013; Tsugawa, 2013), and reductions in pollutant emissions up to 10% (DAF, 2016; ACEA, 2016; Tsugawa, 2013), depending on the characteristics of the platoon and the position each vehicle occupies.

2.3. Hurdles to autonomous vehicles

The technology that allows the manufacture of autonomous vehicles already exists. However, the existence of different regulations at national and international level is preventing the widespread introduction of such vehicles and is its main obstacle (European Union, 2016d).

Road traffic is governed by a number of international conventions, notably the Paris Convention (1926), the Geneva Convention (1949) and the Vienna Convention (1968). Particularly the last one, known as the "Convention on Road Traffic", gives contracting States the right to reject future amendments to the document, which has led to a heterogeneous regulatory framework in the european plan. The original version of the paper stated that "every moving vehicle or combination of vehicles shall have a driver" and "every driver shall at all times be able to control his vehicle", which does not predict, therefore, the automation of the vehicle. On the other hand, the entry of new vehicles on the european market requires the EC type approval (Directive 2007/46/EC), Regulation nr. 79 being the main issue, which regulates the use of ADAS (Lutz, 2016). Legislation

on truck drivers is also an obstacle that needs to be addressed, particularly in what regards to the operation of the tachograph (EC Regulation nr. 3821/85) and to the driving time and resting periods (EC Regulation nr. 561/2006). Finally, some european countries establish a minimum safety distance between trucks, which may hamper the use of truck platooning (Sharman, 2015). Nevertheless, at the european level, the first offical political efforts are being developed for the introduction of this technology, notably through the proposal for amendments to the Vienna Convention by some Member States (Lutz, 2016), the signing of the Treaty of Amsterdam and the realization of the Truck Platooning Challenge by the EC, thus trying to involve all stakeholders (European Union, 2016; European Union, 2016a; European Union, 2016c).

In addition to the above, there are other issues that need to be considered in this discussion:

- **Liability** – It must be clarified who is responsible in the event of an accident with an autonomous vehicle. This issue also involves the insurance industry, with insurance premiums expected to decline as security is increased by the use of this technology. Some authors predict that liability for damage will progressively pass from the driver to the manufacturer as the level of automation in the vehicle is higher (Frisoni *et al.*, 2016; Munich RE, 2016; Anderson *et al.*, 2016; Heutger & Kückelhaus, 2014), but the answer is still not clear.
- **Extreme conditions** – Before this technology can be made available to customers, manufacturers will still need to run multiple tests to ensure that it works in all possible locations and adverse weather conditions such as heavy rain, snow or extreme temperatures (Davies, 2015);
- **Technological requirements** – The V2V and V2I communication systems used in vehicles require a consensus among manufacturers regarding the technology and information exchange protocols used, so that they are common between vehicles (Glielmo, 2011), allowing communication between vehicles of different manufacturers (The Guardian, 2016);
- **High costs** – Although not yet fully quantified, the cost involved in the manufacture of an autonomous truck is expected to be quite high at an early stage, given all the technology involved and the quality and safety requirements that it must guarantee. Janssen *et al.* (2015) report that, at present, the additional cost of introducing the technology that allows communication between vehicles is around 10 000€ per truck, and that in the future this cost will be reduced to around 2000€;
- **Public opinion** - In general, public opinion is skeptical of new technologies. In this way, it is a relevant factor in the quickness with which this technology will be implemented, and so it must be clearly informed and educated in advance by public authorities and stakeholders involved on issues such as user safety, or the impacts of this technology on social, economic and environmental levels (Baratta Jr, 2015);
- **Drivers jobs** – For, at least, the next decade, the presence of a driver is required, even in vehicles with a higher automation level. The technology will significantly improve the working conditions of drivers and increase their productivity. Nevertheless, the arrival of

fully autonomous trucks in which no driver is required, as well as their impact on local economies and sectors dependent on the activity of drivers, should be discussed in a timely manner.

3. CASE STUDY

3.1. Brief presentation of the case study

The study developed in this work is based on the activity of the main portuguese logistics operator and one of the most important at the Iberian level, Luis Simões (LS), who kindly provided the data that underlies the study. Every day in Portugal, LS serves more than 1000 customers scattered throughout the country. The data used in this case study refer to services performed in mainland Portugal, from three warehouses – COL Benavente, COL Carregado 1 (COL C1) and COL Carregado 2 (COL C2), from which 592 routes were carried out on 01/09/2016. Given the proximity between the original warehouses, and in order to reduce the computational load of the model, the three origins were grouped in a single point, centered in Carregado.

3.2. Data processing

Prior to the construction of the model, there was a need to compile the data in an appropriate format to the purpose of this study. The data processing process can be systematized in the following steps:

- In total, the centers COL Benavente, COL C1 and COL C2 served 592 clients distributed by 202 localities (Figure 1). Since platooning will only be allowed on highways (in an early stage), highway exits to the municipalities associated with these localities have been adopted as destination, representing customers (Figure 2). 92 independent destinations were obtained;

- In order to alleviate the computational load of the model, the number of platoons that could be formed from the beginning was calculated, leaving only the spare trucks to be introduced in the model. In other words, of the 592 initial trucks, it was possible to exclude 266 platoons (consisting of two trucks), leaving 60 trucks to run on the model;

- The cost matrix (symmetric) was calculated by multiplying the length of each arc by the average fuel consumption of a truck (a reference value of 34 L/100km = 0.34 L/km was adopted, suggested by Luís Simões).
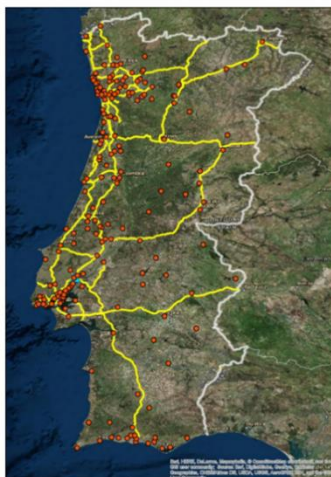

Figure 1 – Initial localities.

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Figure 2 – Highway exits adopted.

3.3. Optimization Model

The model was developed in Mosel language, using Xpress 8.0 software. Next, the main sets of model elements, the decision variables, the parameters introduced as model inputs, the objective function and the constraints are specified.

- **Main Sets**
  - $NODES$: $N = \{ORIGEM, P1, P2, \dots, i, \dots, j\} - Set\ of\ network\ nodes$
  - $PLATOON$: $P = \{1, \dots, t\} - Set\ of\ trucks\ in\ platoon$
  - $TRUCKS$: $T = \{1, \dots, n\} - Set\ of\ fleet\ trucks$

- **Decision Variables**
  - $ASSIGN$: $x_{ijnt} = \begin{cases} 1, if\ truck\ n\ goes\ from\ node\ i\ to\ node\ j \\ 0, o/w \end{cases}$
  - $USED$: $b_{ijt} = \begin{cases} 1, if\ arc\ i\ to\ j\ is\ used \\ 0, o/w \end{cases}$
  - $FUEL\_SAVING$: $g_{ijt} - fuel\ consumption\ from\ node\ i\ to\ j$
  - $TOTAL\_TRUCKS$: $v_{ijt} - total\ trucks\ in\ arc\ i\ to\ j$
  - $TRUCKS\_IN\_PLATOON$: $p_t - total\ trucks\ in\ use$

- **Model Parameters**
  - $TRANS\_COST$: $C_{ij} - matrix\ of\ travel\ costs\ from\ node\ i\ to\ node\ j$
  - $DEMAND$: $d_j - demand\ of\ customer\ j$
  - $saving\_factor$: $\eta - fuel\ reduction\ factor\ from\ platooning$
  - $maxTrucks - maximum\ number\ of\ trucks\ allowed\ in\ each\ platoon$

- **Objective Function**

$$Min\ F = \sum_i \sum_j \sum_t C_{ij} \cdot g_{ijt} \tag{1}$$

The objective function (1) minimizes the total travel cost of all vehicles on their routes.

- **Constraints**

$$\sum_i x_{ijnt} = \sum_k x_{jknt} \qquad \forall\ j \in N, n \in T, t \in P \tag{2}$$

$$\sum_n \sum_t x_{j0nt} = d_j \qquad \forall\ j \in N \tag{3}$$

$$\sum_i \sum_n \sum_t x_{ijnt} \geq d_j \qquad \forall\ j \in N \tag{4}$$

$$g_{ijt} = b_{ijt} + \eta \left(\left[\sum_n x_{ijnt} \right] - b_{ijt} \right) \qquad \forall\ (i,j) \in N, t \in P \tag{5}$$

$$b_{ijt} \geq x_{ijnt} \qquad \forall\ (i,j) \in N, n \in T, t \in P \tag{6}$$

$$x_{jjnt} = 0 \qquad \forall\ j \in N, n \in T, t \in P \tag{7}$$

$$v_{ijt} = \sum_n x_{ijnt} \qquad \forall\ (i,j) \in N, t \in P \tag{8}$$

$$p_t = \sum_j \sum_n x_{0jnt} \qquad \forall\, t \in P \tag{9}$$

$$p_t \leq maxTrucks \qquad \forall\, t \in P \tag{10}$$

$$x_{ijnt} \in \{0,1\} \qquad \forall\, (i,j) \in N, n \in T, t \in P \tag{11}$$

$$b_{ijt} \in \{0,1\} \qquad \forall (i,j) \in N, t \in P \tag{12}$$

Constraint (2) represents an equilibrium equation, ensuring that the number of trucks entering a given node is equal to the number of trucks leaving that node. Constraint (3) is another equilibrium equation, which ensures that the number of trucks leaving the depot (designated node 0) is equal to the demand of the destination nodes. Constraint (4) ensures that the number of trucks going through the sum of the arcs entering a given node is equal to or greater than the demand of that node. Constraint (5) corresponds to the calculation of fuel consumption in a given arc. Constraint (6) defines that a given arc is in use if there is a route from node i to node j. Constraint (7) prevents a truck from returning to the same node. Constraint (8) ensures that the total number of trucks present in an arc is equal to the total number of trucks associated with that arc through the *ASSIGN* variable. Constraint (9) ensures that the total number of trucks in use is equal to the number of trucks that left the depot. Constraint (10) states that the number of trucks in a platoon must be equal to or less than the *maxTrucks* variable (in the context of this model, *maxTrucks* = 2). Constraints (11) and (12) define the *ASSIGN* and *USED* variables as binary.

The main assumptions adopted in the model are as follows: (i) a constant speed for trucks on the highway, this value was not considered in the model; (ii) a homogeneous fleet of vehicles with identical capacities, this value was not included in the model; (iii) the maximum number of driving hours allowed for drivers was not considered; (iv) the average value of 12.5% for fuel savings was adopted, using platoons of two trucks, based on ERTRAC (2015) study; (v) no account has been taken of the effects of traffic, infrastructure conditions, or the gap between trucks during platooning; (vi) for the calculation of the fuel cost, it was adopted the monthly reference price for gas oil, mentioned on the website of the National Entity for the Fuel Market (ENMC), valued at 1,098 €/L; and (vii) the pollutant emissions were calculated on the basis of point 4.1.b) of the ECTA (2011) guidelines.

However, running the model with the 60 trucks that resulted from the data treatment phase, it was verified that the model could not present a solution, running for three days without interruption. Thus, due to temporal limitations and the means available to perform this work, it was decided to carry out the calculation of fuel consumption "manually", based on the optimized routes obtained in the first experiments with the model.

4. RESULTS

4.1. Scenarios results

- **Scenario 1: Current situation**

The results for the situation currently implemented, in which the trucks make their routes individually, are represented in Table 1:

Table 1 – Results of Scenario 1.

Fuel consumption (L/day)	CO$_2$ emissions (ton/day)	Total cost of fuel (€/day)
45 521	132	49 982

- **Scenario 2: Application of platooning (model)**

This scenario is based on the optimized routes obtained in the experimentation phase of the model, for the manual calculation of the fuel consumption. The results are shown in table 2. On the other hand, in order to evaluate the costs inherent to the introduction of the technology that allows for platooning, compared to the benefits provided by its application, the study by Janssen *et al.* (2015) and 250 working days per year were considered. This study indicates that the technology currently has an additional cost of 10 000€/truck, with a depreciation period of 7 years. Thus, technology would cost 5.72€/day/truck. In this case, given that platooning allows a saving of 6023€/day/routes (compared to Scenario 1), its use represents a benefit of 10.17€/day/truck.

Table 2 – Results of Scenario 2.

Fuel consumption (L/day)	CO$_2$ emissions (ton/day)	Total cost of fuel (€/day)	Cost of technology (€/day/truck)	Platooning benefit (€/day/truck)
40 035	116	43 959	5.72	10.17

- **Theoretical application of platooning**

This situation consists of the theoretical approach of the concept of platooning to Scenario 1, that is, considering the value of 12.5% for fuel savings (average value of the range indicated by ERTRAC (2015)), and 10% for the reduction of pollutant emissions, referred to by ACEA (2016). Through the application of platooning, a saving of 6248€/day/routes (compared to Scenario 1) is obtained, which is a benefit of 10.55€/day/truck.

Table 3 – Results of the theoretical approach.

Fuel consumption (L/day)	CO$_2$ emissions (ton/day)	Total cost of fuel (€/day)	Cost of technology (€/day/truck)	Platooning benefit (€/day/truck)
39 831	119	43 734	5.72	10.55

4.2. Results analysis

In this section, the results obtained in the three scenarios presented previously will be compared and commented. Although the value of the fuel consumption has been calculated "manually" and not through the optimization model (and therefore does not represent the optimum solution), it is verified that the results obtained are similar to the theoretical maximum values mentioned in theoretical approach.

In relation to the fuel consumption, the value obtained in Scenario 2 by the use of platooning (40 035L/day/routes) is very close to the theoretical value (39 831L/day/routes), representing a reduction of about 12.1% in relation to the conventional routes of Scenario 1 (45 521L/day/routes) (see Figure 3). Annually, this reduction saves 1 371 500L of fuel. With regard to the total fuel cost, the value obtained in Scenario 2 (43 959€/day/routes) is also close to the value indicated in the theoretical approach (43 734€/day/routes). Compared with Scenario 1 (49 982€/day/routes), there is a reduction of approximately 12.1%, which translates into an annual saving of 1 505 750€ (see Figure 4). Finally, regarding the pollutant emissions produced, the reduction in the results exceeded the 10% value adopted in the theoretical approach. When compared to Scenario 1 (132ton/day/routes), the result obtained in Scenario 2 (116ton/day/routes) represents a reduction of about 12.1%, which is a decrease of 4000 tonnes emitted annually (see Figure 5).
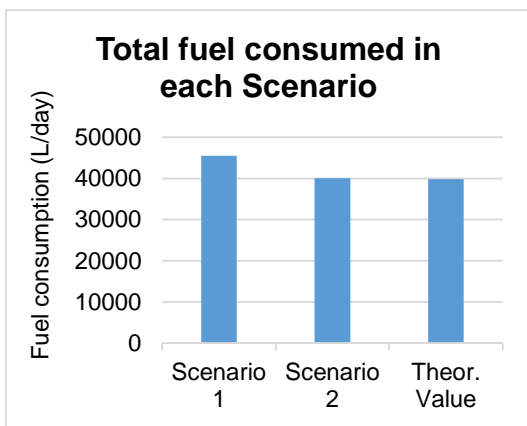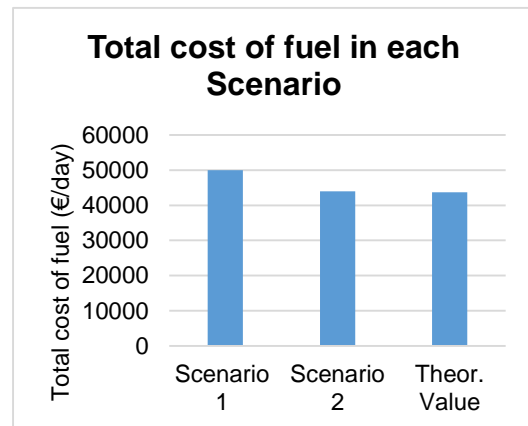

Figure 3 – Total fuel consumed in each Scenario.

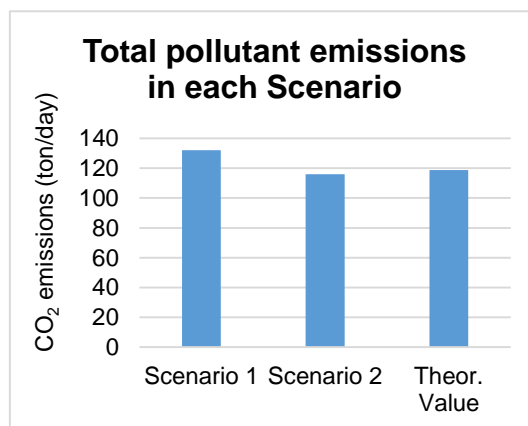**Figure 4 – Total cost of fuel in each Scenario.**

Figure 5 – Total pollutant emissions in each Scenario.

5. CONCLUSIONS

Road transport is responsible not only for the greater number of accidents and fatalities recorded in all modes, but is also the main contributor to the polluting emissions produced by the Transport sector. The search for new, more efficient and sustainable solutions for the sector is therefore urgent. In this context, the study presented in this work intended to explore the benefits of introducing truck platooning on a set of Luís Simões daily routes across Portugal. To that end, a route optimisation algorithm was used, based on the work developed by Larsson *et al.* (2015).

The results obtained are interesting. Comparing the situation in which the trucks make their individual routes (Scenario 1) and the use of platooning to carry out these routes (Scenario 2), there were reductions of around 12.1% in both the fuel consumption and the pollutant emissions produced, translating into annual reductions of 1 371 500L and 4000 ton, respectively. As regards the total fuel cost, the observed reduction was 12.1%, which represents an annual saving of 1 505 750€. On the other hand, in Scenario 2, the savings in fuel costs generated by platooning (2543€/year/truck) are significantly higher than the cost of technology (1429€/year/truck). Considering these results, it is possible to recognize favorable indicators for the use of platooning in the case of study, and for the continuation of the study of this technology applied to the portuguese highway network in particular, as well as other networks characterized by short distances. In this way, it can be affirmed that the objectives of this work were achieved.

As future developments in this topic, it is suggested:

- Simplification of the computational complexity of the model developed in this work, for using in case studies with a depot of origin serving several clients;
- Consideration of more than one depot of origin, analyzing not only the early planning of platooning services but also the possibility of formation of on-the-fly platoons;
- Inclusion of additional parameters to make the model more realistic, such as the speed and capacity of the trucks, the maximum number of driving hours allowed to drivers, the gap between trucks in platoon, or the effects of traffic and infrastructure conditions;
- Application of other methodologies, such as simulation, to evaluate the benefits provided by the use of platooning.

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