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Developing a micro-simulation tool for autonomous connected vehicle platoons used in city logistics

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Abstract

The future holds great promise for the use of autonomous vehicles. Many daily activities which require the use of extensive manpower, will soon be performed with much less human interference, if at all. City logistics is an example of one such arena, which will most surely benefit from the introduction of autonomous vehicles. Autonomous vehicles will replace human couriers in the near future, and conduct delivery tasks. Given the current trends in the freight industry, this will probably be integrated with the use of platoons, which has recently gained an increasing interest in the freight sector. In this paper we present an urban freight delivery system, which is based on the use of autonomous connected platoons. In the presented system, autonomous vehicles carry out delivery tasks, traveling from an origin depot to a customer, by joining platoons along the way, which bring them closer to their destination.

Many issues can be analysed with respect to the proposed system. In this paper, we choose to focus on the travel time issue. In particular, we examine the effects different platoon configurations (total number of platoons in the network and their size) have on the travel time of the vehicles performing the delivery tasks. In order to examine the proposed system, a traffic microsimulation is used. A case study is presented, demonstrating the effects of varying the platoon number and size on the travel time. The results show a relation between the configuration of platoons and the travel time, especially with respect to the delay in intersections, and the waiting time while switching platoons.

Keywords: city logistics; platooning; autonomous vehicles; connected vehicles, micro-simulation

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1. Introduction

The demand for transport is constantly increasing. This applies to both passenger transport as well as freight transport. Focusing on urban freight transport, the growth in internet shopping, especially in the last decade, has contributed tremendously to the ever-growing demand for home deliveries (Visser et al., 2014) and necessitated developing new approaches to meet the market needs.

The dramatic technological evolution of the recent decades, which also affected the transportation industry, opens new possibilities for mitigating the supply-demand gap of the freight sector. The introduction of the autonomous vehicle and other advancements in communication technologies led to rethinking many of the practices underlying logistic processes, and to the development of new concepts in this regard.

One of the concepts that has gained momentum in recent years is platooning. A platoon is a group of vehicles traveling together, with a relatively small distance between one another. Platoons are mostly used for freight purposes (Ramakers et al., 2011; Alam et al., 2015; Liang et al., 2016) and are considered quite promising in terms of road utilization and road safety (Varaiya, 1993; Alam et al., 2015). They are also considered an effective means of reducing fuel consumption (Tsugawa et al., 2011; Janssen et al., 2015; Van De Hoef, 2015).

When concentrating on the evolution of platooning techniques over the years, one can identify several trends. These have mostly to do with the control system of platoons. While at first Adaptive Cruise Control (ACC) systems were used, these where later replaced by Cooperative Adaptive Cruise Control (CACC) systems, allowing for an even smaller gap between platoon vehicles, and thus for an increased road throughput (Ploeg et al, 2011). Later studies relying on the introduction of CACC, focused on ensuring string stability (Ploeg et al, 2014), and others concentrated on analyzing the information flow within the platoon (Zheng et al., 2016).

With the increasing interest in developing sustainable transport, more efforts have been also invested in studying the environmental benefits of using platoons in terms of fuel consumption, either by conducting field experiments (Bonnet and Fritz, 2000; Al Alam et al, 2010), or by examining various cases. One example for that is identifying situations where it is advantageous to travel as part of a platoon and enjoy fuel reduction benefits (Liang et al., 2013).

In spite of the promising perspectives in many different aspects, it seems like in recent years the main focus has been put on the environmental benefits of using platoons, while other aspects, and especially traffic-related ones were getting less attention. In particular, not much research has been conducted concentrating on different platoon configurations (varying the total number of platoons in the network and their length), and the possible effects these might have on the travel time. Considering the fact that in the future platoons may also be used in urban environments, such concerns cannot be overlooked. The current research focuses exactly on this issue. With this respect, a specific setting is examined using traffic microsimulation, where platoons are used for freight purposes. In this setting, the effects are examined of the total number of platoons and their length (no. of vehicles per platoon) on the travel time.

The rest of the paper is organized as follows. In the next section the presented setting is described in detail. Then, a case study is presented based on the proposed setting. The results of the examined case study are briefly analyzed, and finally conclusions are drawn and future research directions are outlined.

2. Methodology

2.1. Conceptual framework

Considering the accelerated development in freight transport, it seems like the day is not far away, where autonomous connected platoons will be an integral part of city logistic system, serving customers up to their doorstep. Such a system should include several features, and requires several decisions to be taken with respect to its capabilities and attributes. In this section, we first describe briefly the proposed system. Then we focus on several main attributes of the system and explain the reasoning underlying different decisions regarding its design.

The proposed system offers an alternative to existing urban freight transport practices. It is based on the use of autonomous connected platoons, where each platoon is human-driven and the platoon members are autonomous vehicles. The platoons travel in fixed short routes. In order to carry out a single delivery task, each vehicle joins a platoon and travels with it, as long as it is advantageous for it to do so (brings it closer to its destination). When the route of the platoon is no longer relevant for the joining vehicle (continues in a different direction), the vehicle leaves the platoon and waits in a designated parking facility for the next platoon to arrive, to continue its travel. The autonomous capabilities of the vehicles in the system allow them to travel not only while being part of the platoon but also independently. This capability is essential for the stages where the vehicles are required to switch between platoons. The connectivity between vehicles is another important attribute of the system, which keeps the vehicles constantly informed about the position of the platoons in their vicinity and their destination. Using this information, the joining vehicles can decide which platoon to join next, and when to do so.

When considering the above presented system, several issues comes to mind. First, a question arises with respect to the level of segregation of the platoons, namely, whether the platoons would be segregated from the general traffic and operated using designated lanes, or would they share the same lanes as the general traffic. Since the guiding principle in designing the proposed system is keeping all costs as low as possible (system construction, operation and maintenance), we assume that the platoons would use the same lanes as the general traffic.

Another issue that should be considered is the congestion level of the network. Since the considered setting is the urban network, which is known as highly congested, an emphasis should be also put on designing ‘a light system’, one which would not impose an additional load on an already congested network. In this regard, a decision should be taken with respect to the level of independency given to the platoons; should they be allowed in all parts of the network, or should they be restricted to specific parts of it. When considering this issue, we assume that until autonomous vehicles will be fully integrated in the road network, they will first be restricted to travel in specific parts of the network (integrated in the general traffic), and therefore their negative contribution to the congestion in city center would be kept in a tolerable level. With respect to the potential increase in congestion, one should also keep in mind that a use of such a system would partly obviate the use of existing delivery vehicles that are an integral part of the general traffic today. Therefore the proposed system would not necessarily impose an additional load, when compared with the current state of the network.

A question arises also with respect to the routes of the system, or more precisely, whether the platoons should follow fixed routes, or should their routes be tailored according to the changing delivery tasks. When considering this question, several arguments should be taken into account. Since according to the above presented assumption platoons are restricted to specific parts of the network, then their routes should be planned accordingly, within this restricted area. However, even after placing restrictions on the sections of the network where platoons are allows, there might still be enough room for planning different platoon routes. Therefore additional considerations have to be taken into account. Designing a fixed set of routes may decrease the flexibility of the system, and is therefore not recommended. On the other hand, having such a set might contribute to the simplicity of the system and make it easier to operate. For that reason, finding a method that would allow carrying out delivery tasks for a variety of origin-destination combinations on the one hand, while keeping a relatively small routes for the platoons on the other, would be most advantageous.

Some parallels can be drawn between designing platoon routes to transit-related problems. One of the core problems in transit planning is related to the design of transit lines, also known as the transit network design problem. In this respect, three main route structures can be identified: a radial structure, which is most suitable for highly centralized areas; a direct trip-based structure, where each route is independent of the other; and a transfer-based structure, where in order to complete a trip, or a delivery in our case, a transfer between routes is essential. According to Badia et al. (2016) the selection of the optimal structure has to do with the mobility spatial pattern, and in the transit network context to the spatial distribution of activities. In our case, since deliveries are considered, we assume that the network can benefit the most if a transfer-based structure is selected. The reason for that is twofold. First, in our case there is no central origin from which all deliveries are carried out, and second this would allow for a greater flexibility, and the possibility of generating varied routes by making multiple transfers. Nonetheless, selecting a transfer-based structure also suffers from several drawbacks that are caused by the transferring stage. Performing such a transfer also means having waiting phases during the travel (until the next platoon arrives) and also requires providing parking facilities for the platoons, while in the waiting phase.

Considering the construction of the platoon, it was decided that each platoon would include a human-driven leader, and the platoon members would be autonomous vehicles. This formation was chosen since it meets the needs of the intermediate stage, right after the introduction of autonomous vehicles in networks, where autonomous vehicles and human-driven vehicles will travel side by side. It would also facilitate an early implementation of the system, because it is partly based on the use of human-driven vehicles.

2.2. Main objectives and implementation method

The potential integration of platoons in urban logistic systems raises many operational issues. In this paper, we consider the above presented system, and try to analyze the traffic-related impacts related to its implementation. In particular we examined the influence on the travel time, caused by different number of platoons per route, and the maximal number of vehicles per platoon.

To this end, we use traffic microsimulation and generate a specific scenario, as will be described in detail in the next section. The use of microsimulation allows us to examine different scenarios easily and retrieve data regarding the travel time in different stages of the simulation.

Note that quick arrival of the vehicles to their destination is an objective sought by the delivery providers, and may not necessarily reflect the objectives of the network operators. The latter might be more interested in providing an equal service level to all users, also at the expense of longer travel times for a certain user's group. In this paper, however, we focus our attention on the perspective of the delivery providers only.

2.3. Modelling platoons in a microsimulation environment

Following the increasing interest in platoons in recent years, special packages have been developed, extending the capabilities of microsimulation tools and enabling them to work with platoons (Segata et al., 2014). These adaptations are essential since platoons are considered unique entities; they cannot be viewed as single vehicles, as they travel in a group, and their movement is controlled by a controller. At the same time, they cannot be viewed as an especially long vehicle with a fixed length, since they may change their length during their travel (vehicles may join a platoon or leave it at all times). This necessitates performing certain adaptations in the microsimulation, provided by those recently developed packages. However, since the research in this field is relatively new, not every aspect concerning the behavior of platoons have been fully implemented.

One of the issues that has not been addressed yet with respect to working with platoons in a microsimulation environment is the treatment of platoons in roundabouts. The most critical capability with respect to roundabouts has to do with the right-of-way. While one of the inherent features of microsimulation tools is the treatment of the right-of-way for single vehicles, this is not the case for platoons. This feature has been developed as part of this work.

When considering the right-of-way of platoons in a roundabout, different policies can be implemented. For example, an emphasis can be put on equity. That is, striving to keep an even as possible waiting time for platoons arriving from different approaches. Another possibility is to implement a "first-come, first-served" policy, which does not necessarily lead to equal delays in all roundabout entrances.

The principles underlying the treatment of right-of-way for platoons in a roundabout share many similarities with the calculation of red clearance intervals in signalized intersections (McGee et al., 2012). Just like in signalized intersections there is a need to define the clearing platoon and the entering platoon. However, unlike signalized intersections where all conflicts are concentrated on a single area, roundabouts include multiple conflict areas, and therefore there are more scenarios that should be considered when compared with signalized intersections. For example, while entering a roundabout, the platoons may be in conflict with platoons which are already in the roundabout and are approaching the same entrance closest to the location of the platoon, as shown in Figure 1(a) (the light blue arrows represent platoon vehicles). At the same time, the entering platoon may also endanger platoons which already started entering the roundabout using another entrance, as shown in Figure 1(b). In Figure 1(b), Platoon 2 started entering the roundabout using the upper entrance, before Platoon 1 started entering using the lower roundabout entrance. Because Platoon 2 will not complete its entrance before Platoon 1 arrives at the upper entrance, a crash is likely to occur. In addition to the above issues, there is also a need to consider the length of the platoons in conflict, and the size of the roundabout, which influence the distances to the conflict points. In the current work, the roundabout entering policy for platoons was based on the "first-come, first-served" principle, while taking into account all the aforementioned issues.

Note that due to space limitations, and in order to keep the focus of the paper on the proposed system, it was decided to describe the roundabout algorithm very briefly, while not mentioning all the considerations taken into account during its development. The full description of the algorithm will be provided in a later publication.

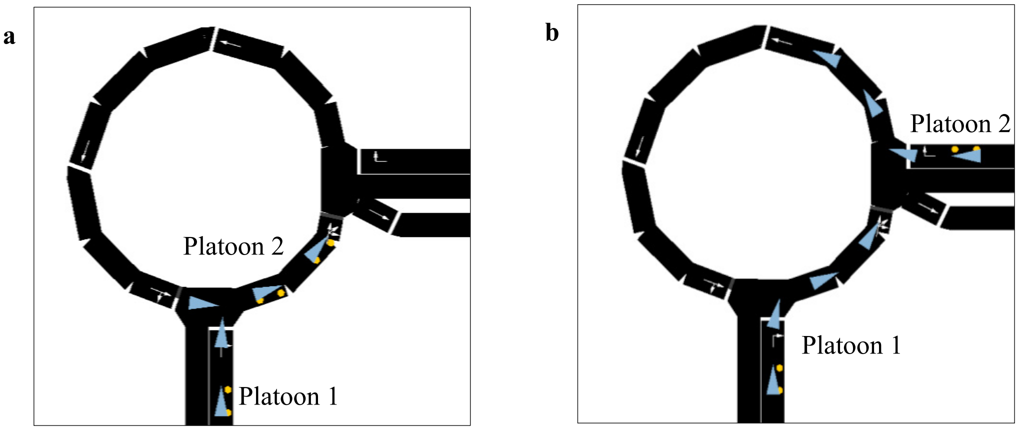

Fig. 1. (a) Conflict while entering the roundabout; (b) Conflict after entering the roundabout

3. Case study

In order to demonstrate the use of the proposed system in a microsimulation environment we used SUMO (Behrisch et al., 2011), combined with PLEXE (Segata et al., 2014), an extension to SUMO that implements the functionality of platoons in a road network. A simple network was constructed. This network includes two sections, 620 m each, with a speed limit of 50 kph, connected by a roundabout, as presented in Figure 2. In each section, platoons consisting of delivery vans were traveling in a circular route constantly. In addition, another vehicle was assigned a delivery task, and had to travel from point A to point B via point C, by joining platoons: first joining to a platoon for the section A-C, and then joining another platoon for the section C-B. Point C was defined as a transfer point, where the vehicle leaves the first platoon, and waits for the next platoon to arrive. When detecting a platoon close by (with a proximity of 100 m or less), the vehicle starts approaching the platoon, and eventually joins it. Except for the platoon vehicles and the vehicle joining the platoons, no additional vehicles were used is this simple example.

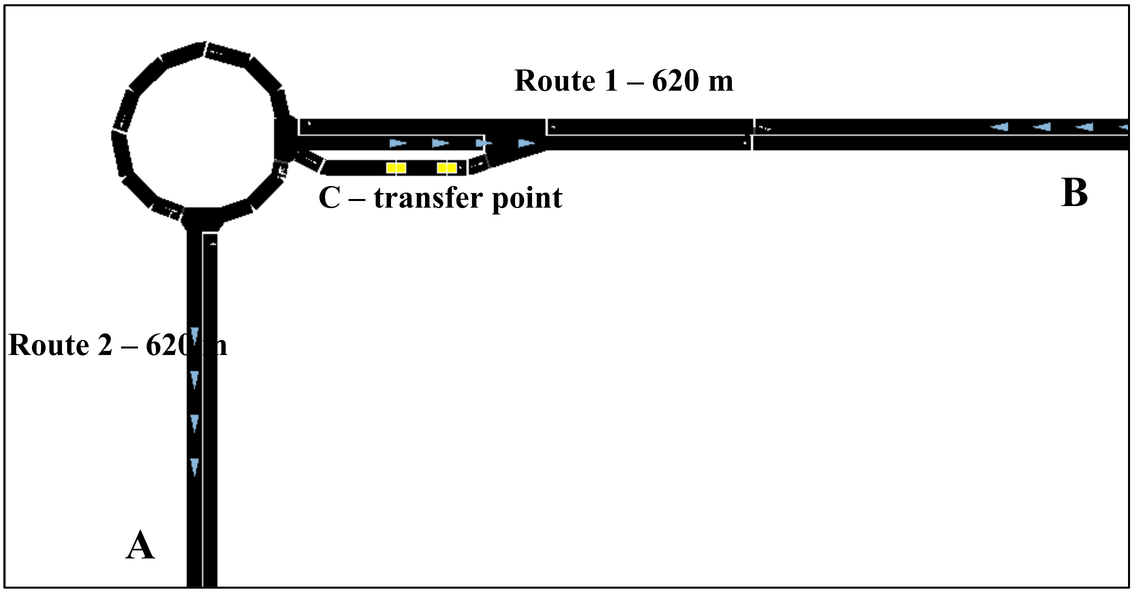

Fig. 2. The case study network

In order to test the proposed system, 9 scenarios were examined, distinguished by the number of platoons per route, and vehicles per platoon, as described in Table 1. The total number of platoons and their size was determined while taking into account the size of the network. We assumed that having more than 16 platoons or increasing their size above 6 vehicles would overload the network.

Table 1. The examined scenarios

Number of platoons in the network (in both sections)	Number of vehicles per platoon	Total number of platoon vehicles
4	6	24
6	4	24
8	3	24
12	2	24
6	6	36
12	3	36
8	6	48
12	4	48
16	3	48

4. Results

We concentrated on the travel time of the vehicle executing the delivery task, and examined it for each of the tested scenarios (distinguished by the number of vehicles per platoon and the total number of platoons). In order to gain more insights on the travel time, it was decided to divide it into 3 phases, corresponding to the travel phases: the travel time from point A to C, the waiting time in transfer point C and the travel time from point C to B. Figure 3 shows the travel time of the vehicle executing the delivery task for every component of the route.

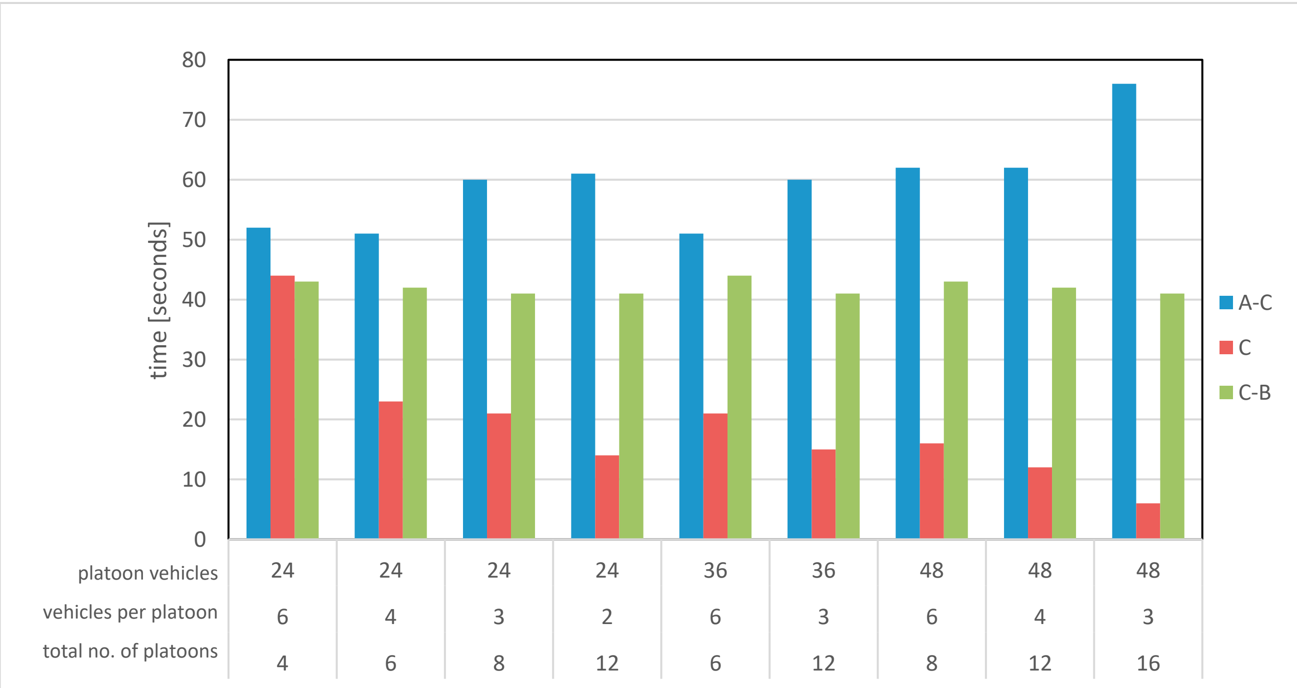

Fig. 3. Travel and waiting time of the joining vehicle in each one of the travel phases

Examining Figure 3, the relation between the total number of platoons and the waiting time in point C is quite evident. As the number of platoons in the system increases, so decreases the waiting time in point C. This result can be explained by the fact that having more platoons in the network also means increasing the frequency of platoon arrivals at point C. As a result, the waiting in point C decreases.

The travel time from point C to point B hardly changes, and that has to do with the fact that this section is hardly affected by the configuration of platoons in the network. That is due to the fact that after passing the roundabout, there are no further intersection points until the route ends at point B. Unlike the section between point C and B, when examining the section between point A and point C, the effect of the roundabout is clear. As suggested by Figure 3, when examining scenarios with the same number of total platoon vehicles, an increase in the number of vehicles per platoon decreases the travel time between point A and point C. This result can be explained by the fact that for vehicles waiting to enter the roundabout, it is more advantageous when the platoons are bigger (include many vehicles), because it implies that more vehicles will enter the roundabout each time. That also implies that the marginal addition of travel time for large platoons in the roundabout is not comparable with the additional waiting time at the entrance to the roundabout, when using small platoons. In this regard, one should keep in mind that this result has to do with the fact that the roundabout is operated using a "first-come, first-served policy". Thus, when a big platoon approaches the roundabout and right afterwards smaller platoons near the roundabout using other approaches, even if the small platoons have a sufficient gap, they will enter the roundabout only after the big platoon.

Another issue that should be noted is that according to the results, the overall travel time is not directly associated with the total number of vehicles in the system, and hence one can achieve the same level of service (reflected by the travel time) by using relatively small number of vehicles in total. However, one should keep in mind that the examined scenarios did not include any additional vehicles except for the platoon vehicles and the additional vehicle performing the delivery task. Once additional vehicles are integrated in the network, this will affect the obtained results.

5. Conclusions and further research

In this paper a new concept for urban freight delivery was presented. This concept is based on the use of autonomous connected platoons led by a human driver. Vehicles are assigned delivery tasks and join platoons, traveling in fixed routes, in order to get from their origin to the destination. The proposed system was demonstrated using a small network, and several scenarios were tested, where the total number of platoons in the system and the number of vehicles per platoon were varied. The goal was to examine the changes in the travel time of the vehicle carrying out the delivery task in different phases of its travel. The results show a possible relation between the total number of platoons in the system and the waiting time in transfer points, suggesting that this waiting can be reduced by increasing the number of platoons in the network. An opposite relation was found with respect to the delay in front of the roundabout, implying that increasing the number of vehicles per platoon may decrease the delay at the entrance to the roundabout, given a fixed total number of platoon vehicles.

Generalizing the results, one can argue that a certain tradeoff exists with respect to the features of the network and the desired configuration of platoons; the more flexibility the system offers, by increasing the number of transfer points, would mean an increase in the waiting time, that can be partly compensated by having a relatively large number of platoons in the network. At the same time, given a fixed number of vehicles in the system, increase in the number of platoons necessarily implies having smaller platoons, which might increase the intersection delay. These issues has to be well thought of when designing a similar system. Having said that, it should be noted that this analysis is based on a single small case study, and in order to confirm the results, further research in this direction is required.

The system presented in this paper, opens the door for a variety of follow-up studies. First, various networks of different sizes should be examined. These networks should have different number of intersection points and should include various types of intersections (roundabouts, signalized and non-signalized intersections). In these networks platoons with different configurations should be tested. In addition, multiple vehicles should be assigned delivery tasks with various origins and destinations.

Another important research direction that was not examined in this paper but is mandatory before a potential implementation of the system can take place is the integration of additional user types. The focus in this paper was on the interaction between the platoons themselves. However, further research should include also an extensive analysis of the impacts on additional road users (private vehicles, transit users, pedestrians, cyclists, etc.). The integration of these additional users will contribute considerably to the possibility to analyze the proposed system in a real-life setting.

On a more general level, there is also a need to examine the potential integration of the proposed system with other complementary urban logistic systems. For example, given that the proposed system will be allowed only in parts of the network, it is essential to examine how deliveries can be made to other parts of the network by using complementary systems. Only such an overall analysis of the whole urban logistic system, will allow a proper evaluation of the proposed system.

As part of this work, an algorithm was developed for the treatment of platoons in roundabouts. The treatment of platoons in intersections in general (not necessarily in roundabouts) is a subject that is worthy of further research. In this regard, many possible research directions can be thought of with respect to the implementation of various possible strategies. These research directions may include behavioral aspects, or traffic related benefits, for example. Each such examined strategy should be thoughtfully analyzed in order to facilitate the introduction of platoons in existing road networks.

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