Article
The Benefits of Truck Platooning with an Increasing Market Penetration: A Case Study in Japan

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Abstract: Truck platooning can potentially reduce carbon emissions caused by the road freight sector because fuel consumption would be reduced when trucks travel in a platoon. While research about the coordination and benefits of truck platooning is underway, the high costs of such technology suggest it will be several years before significant market penetration is achieved. In this study, we develop an improved mixed-integer linear programming model to optimize the formation and route of truck platooning. Then the model is applied to Japanese 10th logistic census data to estimate the benefits and formation pattern of truck platooning with the increase in the market penetration of platooning technologies. The results of the numerical calculations indicate that the largest total cost saving rate, matching rate and fuel saving rate are 1.15%, 57% and 5.7%, respectively. These three rates were all found to increase at first and then decrease as more and more trucks become platoonable, implying that truck platooning is profitable even in the initial stage and that not all trucks are suited to joining a platoon. Furthermore, several scenarios, including a discount on toll fees and different inter-vehicle distances, are considered to determine the effect of these factors on the benefits of truck platooning.

Keywords: truck platooning; market penetration; green logistics; fuel economy; matching rate

1. Introduction
As an increasing number of countries put the Carbon Neutral Goal into their national strategy, the concept of green logistics has gained a lot of attention since the transport sector accounts for around 24% of global carbon dioxide emissions [1]. Due to the large amount of fuel consumed by heavy-duty vehicles (HDVs), road freight is inevitably one of the main targets for reducing carbon emissions. It has been reported that energy consumption costs constitute about 30% of the total operation cost of the truck industry [2]. One solution is truck platooning, which involves a set of virtually linked trucks driving in very close proximity at high speed. Using semi-automated driving technologies with a Cooperative Adaptive Cruise Control system (CACC), trucks in a platoon are virtually linked and can communicate with each other through sensors and wireless communication technology. The leading truck is manually driven and is followed by one or more trucks which automatically brake, steer and (de)accelerate based on the actions of the leading truck [3]. Due to the extra short distance between trucks in a platoon, truck platooning has many benefits. Firstly, aerodynamic friction is reduced significantly, so that truck platooning can reduce fuel consumption and carbon emission. The results of field experiments indicate following trucks in a platoon may obtain a fuel-saving rate between 5% and 20%, depending on the speed and the distances between trucks [4,5]. Considering the extremely high carbon emissions generated by the transportation sector, even a 1% improvement in fuel efficiency has significant meaning in terms of economics and sustainability. Furthermore, truck platooning may reduce traffic congestion by using roads more effectively than trucks
traveling individually [6,7]. Additionally, The platoonable trucks equipped with sensors and wireless communication technology react more quickly than human drivers implying that truck platooning is safer than normal trucks.

Previous studies have investigated the maximum benefits of truck platooning, but the variation of the benefits and formation patterns of truck platooning with the increase in the market penetration of platooning technologies remains to be seen. This study applied an improved mix-integer linear programming (MILP) model to actual Japanese logistics data to study the benefits and formation patterns of truck platooning in several scenarios so that the benefits of truck platooning could be further improved.

The remainder of this paper is organized as follows. The second section reviews pertinent literature and presents the objective of this study. The third section introduces the model and data used in this study. The fourth section presents the results of numerical experiments in several scenarios as the market penetration of platooning technology increases. The last section includes our conclusion, with the implications of this study and directions for future research.

2. Literature Review

The increase in research about the potential of truck platooning can be largely categorized into two types: technique side and fuel economy side. The technique side mainly focused on the engineering applications required to make truck platooning a reality, while the fuel economy side mainly focused on the exact savings obtained from truck platooning and how to maximize the benefits.

Among the studies based on fuel economy, three major issues are being considered: the exact air drag and reduction in fuel consumption obtained from truck platooning, the coordination and optimization of the truck platooning formation and the potential of truck platooning in a specific area. Browand et al. [4] conducted a two-truck test on an unused airfield runway to determine the reduction in fuel consumption and found that a fuel saving with an inter-vehicle distance of 10 m was 10% and 6%, respectively, for the following and leading trucks. When the inter-vehicle distance varies between 3 m to 10 m, the fuel consumption saving rate remains in the range of 10–12% for the following truck and 5–10% for the leading truck. McAuliffe et al. [8] implemented a field experiment with three heavy-duty tractor-trailer trucks on a closed test track and demonstrated that the fuel saving obtained from truck platooning varied from 5% to 13%, depending on speed and inter-vehicle distance. It should be noted that the maximum fuel saving was experienced by the middle truck in a three-truck platoon, while the least fuel saving was found for the leading truck. In addition to field tests, wind tunnel tests and computational fluid dynamics are used to study the reduction in air drag [5,9,10]. While the results show that fuel consumption is influenced by many factors, including the slope of roads and the weight of the trucks, it is still concluded that the fuel saving rate obtained from truck platooning is somewhere between 5% and 18% and that a shorter inter-vehicle distance is associated with a higher fuel saving rate. For the coordination and optimization of truck platooning, Larsson et al. [11] created a mathematical framework to model trucks traveling in road networks and defined a routing problem called the platooning planning problem. They showed this problem is NP-hard and presented several heuristics for obtaining the optimal solutions. Abdolmaleki et al. [12] formulated the truck platooning planning problem as a minimum concave-cost network flow problem by constructing a time-expanded network. They also devised a few solution methods for efficiently finding the optimal solution. In 2016, Larson et al. [13] built a Mixed-integer linear programming (MILP) model to obtain the optimal platooning coordination plan to minimize total fuel consumption.

From their investigation of the potential of truck platooning in a specific area based on extensive truck trajectory data from Liaoning Province, China, Ma et al. [14] showed the average platooning distance and time ratios were 9.645% and 9.943%. They also suggested that platooning strategies could be time-dependent and speed coordination can be executed from 5 a.m. to 7 p.m. Liang et al. [15] investigated the potential of truck platooning
in a region in Europe using the GPS data of trucks by assuming that trucks were in a platoon if the distance between them is smaller than a given value. They concluded that the platooning rate is 6.59%, with the fuel-saving rate of 0.21% when the coordination horizon is set to be 5 km. Noorvand et al. [16] developed a system-level equilibrium model to characterize spontaneous truck platooning. They applied it to freight data in the US, showing that platooning could lead to a 7.9% fuel saving in 2025. Noorvand et al. [16] developed a system-level equilibrium model to characterize spontaneous truck platooning. They applied it to freight data in the US, showing that platooning could lead to a 7.9% fuel saving in 2025.

There are also some researchers interested in the potential of truck platooning on the Japanese expressway. Takeda et al. [17] estimated the matching potential of trucks traveling on the Tohoku expressway using logistic census data, which will be explained in detail later. They divided the Tohoku expressway into several segments 80 km in length and assumed it was possible for trucks in the same segment to form a platoon. According to their research, the fuel cost saving rate of truck platooning on the Tohoku expressway would vary from 3% to 9% for different inter-vehicle distances.

In most of the research in the literature, it has been assumed all trucks on the road are platoonable. It may take several years to popularize such technology since the only trucks able to form a platoon are those equipped with a sensing system (camera, radar, lidar, etc.), an electronic control unit, a vehicle-to-vehicle communication system and a CACC system [18]. In the initial stage of the spread of platooning technology, when the deployment of such technology is not yet widespread, the scarcity of platoonable trucks will mean it will be difficult to find a partner. For this reason, forming a platoon may require waiting for a long time or making a long detour, which may increase total operation cost instead of resulting in savings.

While some researchers have proposed efficient methods to solve the platooning planning problem, these methods have rarely been applied to actual data. However, the benefits of truck platooning in real situations highly depend on the overlap of the spatio-temporal trajectory of trucks traveling in some areas. In other words, the potential of truck platooning varies according to region. Actual energy and cost saving from truck platooning on the real expressways remains to be seen.

In this study, our objective was to improve a MILP model to coordinate the formations and routes of truck platooning, and to apply that model to several groups of trucks traveling along the expressway connecting the Tokyo area and Osaka. The model is designed to minimize the total operation cost, including total fuel cost, total toll cost, and total labor cost. The trucks were assumed to be platoonable and were used to simulate the process of the growth of market penetration of truck platooning technology. Factors like a discount on the toll fee and smaller inter-vehicle distance were considered to determine their influence on the benefits of truck platooning.

3. Methodology

Larsson et al. [11] defined a vehicle routing problem concerned with minimizing the fuel consumption by truck platooning given a collection of starting points, destinations, and deadlines as the platooning problem. And many studies have been conducted to solve the platooning problem. For example, Larson et al. [13] built a MILP model to obtain the optimal platooning coordination plan to minimize total fuel consumption. In addition, some heuristics have been proposed so that a large-scale platooning problem could be solved within an acceptable time [11,19].

Since we only focused on one path consisting of two expressways connecting Tokyo and Nagoya with the maximum number of platoonable trucks of 311, an exact algorithm which can provide a more accurate result is more appropriate for this study. Based on Liang’s work [15], an improved MILP model is proposed to optimize the formation, dissolution and routes of truck platooning. That is, the model would determine the instructions given to each truck: which way they should go and when, as well as where and with whom to form a platoon. In their original model, the focus of Liang et al. was on minimizing the collective fuel use of all platoonable trucks, but the increasing labor cost due to the extra waiting time of trucks was not considered. In this study, the objective function of the model
was modified to consider the total fuel cost, total toll cost, and total labor cost (referred to as “total time cost”) to minimize total operation cost. A hard constraint on the arrival time of each truck was imposed to ensure they all reached their destinations before the deadline in the original model. Since time cost is involved in the total cost, which is minimized by the objective function of the modified model, implying the trucks should never stop for a long period to wait for a chance to form a platoon, such constraint on arrival time is removed from the modified model.

3.1. Assumptions

The coordination of truck platooning could be very complicated not only because of the challenges of conveying spatio-temporal OD information but also because of the many factors which impact fuel cost. In this study, the following assumptions are made:

1. Trucks will announce their trip itineraries, specifically their OD location and departure time, in advance. A platform, called the Platooning Service Provider (PSP), will collect this information and output a route and platooning plan. The trucks will be informed of the route they should take and when, where, and with whom to form a platoon. In practice, logistics companies, governments or expressway companies could take on the role of centralized coordinator.

2. Truck platooning is required to form and dissolve at specified facilities along the expressway. According to a facility development plan for truck platooning proposed by the Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT), the Japanese government is considering developing such facilities near the interchange (IC) of major expressways [20]. Therefore, ICs are assumed to serve this function on the expressway network.

3. From the perspective of fuel economy, more fuel savings will be obtained when there are a greater number of following trucks. On the other hand, long truck platoons would increase the wear and tear of roads due to channelized traffic and excessive concentration of the wheel path [16]. From this perspective, a limitation on the size of a platoon post such technology becomes widely applied. In this study, the platoon size is unlimited since most countries have yet to implement clear policies.

3.2. MILP Model

Based on the above assumptions, a MILP model is proposed to optimize the formation and route plans of trucks traveling on the expressway. The variables and parameters used in the model are listed in Table 1.

In Liang’s original model, the objective function only tries to minimize the total fuel cost, while the objective function of this study is to minimize the total operation cost of all platoonable trucks, including total fuel cost, total toll cost, and total labor cost. Additionally, the hard constraint on arrival time in the original model was removed. Constraint (2) requires each truck to arrive at its destination ultimately. Constraint (3) makes the time the leading truck enters an edge equal to the following trucks when a platoon is formed. Note that $M$ is a big enough number, which should be larger than the largest time gap between vehicles that can possibly join a platoon. Constraint (4) stipulates that one vehicle can only be followed by one vehicle. While this last constraint is arguably unrelated to the operation of truck platooning, it serves to break the symmetries in the problem and therefore improves efficiency. We assume that platoonable trucks are numbered, and trucks with smaller indices are always ahead in a platoon. Without constraint (4), if $v_1$, $v_2$, and $v_3$ are in the same platoon on edge $(i, j)$, either $q_{i [3,2]} v_{1,j} = 1$ or $q_{i [3,2]} v_{2,j} = 1$ is a valid solution which significantly increases the complexity of this problem. Constraint (5) and Constraint (6) stipulate that trucks can lead or follow other trucks only when they travel on that edge. Constraint (7) requires the time that a truck enters the expressway network to be equal to its initial departure time plus the waiting time at origin. Constraint (8) sets the waiting time of all trucks at destinations to be 0, which is computationally time-consuming despite being an obvious condition. Constraint (9) is that the new time of entering the next
Table 1. Variables in the model.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V$</td>
<td>Set of vehicles</td>
</tr>
<tr>
<td>$I$</td>
<td>Set of network nodes, i.e., ICs</td>
</tr>
<tr>
<td>$E$</td>
<td>Set of links connecting nodes, i.e., a section of an expressway</td>
</tr>
<tr>
<td>$O_v$</td>
<td>Origin node of truck $v$</td>
</tr>
<tr>
<td>$D_v$</td>
<td>Destination node of truck $v$</td>
</tr>
<tr>
<td>$T_v^O$</td>
<td>Departure time of truck $v$</td>
</tr>
<tr>
<td>$C_{i,j}$</td>
<td>Fuel cost of traveling link $(i,j)$</td>
</tr>
<tr>
<td>$T_{i,j}$</td>
<td>Travel time of passing link $(i,j)$</td>
</tr>
<tr>
<td>$G_{i,j}$</td>
<td>Toll cost of traveling link $(i,j)$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Fuel consumption saving coefficient</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Driver’s wage per minute</td>
</tr>
<tr>
<td>$M$</td>
<td>A big enough number</td>
</tr>
<tr>
<td>$f_{v,i,j}$</td>
<td>Equals 1, if truck $v$ travels on edge $(i,j)$, otherwise 0</td>
</tr>
<tr>
<td>$q_{v,w,i,j}$</td>
<td>Equals 1, if truck $v$ follows $w$ on edge $(i,j)$, otherwise 0</td>
</tr>
<tr>
<td>$e_{v,i,j}$</td>
<td>Time that truck $v$ enters edge $(i,j)$</td>
</tr>
<tr>
<td>$w_{t_v,i}$</td>
<td>Duration that truck $v$ waits at node $i$</td>
</tr>
</tbody>
</table>

Objective function:

$$\min \sum_{v,i,j} C_{i,j} (f_{v,i,j} - \eta \sum_{w} q_{v,w,i,j}) + \sum_{v,i,j} G_{i,j} \cdot f_{v,i,j} + \alpha \sum_{v,i,j} f_{v,i,j} (T_{i,j} + w_{t_v,i})$$ (1)

Constraints:

$$\sum_{j \in (i,j)} f_{v,i,j} - \sum_{j \in (j,i)} f_{v,j,i} = 
\begin{cases} 
1, & \text{if } i = O_v \\
-1, & \text{if } i = D_v \\
0, & \text{otherwise}
\end{cases} \forall v \in V, i \in I$$ (2)

$$-M(1 - q_{v,w,i,j}) \leq e_{v,i,j} - e_{w,j,i} \leq M(1 - q_{v,w,i,j}) \quad \forall v, w \in V, (i,j) \in E, v > w$$ (3)

$$\sum_{v} q_{v,w,i,j} \leq 1 \quad \forall w \in V, (i,j) \in E, v > w$$ (4)

$$q_{v,w,i,j} \leq f_{v,i,j} \quad \forall w \in V, (i,j) \in E, v > w$$ (5)

$$q_{v,w,i,j} \leq f_{v,j,i} \quad \forall v \in V, (i,j) \in E, v > w$$ (6)

$$-M(1 - f_{v,O_v}) \leq e_{v,O_v} - T_v^O - w_{t_v,O_v} \leq M(1 - f_{v,O_v}) \quad \forall v \in V, i \in I$$ (7)

$$w_{t_v,D_v} = 0 \quad \forall v \in V, i \in I$$ (8)

$$-M(2 - f_{v,i,j} - f_{v,j,i}) \leq e_{v,i,j} - e_{v,j,i} - w_{t_v,i} - T_{i,j} - f_{v,j,i} \leq M(2 - f_{v,i,j} - f_{v,j,i}) \quad \forall v \in V, (i,j), (j,k) \in E, D_v \neq i \neq O_v$$ (9)

$$e_{v,i,j} \leq M f_{v,i,j} \quad \forall v \in V, (i,j) \in E$$ (10)

$$w_{t_v,i} \leq M \left( \sum_{i,j} f_{v,i,j} + f_{v,j,i} \right) \quad \forall v \in V, (i,j) \in E$$ (11)

edge is equal to the time the last edge was entered plus the required time to travel on the last edge plus the waiting time at the current node. Constraints (10) and (11) set the time of entering an edge and the waiting time at a node of trucks to 0 if trucks do not pass that edge or node.
3.3. Data
3.3.1. Target Area
Currently, the Japanese government is conducting operational field tests of truck platooning on Japanese expressways [20]. It is said that Japan would be one of the first countries to achieve commercial operation of truck platooning. Thus, we set our sights on Japan.

It is reasonable to assume that, like other emerging technologies, truck platooning will be first deployed in some regions and not suddenly rolled out across the country. According to the report of the 10th Logistics Census [21], the flow of goods between the Tokyo-Nagoya-Osaka areas accounts for 30.3% of the national cross-regional cargo movement. Therefore, the Japanese government and some logistics companies are considering beginning the commercial operation of truck platooning on the expressways connecting these three cities, and many field tests have been done on the Shin-Tomei expressway [20]. It should be noted that only a few interchanges were available along the Shin-Tomei expressway in 2015 when the 10th Logistics Census was conducted. For this reason, we chose to use the Tomei expressway, which connects Tokyo and Nagoya, and the Meishin expressway, which connects Nagoya and Osaka, in our study on truck platooning. The Tomei and Meishin expressways have a combined length of 586 km and a total of 50 Interchanges, as indicated in Figure 1. Since trucks traveling in opposite directions cannot form a platoon, this study only focuses on trucks traveling the Tokyo to Osaka route.

![Figure 1. Target area: Tomei expressway-Meishin expressway.](image)

3.3.2. Nationwide Commodity Flow Survey of Japan
In Japan, a nationwide commodity flow survey is conducted to understand cargo movements. This Logistics Census [22] is conducted by the Ministry of Land, Infrastructure and Transport every 5 years. A questionnaire is sent to companies in various industries which deal with large shipments of cargo to obtain an overall understanding of freight transportation in Japan. In this study, we used the 10th Logistics Census in 2015. From the responses to this survey, we can extract detailed information about the three-day trips, including origin IC, destination IC, and the departure time of trucks which traveled on the expressway. This information was input into the model introduced above.

3.3.3. Data Processing
We obtained detailed trip data from the 10th Logistic Census, which contained 898,477 items of trip information of trucks generated between 20 October 2015 to 25 October 2015. Since such a huge volume of data cannot be used as direct input, we
performed two data processing tasks. First, since approximately 70% of trucks originating from this path (the Tomei and Meishin expressways) do not end up on this route, they had the potential to join a platoon for part of their trip. For these trucks, the “destination IC” was changed to the closest IC before they left this route.

In the original data, the trucks depart hourly, which is unrealistic. This may have been because the person who answered the questionnaire did not know the exact departure time of each truck and recorded the departure time on the hour for convenience. This was adjusted by adding a random time factor of 30 min to +30 min following the uniform to the original departure time. Furthermore, to reduce the effect of non-sampling error, all trip information was copied three times before adding the random time factor since the response rate of this survey is 38.5%.

As Figure 2 shows, a similar pattern distribution of the departure times of trucks on different days was found, with most trucks departing in the afternoon. To simulate the process of growth of truck platooning technology, 10 groups of trucks with different numbers (10%, 20%, . . . , 100%, of all trucks) were randomly selected from trucks that departed between 5 p.m. and 6 p.m. on 22 October 2015, and were assumed to be platoonable. To decrease the error caused by random sampling, sampling and numerical experiments were conducted 4 times.

![Figure 2. Distribution of the departure time of trucks.](image)

3.4. Input Values

The parameters used in the numerical experiments are listed in Table 2 with their values. Although different fuel consumption savings rates have been obtained from experiments on truck platooning, 10% is the most often used in calculations [23]. This study also adopts 10% as the fuel consumption savings rate in the general scenario. Truck drivers’ wages are calculated by different standards depending on the companies and the form of employment. This study assumes all drivers are paid according to their total working time, including driving time and waiting time to form a platoon at a standard of 50 yen/min. All trucks are assumed to travel on the highway at a constant speed of 80 km/h, even though the speeds of the trucks vary in practice. Fuel efficiency is set at 21.5 L/100 km no matter the brand and weight of the trucks, which means the fuel cost of one truck for 100 km is yen 2709 with an oil price of yen 126/L. The expressway toll of HDV is yen 47.39/km, assuming all trucks are equipped with ETC (electronic toll collection). With such parameter settings, the percentages of fuel cost, labor cost, and toll cost of the operation cost are 25%, 33%, and 42%, respectively.
Table 2. Parameters of numerical experiments.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$ (Fuel consumption saving coefficient)</td>
<td>0.1</td>
</tr>
<tr>
<td>$\alpha$ (drive’s wage)</td>
<td>50 yen/min [24]</td>
</tr>
<tr>
<td>Truck speed</td>
<td>80 km/h</td>
</tr>
<tr>
<td>Fuel consumption per 100 km</td>
<td>21.5 L/100 km [25]</td>
</tr>
<tr>
<td>Fuel price</td>
<td>126 yen/L [26]</td>
</tr>
<tr>
<td>Expressway toll</td>
<td>47.39 yen/km [27]</td>
</tr>
</tbody>
</table>

1 JPY = 0.008 USD.

That is, besides the length of each edge, there are 4 extra attributes: Fuel cost (yen), Time cost (min) and Toll cost (yen). Note that the time and fuel costs are not exactly proportional to distance (though very close) and are influenced by traffic conditions, the road gradient, and other factors in practice.

Mathematically, a longer planning horizon results in a higher platooning rate because more possibilities are considered. However, the uncertainties will be too many, and departure time will be delayed when plans are made too far in advance, compromising the benefits of truck platooning. The planning horizon is 60 min in this study, with platooning planning being updated every hour. In other words, a truck can only platoon with another if their departure time difference is within 1 h.

3.5. Indicators

To quantify the benefits and formation pattern of truck platooning, 4 indicators are presented in Table 3. Trucks in a platoon may obtain less fuel cost but more labor cost because of extra waiting time for drivers at the truck platooning formation facility. The total cost saving rate is the ratio of saved total operation cost of all platoonable trucks to the original total operation cost of all platoonable trucks. The matching rate is the ratio of the total platooning distance of all platoonable trucks to their total travel distance, representing the number of times opportunities to join a platoon are seized by those platoonable trucks. The fuel saving rate is the percentage of saved fuel cost obtained from truck platooning. The delay rate is the ratio of extra traveling time caused by waiting at a truck platooning formation facility, or making a detour, to the original travel time when no trucks stop to wait for others or make a detour. The delay rate could be regarded as an indicator of the logistics service quality.

Table 3. Several indicators.

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cost saving rate</td>
<td>$\frac{\text{Original total cost} - \text{Total cost with platooning}}{\text{Original total cost}}$</td>
</tr>
<tr>
<td>Matching rate</td>
<td>$\frac{\text{Platooning distance of all platoonable trucks}}{\text{Total distance of all platoonable trucks}}$</td>
</tr>
<tr>
<td>Fuel saving rate</td>
<td>$\frac{\text{Original fuel cost} - \text{Fuel cost with platooning}}{\text{Original fuel cost}}$</td>
</tr>
<tr>
<td>Delay rate</td>
<td>$\frac{\text{Travel time with platooning} - \text{Original travel time}}{\text{Original travel time}}$</td>
</tr>
</tbody>
</table>

4. Results

4.1. General Scenario

For the general scenario, no special policy is adopted to promote truck platooning, and the fuel consumption saving rate of the following trucks in a platoon is set to be 0.1. As explained in the last section, 10 groups of trucks with different numbers (10%, 20%, ..., 100%, of all trucks) were randomly selected from trucks that departed between 5 p.m. and 6 p.m. on 22 October 2015, and were assumed platoonable. To decrease the error caused
by random sampling, sampling and numerical experiments are conducted a total of four times. The results are shown as a boxplot, as seen in Figure 3.

Figure 3. Results of the general scenario (22 October 2015). The maximum number of platoonable trucks, which is the “100%” case, is 311: (a) Total cost saving rate; (b) Matching rate; (c) Delay rate; (d) Fuel saving rate.

Figure 3a shows the variation in the total cost saving rate as more and more trucks become platoonable. The total cost-saving rate of all platoonable trucks increases at first and then stabilizes at about 1.1%. In addition, even in the early stage, when the mark penetration of platooning technology is less than 50%, the cost-saving rate is already close to the maximum.

Figure 3b shows the variation in the matching rate as more trucks become platoonable. The matching rate first increases and then stabilizes at about 55% and even declines in some cases. This is because most of the benefits are obtained by trucks close by in terms of space and time, and there are always some trucks which are not suitable for joining a platoon because of their distance from the other trucks. Therefore, in the case of a larger number of trucks, it is more likely that the lonely trucks are included in the system, which leads to a reduced matching rate. As the almost straight orange line in Figure 4 demonstrates, the total distance of the trucks is proportional to the number of platoonable trucks. However, the platoon distance does not increase as quickly as the total distance, which results in a reduced matching rate in the later stage. Therefore, it is not necessary to upgrade all trucks in the network.
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Figure 4. Why matching rate decreases in the later stage (22 October 2015).

Figure 3c shows the variation in the delay rate as more and more trucks become platoonable. Like the matching rate, the delay rate first increases and then decreases. This is reasonable since it is more likely that a truck finds a partner to create a platoon when there are more platoonable trucks. Since there are considerable fuel savings, they would like to stop and wait for others. With a greater number of platoonable trucks, the wait to create a platoon would not be long; i.e., the delay rate would be reduced. For this reason, the total cost savings rate remains stable even though the matching rate is slightly lower in the later stage. While intuition would suggest otherwise, even without a hard constraint on arrival time, the maximum delay rate is only 1.4%, which is quite low. This is because the fuel cost saving of joining a platoon for 1 km is about 2.7 yen, while the extra labor cost of 1 min waiting is 50 yen. As a result, trucks prefer to stop for a long time only when the platoon distance is expected to be long. This route, however, is only 586 km in length in total.

Figure 3d shows the variation in the fuel saving rate as more and more trucks become platoonable. The fuel saving rate was found to have the same trend as the matching rate because fuel saving is proportional to the platoon distance.

In addition to those macro indicators, detailed matching results (like which section of the target path is crowded with truck platooning in a day) are important to understand the formation pattern of truck platooning. They also serve as the basis for making decisions regarding infrastructure construction. As Figure 5 illustrates, most platoons are formed in the morning and afternoon, corresponding to the distribution of the departure time of trucks. Since the expressway connecting outer cities of Tokyo, Nagoya and Osaka is more crowded with platoons, the development of facilities to support forming and dissolution of truck platooning is required near the interchange in the suburbs of these three major cities.
4.2. Other Scenarios

Countless computer simulations and field experiments have shown that a larger fuel consumption saving rate will be obtained through smaller inter-vehicle distance. Individual truck owners prefer a higher fuel consumption saving rate for lower operation costs. At the same time, the governments expect higher fuel consumption savings for lower carbon emissions. However, a short inter-vehicle distance will cause more wear and tear on roads and provide less time for drivers to react when accidents occur. Thus, there are some arguments for not reducing the inter-vehicle distance.

As the result of the general scenario shows, the cost-saving rate is low in the early initial stage. This may mean that no companies would like to upgrade their trucks in the first place, and the platooning technology will never be rolled out. To encourage trucks to join a platoon and increase the matching rate, toll discounts for trucks in a platoon should be provided. But whether such a strategy does increase the matching rate and fuel saving rate remains to be seen.

To answer the above questions, several scenarios are proposed. A comparison of the scenarios in Table 4 provides a better understanding of the effectiveness of the strategies: comparing scenario 1 (the general scenario), scenario 2 and scenario 3 indicates whether the inter-vehicle distance should be shorter, and a comparison of scenario 1 (the general scenario) and scenario 4 indicates the effect of toll discounts.

The results of scenario 1, scenario 2 and scenario 3 are shown in Figure 6. From a comparison of these scenarios, it can be concluded that a larger fuel consumption saving rate, and also a closer inter-vehicle distance, increases the total cost saving rate and fuel saving rate, while matching patterns, like the matching rate and delay rate, do not change significantly. Note that the matching and delay rates in each scenario are similar when the market penetration is more than 80% because of the increased ease of finding a partner for platooning when there are many platoonable trucks without a long wait. That is, trucks
which have the potential to join a platoon can always join a platoon, which would result in the same matching rate and delay rate even when the fuel consumption saving rate is different.

Table 4. A comparison of several scenarios provides a better understanding of the effectiveness of the strategies for promoting platooning technology.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>(\eta = 0.10)</th>
<th>(\eta = 0.08)</th>
<th>(\eta = 0.12)</th>
<th>30% Discount on Toll</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1 (general scenario)</td>
<td>√</td>
<td></td>
<td></td>
<td>×</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>√</td>
<td></td>
<td></td>
<td>×</td>
</tr>
<tr>
<td>Scenario 3</td>
<td></td>
<td>√</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>Scenario 4</td>
<td></td>
<td></td>
<td>√</td>
<td></td>
</tr>
</tbody>
</table>

The results of scenario 1, scenario 2 and scenario 3 are shown in Figure 6. From a comparison of these scenarios, it can be concluded that a larger fuel consumption saving rate, and also a closer inter-vehicle distance, increases the total cost saving rate and fuel saving rate, while matching patterns, like the matching rate and delay rate, do not change significantly. Note that the matching and delay rates in each scenario are similar when the market penetration is more than 80% because of the increased ease of finding a partner for platooning when there are many platoonable trucks without a long wait. That is, trucks which have the potential to join a platoon can always join a platoon, which would result in the same matching rate and delay rate even when the fuel consumption saving rate is different.

The results of scenario 1 and scenario 4 are provided in Figure 7 for comparison purposes. The total cost saving rate, matching rate and fuel saving rate in scenario 4 are clearly much higher because of the much-improved economic benefits of truck platooning because of the discounted toll. Therefore, this type of government subsidy for trucks in a platoon would accelerate the popularization of this technology. Note that although the cost-saving and matching rates are high, the delay rate is also high. To decrease the delay rate and improve the quality of logistics services, it may be possible for the government to subsidize platoonable trucks at a certain time of day, such as afternoon. This would have the effect of concentrating the platoonable trucks and making it easier to join a platoon without waiting too long.
5. Conclusions

In this study, an optimization model of coordinating truck platooning is developed and applied to actual survey-based data to estimate the benefits and formation pattern of truck platooning as more trucks become platoonable.

The numerical results reveal that the total cost saving rate and fuel saving rate obtained from truck platooning increase at first and then decrease as the market penetration of such technology grows. This is because some trucks, too far in terms of time and distance, will not be suited for joining a platoon even if most trucks depart in the afternoon and have a similar OD pattern along the target expressway. It will be easier to involve those single trucks when the market penetration of truck platooning is high. Rather than not encourage more trucks to upgrade, the government should encourage as many trucks as possible to be equipped with truck platooning technology. This would increase the numeric value of the reduction in fuel consumption even though the total fuel consumption “rate” of all platoonable trucks will be lower. Another implication is that truck platooning technology is not suitable for all trucks. It is better only to upgrade trucks which have a significant overlap in their spatio-temporal trajectory with other trucks to avoid reducing the cost-saving and matching rate in the later stages.

The maximum fuel saving rate of all platoonable trucks was just 5.7%. Since the transport sector accounts for around 24% of global carbon dioxide emissions, a reduction of 5.7% of fuel consumption and carbon emissions has significant meaning in sustainability. While a 5.7% reduction in fuel consumption and carbon emissions may be attractive to the government, it may not be attractive to individual truck owners, especially given the additional costs involved in upgrading their trucks with the required technology.
Therefore, it is recommended that truck manufacturing companies and governments pay more attention to the development of driverless truck platooning since this would significantly reduce operating costs and address the labor shortage.

Another interesting finding is that a larger fuel consumption saving rate and a toll discount encourages more platoonable trucks to join a platoon when there are a few platoonable trucks. However, when the market penetration of truck platooning technology is sufficiently high (for example, more than 80% in the numerical experiments of this study), the matching rate and delay rate in each scenario are remarkably close. Since the closeness of these rates does not depend on the value of the fuel consumption saving rate or whether the tolls are discounted when the market penetration of truck platooning technology is high enough, it can be concluded that a subsidy in the form of discounted tolls is only useful in the early stage to improve the matching rate. This is because when the market penetration of truck platooning technology increases, the benefits of truck platooning also increase because of less waiting time resulting in additional benefits from discounted toll or larger fuel consumption saving rate becoming insignificant.

It must be acknowledged that this study assumes that there will be a centralized coordinator, and all decisions are made to optimize the system benefits of all trucks while some trucks will be sacrificed, even if platooning is in their interests. This would be unfair in practice since not all trucks belong to the same company, and they will therefore not share the cost savings. Therefore, a reasonable benefits redistribution system may be needed to guarantee that each truck which joins a platoon will obtain the benefits they deserve.

A few extensions can be made to this study:

1. Since the Logistics Census is questionnaire-based and the response rate is not high, the trip information, including OD and departure time of trucks used in the numerical experiments, may not accurately reflect the actual situation. Efforts to obtain more accurate data of a specific area or a logistics company may result in improved results.

2. As discussed above, hybrid and driverless truck platooning is more promising than normal truck platooning. However, the operation of hybrid and driverless truck platooning brings further problems since the coordination and transfer of truck drivers is costly and complicated. Moreover, hybrid and driverless truck platooning have higher requirements to enable automated driving; these trucks are likely to exist alongside normal truck platooning with drivers in the following trucks. It would be interesting to consider such a scenario.

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