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Optimization of Platoon Formation Center Location for Truck Platooning in Turkey

Türkiye'de Kamyon Müfrezesi için Müfreze Oluşturma Merkezi Konumunun Optimizasyonu

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ABSTRACT

In Road Transportation, truck transportation is commonly being categorized into Less Than Truckload (LTL), Partial Truckload and Full Truckload (FTL). The standard LTL transportation is carried out by means of consolidated freight at optimized depots of designation, in the form of single or multiple assignment. Nowadays, freight transportation industry is now facing a serious problem of scarce labor force and environmental concerns. One solution for that is truck platooning. Truck Platooning is a grouping of freight vehicles into connected vehicle convoys using electronic coupling as an application in automated driving technology with the aim of saving fuel, reducing travel costs, and improving infrastructure efficiency. Platoon planning is required to obtain the best results of platooning. Therefore, the objective of this study is to find the optimal locations of Platoon Formation Center (PFC) in Turkey for (de)formation truck platoons by using discrete mathematical optimization.

Keywords: Truck Platooning, Logistics, Discrete Mathematics, Transportation, Optimization, Facility Location.

ÖZ

Karayolu Taşımacılığında, kamyon taşımacılığı yaygın olarak Kamyon Yükünden Az(LTL), Parsiyel Kamyon Yükü ve Tam Kamyon Yükü(FTL) olarak sınıflandırılmaktadır. Standart LTL taşımacılığı, tek veya çoklu atama şeklinde optimize edilmiş atama depolarında konsolide navlun vasıtasıyla gerçekleştirilir. Günümüzde yük taşımacılığı sektörü, artık kıt işgücü ve çevresel kaygılar gibi ciddi bir sorunla karşı karşıyadır. Bunun için bir çözüm kamyon müfrezesidir. Kamyon Müfrezesi, yakıt tasarrufu sağlamak, seyahat maliyetlerini azaltmak ve altyapı verimliliğini artırmak amacıyla otomatik sürüş teknolojisinde bir uygulama olarak elektronik kuplaj kullanan yük araçlarının bağlı araç konvoyları halinde gruplandırılmasıdır. Takım oluşturmanın en iyi sonuçlarını elde etmek için takım planlaması gereklidir. Bu nedenle, bu çalışmanın amacı, ayrık matematiksel optimizasyon kullanarak (de)formasyon kamyon takımları için Türkiye'deki PFC'nin en uygun yerlerini bulmaktır.

Anahtar Kelimeler: Kamyon Takımı, Lojistik, Ayrık Matematik, Taşıma, Optimizasyon, Tesis Yeri.

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1. INTRODUCTION

Road transport occupies a vital role of this transport system. It has high flexibility in trip scheduling, allowing a more frequent freight transport service. Road transport can be served as the initial and final transport phase in supply chain process, thus serving a bridge to connect with other transportation modes.

Nowadays, road freight transportation industry is now facing a serious problem of scarce labor force while, on the other hand, the transportation demand is growing very rapidly (Watanabe et al. 2021). Moreover, air pollution and global warming have become top concerns in freight transportation. To tackle such challenges, truck platooning technology has been adopted. A truck platoon is a convoy of electronically connected vehicles, which can be achieved by using Cooperative Adaptive Cruise Control(CACC).

In Japan, field operational tests on expressways have been conducted with manned following vehicles since 2017 and unmanned following vehicles since 2018 respectively. The optimal location models for truck platooning considering the case in Japan were presented by a continuous approximation model(Watanabe et al.2021) and a discrete mathematical optimization(Watanabe and Aung 2022). It is necessary to consider the optimal facility location that corresponds to the deployment of truck platooning in various countries. Therefore, the objective of this study is to find the optimal locations of Platoon Formation Center (PFC) in Turkey for (de)formation of truck platoons by using discrete mathematical optimization.

2. TRUCK PLATOONING CHARACTERISTICS

In fact, truck platooning is not a novel technology, and it has been reasonably researched since the 1940. So far, the focus area has been on the vehicle connection and sensor technology. Bhoopalam et al.2018 provided a framework to classify various new transportation planning problems that arise in truck platooning, as well as surveying relevant operational research models for these problems in the literature. Truck platooning scenario can be different depending upon trip information management. A platoon plan generally requires information such as (1) which trucks will form a platoon, (2) where and when the platoons will be created, (3) which routes they will travel, and (4) what is the order of the trucks in that platoon. Nevertheless, based on truck platooning management and trip information, three platoon formation scenarios have been mainly considered as follows (Janssen, 2015).

(1) Scheduled platooning: Trip information is obtained before travel and platoon management is made in advance. Therefore, this is also known as off -line or static planning.

(2) Opportunistic platooning: Platoons are formed spontaneously on the road between the trucks travelling at a proximity. This type of platoon planning does not require much trip information early or before departure. Since this platooning system does not need prior platoon planning, it is called spontaneous or on-the-fly platooning.

(3) Orchestrated Platooning: It is a platooning managed by Platooning Service Providers(PSPs). Platoon Formation Center(PFC) for (de)formation of platoons plays a vital role in this platooning technology.

It should be noted that platooning technology is still at its early stage, and it still needs a lot of infrastructure development and legal maturity for large-scale business operation and spontaneous platoon formation. There are still compatibility challenges existing for platoon creation among different truck makers. In addition, a simulation study by Liang et al. 2014 showed that there can be tremendous amount of economic and environmental benefits due to precise planning of platoons before their departure. Therefore, it can be concluded that some of platooning management is required to obtain the best results of platooning.

3. PLATOONING FACILITY CENTER (PFC) LOCATION MODELLING USING DISCRETE MATHEMATICAL OPTIMIZATION

3.1. Truck Platooning and Hub Location Research

Hub Location is a fertile area for multi-disciplinary research such as operation research, transportation, geography, network design, telecommunications, regional science, economics etc. (Campbell et al. 2012). Therefore, hub location research can also be applied to logistics industry in order to solve various economical and sociological problems(Kara and Tansel 2003, Alumur et al. 2009, Kara and Tansel 2009).

There is a need to locate the PFC for the formation of truck platooning to run unmanned operation in platoon (Watanabe et al. 2021). Larsen et al. (2019) presents a model for optimizing truck platoons formed at a PFC at a fixed location using a dynamic programming based local search heuristics. PFC optimizing problem can be considered as hub location problems (HLPs) and there are a lot of related studies for hub location optimization for logistics operation (Laporte et al. 2015). Considering discrete optimization scheme, truck platooning operation can be modelled by using inter-hub travel (inter-PFC in the case of truck platooning). There will be cost efficiency benefit for inter-PFC travel, due to fuel saving and reduction in aerodynamic drag between trucks. There have been a lot of research about discount factor calculation in hub location research. Almost all researchers consider discount factor calculation on the grounds of economies of scale. When we model truck platooning scenario, it will be reasonable to consider the discount factor calculation due to other factors rather than freight consolidation. The factors that can reduce the cost in truck platooning can be the number of trucks in a platoon and the driving system of the truck platooning and so on. So far, there has been almost no research which discusses about truck platooning discount factor except a recent study by Watanabe et al. (2021) and Watanabe and Aung (2022) about unmanned platooning system in Japan. He considered discount factor calculation based on the number of trucks in a platoon and the vehicle driving system such as manual or automated. Apart from that, there has been very few research about PFC optimization for truck platooning.

3.2. Modelling

The hub location model has started gaining its popularity since O’Kelly (1987) adopted a single allocation P-hub location problem. Almost all later hub location models and heuristics algorithms are developed based on this model. In this model, it is necessary to locate exact number of hubs exogenously. This is a discrete mathematical model problem where the number of participant nodes is finite. As the model’s name suggests, each non-hub node is allocated to exactly one hub node out of p nodes. This model assumption is also based on complete graph in which there is a complete connection between each and every hub node. There is also a constraint that travelling between two non-hub nodes needs to go through two hubs at most, i.e. there is no direct connection between non-hub nodes. The fixed cost of locating hubs is not considered. There is no consideration of capacity limit of the hubs as well. All decision variables of the model are binary variables.

The problem with the above formulation is that there is a quadratic term, which makes the optimization relatively difficult to be solved. Since O’Kelly (1987) first introduced such discrete hub location problem, there were rapid advances in mathematical models which attempted to locate the exact solutions in several hub location networks. A large number of research was also carried out and an example of this was that Campbell (1994) reviews over 70 papers on hub network optimization. O’Kelly and Miller (1994) also identified several prototype models for hub network design analysis. The two most well-known versions of design networks are based on completely connected hubs, with two types of spoke-hub connectivity— single allocation and multiple allocation. In both assignments, the hubs are assumed to be completely connected and all flow must be through hubs. A linearization developed by (Skorin-Kapov et al., 1995) gives an effective method of finding solutions especially in case of small hub and spoke network models.

3.3. Multiple Allocation

As the name suggests, all the origin and destination nodes are assigned to more than one PFC node. There can be multiple network assumptions based on how PFC nodes are connected with each other. In our analysis, we will consider the complete connection among all PFC nodes as shown in the following figure.

In Fig 3.1, all the yellow nodes serve as origin, blue as PFC and orange as destination. The thick red arrows represent the complete connection among PFC nodes without any detour. In the multiple assignment hub location (Campbell, 1994), each origin-destination pair is allowed to utilize the hub that will give the lowest travel cost, independent of how this flow can produce a large amount of interaction. As a result, the objective function can minimize the total travel cost for the system. A compact formulation of that model, known as HUBLOC (Skorin-Kapov et al. 1997) is as follows, which is used in our analysis.

Minimize $\sum_{i,j} \sum_{k,m} t_{ij} c_{ij}^{km} z_{ij}^{km}$, where $c_{ij}^{km} = c_{ik} + \alpha c_{km} + c_{mj}$ [3.1]

Subject to

$\sum_k X_k = P$ [3.2]

$\sum_{k,m} z_{ij}^{km} = 1 \ \forall \ i, j$ [3.3]

$\sum_m z_{ij}^{km} - X_k \leq 0 \ \forall \ i, j, k$ [3.4]

$\sum_m z_{ij}^{km} - X_m \leq 0 \ \forall \ i, j, k$ [3.5]

$X_k = [0,1] \ \forall \ k$ [3.6]

Let's consider the transportation networks modelled by complete graphs *G=(V,E)*, where the node set *V = {1,2,….,n}* represents the origin, destination and possible hub locations. Let tij be the number of trucks (the total flow in the classical model) travelling from node i to node j. The cost c_{ij}^{km} is a total cost of (from origin i to PFC k), αc_{km} (discounted inter-PFC cost) and c_{mj} (from PFC *m* to destination *j*). Constraint (3.2) ensures that the number of PFCs (*P*) is determined exogenously. Constraint (3.3) ensures that all flow be routed via exactly one path. Constraints (3.4) and (3.5) prevent flow from being routed via a non-PFC node. All flow must travel through at least one PFC. Constraint (3.6) ensures the integrity of the decision variable.

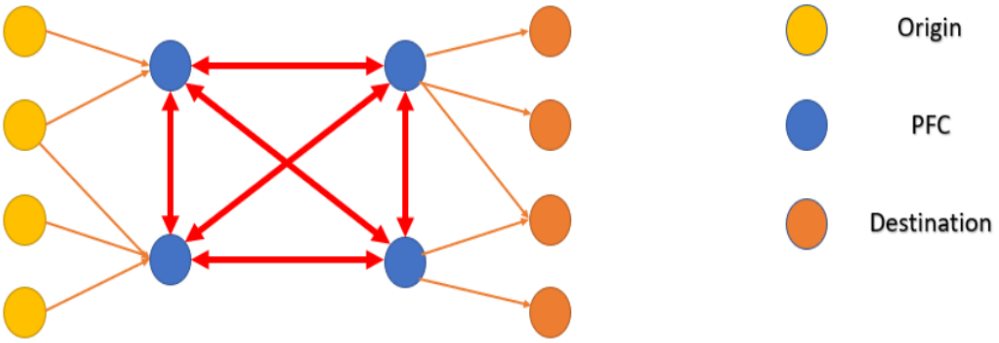


***Fig 3.1** Complete Connection among PFC nodes (Multiple Assignment)*

3.4. Multiple Allocation

Similar to multiple allocation, the complete connection among the PFC nodes is assumed as in the following figure.

It can be noted that in Fig 3.2, all origin and destination nodes are connected to each respective PFC node via a single link. From the modelling perspective. the following model by Skorin-Kapov (1996) is used for single assignment in our study. This model is a LP relaxation of Campbell (1996b).

$$\text{Minimize } \sum_{i,j}\sum_{k,m} t_{ij}\, c_{ij}^{km}\, z_{ij}^{km}\text{ , where } c_{ij}^{km} = c_{ik} + \alpha c_{km} + c_{mj} \qquad [3.7]$$

Subject to

$$\sum_k X_{kk} = P \qquad [3.8]$$

$$\sum_k X_{ik} = 1\ \forall\, i \qquad [3.9]$$

$$X_{ik} \le X_{kk}\ \forall\, i, j \qquad [3.10]$$

$$\sum_m z_{ij}^{km} = X_{ik}\ \forall\, i, j, k \qquad [3.11]$$

$$\sum_m z_{ij}^{km} = X_{jm}\ \forall\, i, j, m \qquad [3.12]$$

$$z_{ij}^{km} \ge 0\ \forall\ i, k \qquad [3.13]$$

$$X_{ik} = [0,1]\ \forall\ i, k \qquad [3.14]$$

Constraint (3.8) ensures that the number of PFCs, which is *P*, is determined exogenously. Constraint (3.9) forces single assignment. Constraint (3.10) ensures that no node is assigned to a location unless it is a PFC. Constraints (3.11) and (3.12) determine that there must be only one flow through the link *i-k-m-j*. Constraints (3.13) and (3.14) determine the decision variables. The objective is to minimize the total transportation cost for the trucks travelling through the *i-k-m-j* link.

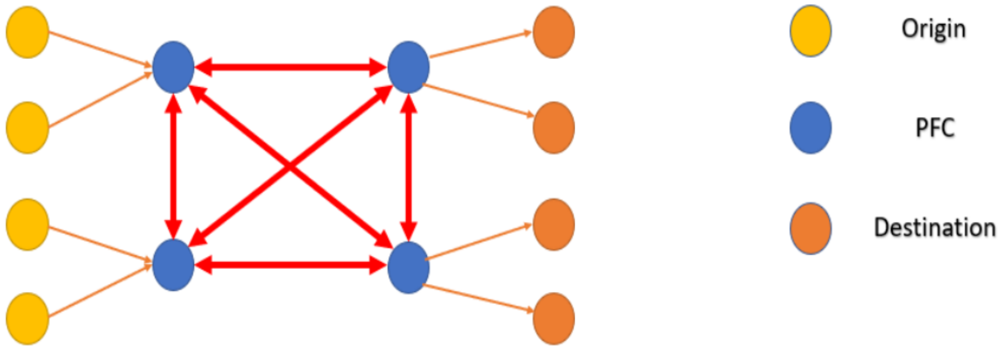


***Fig 3.2** Complete Connection among PFC nodes (Single Assignment)*

3.5. Platooning Discount Factor Calculation

Watanabe et al. (2021) considers the discount factor calculation thanks to truck platooning. The discount factor calculation in truck platooning should be different from the traditional calculation of discount factor which highly depends on trade flow due to economies of scale. Truck platooning mainly benefits from the platoon in which trucks travel together, which must be included in the discount factor calculation. Driving at a close distance between trucks reduces the aerodynamic drag between them, which leads to the reduced fuel emission and cost saving.

The normal truck travel costs without platooning can be calculated as follows.

$$Ts = sn \quad [3.15]$$

The truck travel costs without platooning (Ts) can be calculated as the single truck travel cost (s) multiplied by the number of trucks (n). In the case of platooning, there will be two different types of truck travel costs— the first leading truck travel cost and the following truck travel costs because these two types of costs are different due to aerodynamic properties. The truck travel costs in the case of platooning can be calculated as follows.

$$Tp = a + (n - 1)b \quad [3.16]$$

The platooning truck travel cost is calculated by the leading truck travel cost (a), the following trucks travel cost (b) and the number of vehicles (n). We will always assume that s>a, s>b and a>b. The discount factor (α) is simply the ratio of the platooning truck travel costs (Tp) to the normal traveling truck costs (Ts), which can be calculated as follows.

$$\alpha = \frac{T_p}{T_s} = \frac{a+(n-1)\,b}{sn} \quad [3.17]$$

From the equation (3.17), it is obvious that the discount factor (α) is highly dependent on platooning trucks travel costs (a and b) and the number of platooning trucks (n). If we can decrease a and b, and increase n; we can hypothetically assume that we can enjoy more of the benefits of the platooning discount factor (α).

3.6. Platooning Scenario

In this section, we will consider the parameter settings for calculating discount factor (α). Watanabe et al (2021) assumes that based on Japan condition, the ratio of the labor costs in the trucking industry is around 40 % , which implies the cost difference between unmanned and manned driving. When it comes to the fuel saving due to platooning, leading vehicle can enjoy around 10% and the following vehicles around 20%.We assume the same parameter settings based on the aforementioned Japan condition. As a result, three platooning scenarios can be considered as follows.

In the table 3.1, for scenario I, when there are all manned trucks in a platoon, there will be cost saving benefit solely due to the platooning. When the trucks are unmanned in the scenario II and III, the platooning benefits can be added by the labor cost saving benefits, leading to more saving in total travel cost. Therefore, in scenario II, the cost saving for the following trucks becomes 60% (20% + 40%), leading to the discount value 0.4. In the case of unmanned scenario III, not only the leading vehicle has the discount value benefit of 50% (10% + 40%), but also the following vehicles have the discount value benefit of 60% (20% + 40%). The number of platooning trucks is restricted depending upon each country's regulation requirement. In our analysis, the number of platooning trucks is hypothetically varied from 3 to 10 in order to provide a wide range of discount factor value, which can be analyzed for its impact on total travel cost in both single and multiple assignments. As a result, the following table 3.2 is obtained.

In the table 3.2, for platooning scenario I, although the number of platooning trucks is hypothetically varied from 3 to 10, α value does not change much and stays around 0.8. Therefore, we assume the average α value as 0.8 in manned platooning scenario, for all number of platooning trucks from 3 to 10. For unmanned following vehicles in scenario II, the number of platooning trucks from 4 to 10 provides α value around 0.5. For almost all the instances at which our optimization are made, α values 0.6 and 0.5 give the same PFC. Similarly, the platoon of all automated vehicles gives the α value of around 0.4. Therefore, it can be summarized that in each platooning scenario, the discount factor value does not change very much for a range of number of platooning trucks from 3 to 10 and hence, it gives almost the same optimal PFCs for each instance in each scenario. In other words, the number of platooning trucks do not have much impact on discount factor for each different platooning scenario.

Table 3.1 *Three platooning scenarios based on different driving systems*

No	Scenario	s	a	b
I	Platoon with all manned vehicles	1	0.9	0.8
II	Platoon with unmanned following vehicles	1	0.9	0.4
III	Platoon with all fully automated vehicles (FAVs)	1	0.5	0.4

Table 3.2. *Three different platooning scenarios based on the number of platooning trucks*

Scenario		s	a	b	n	α
I	Platoon of all manned vehicles	1	0.9	0.8	3—10	0.8
II	Platoon with unmanned following vehicles	1	0.9	0.4	3	0.6
					4—10	0.5
III	Platoon of all fully automated vehicles (FAVs)	1	0.5	0.4	3—10	0.4

3.7. Computational Environment

All optimization instances are carried out by using XpressIVE 8.11 commercial optimizer. Regarding the device specification, Intel Xeron Bronze 1.9 GHz (16 CPUs) computer with 32768 MB RAM, and 1 MB Cache was used for data analysis. Computation time highly depends upon computational complexity. It was found out that single assignment takes a wide range of duration, ranging from half an hour to even more than 12 hours in rare cases. In addition, more PFC node assignment also lead to more computational duration, regardless of single and multiple allocation. Multiple assignment generally takes about 2-3 hours as an average.

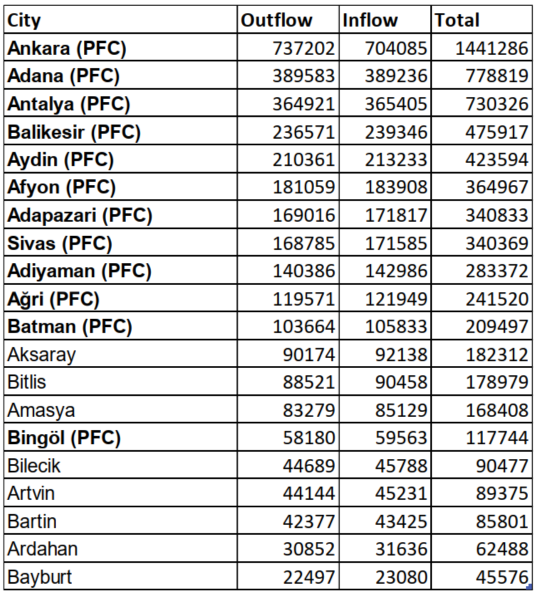
4. OPTIMIZATION

4.1. Dataset

The dataset is the Turkish Network Dataset with Freight Transported provided by Kara, B.(https://ie.bilkent.edu.tr/~bkara/dataset.php), which includes 81 cities as demand nodes. This includes different data for travel distance, travel times, freight flow and fixed link costs for Turkish 81 cities. As a benchmark size, we took 20 cities which represent uniform distribution across the region as shown in Figure 4.1. For the simulation of truck platooning, we took the freight flow in Table 4.1 and travel time data.

Figure 4.1. *Turkish Dataset Spatial Distribution Pattern*

***Table 4.1**. Decreasing Order of Trade Flow*



City	Outflow	Inflow	Total
Ankara (PFC)	737202	704085	1441286
Adana (PFC)	389583	389236	778819
Antalya (PFC)	364921	365405	730326
Balikesir (PFC)	236571	239346	475917
Aydin (PFC)	210361	213233	423594
Afyon (PFC)	181059	183908	364967
Adapazari (PFC)	169016	171817	340833
Sivas (PFC)	168785	171585	340369
Adiyaman (PFC)	140386	142986	283372
Ağri (PFC)	119571	121949	241520
Batman (PFC)	103664	105833	209497
Aksaray	90174	92138	182312
Bitlis	88521	90458	178979
Amasya	83279	85129	168408
Bingöl (PFC)	58180	59563	117744
Bilecik	44689	45788	90477
Artvin	44144	45231	89375
Bartin	42377	43425	85801
Ardahan	30852	31636	62488
Bayburt	22497	23080	45576

4.2. Optimization Analysis

Multiple PFC allocation can also reduce the travel cost considerably. Figure 4.2 is the graphs which show the total travel cost of the different datasets in cases of single and multiple assignment with respect to the number of PFCs. For all platooning scenarios, increasing the number of PFCs can significantly reduce the total travel cost, no matter whether the PFC assignment pattern is single or multiple allocation. However, the decline rate of the cost becomes less steep when the number of platooning trucks becomes larger. For example, the travel cost reduction rate is quite noticeable from two to five platooning trucks but becomes less significant when the number of PFCs becomes larger.

The nodes with the larger trade flows mostly serve as PFCs. The trade flow here is defined by the total value of incoming and outgoing flows. Incoming trade flow of a node is the total value of the trade flows coming to that node from the other nodes. Outgoing trade flow of a node is the total value of the trade flows going out of that node to the other nodes. Therefore, trade flow value of a node shows how much trade is flowing through that certain node and how strategically important that node can be in terms of trade volume for the whole transport system. In table 4.1, all nodes which appear as PFCs in optimization instances are described as PFC besides their names. The table is sorted in decreasing order of trade flows, i.e. the nodes in the top positions have a larger trade flow than the ones in the bottom positions. It is easily noticeable that the nodes with the larger trade flows mostly appear as PFCs in most optimization instances with some exceptions. Moreover, most of the nodes with the lower trade flows never appear as PFCs as well. Therefore, it can be reasonably concluded that the nodes which have greater importance in terms of trade flow have high possibility to become PFCs in all platooning scenarios and assignment systems.

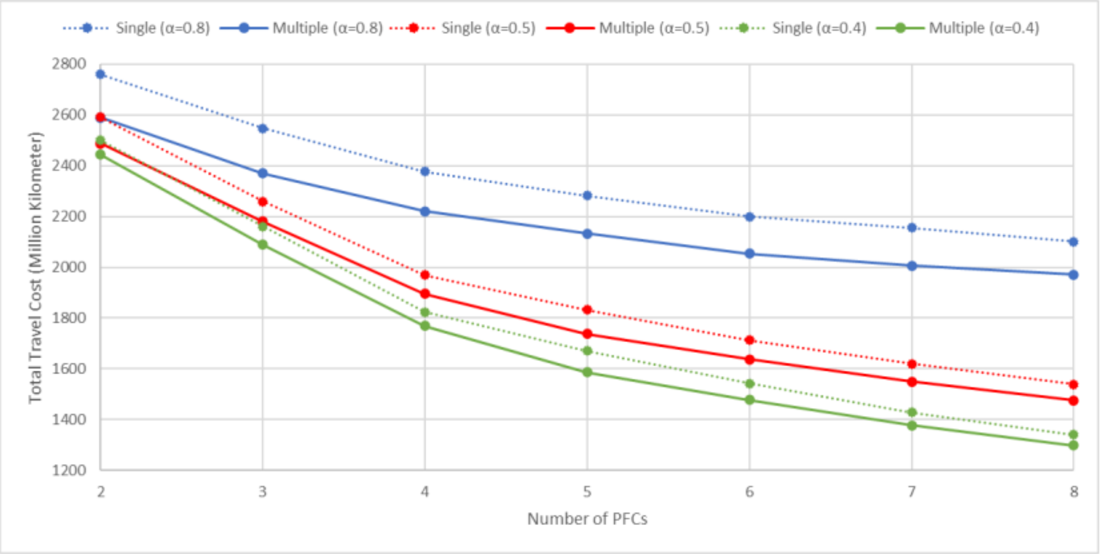


Fig 4.2 *Travel Cost with respect to the number of PFCs in Turkey*

4.3. Optimal Location

As discussed above, the platoon driving system has high impact on α value. That α value, in turn, has a certain degree of impact on PFC location. The lower α value makes PFC locate at a far distance between two PFCs. The reason is that when there is much inter-PFC benefit, the trucks have much interest to travel by platooning for a larger distance. Therefore, in other words, unmanned platooning scenarios tend to have further PFCs than manned platooning scenario.

From figures 4.3 and 4.4, when α value is 0.8, PFCs tend to locate closely, with not much great distance between them. When it comes to α value 0.5, even for the same number of PFCs which is 4, PFCs tend to locate at a far distance. The PFC location at Sivas from figure 4.3 shifts towards Bingöl in figure 4.4. This same characteristic can also be found in Japan dataset as well(Watanabe and Aung 2022).
When it comes to multiple assignment, PFCs do not change a lot depending upon α value, at least as frequently as what it happens in single assignment. For example, when we will decide to assign four PFCs in multiple assignment, the same four PFCs appear no matter what α value is, which in other words, no matter what the platooning scenario is. This finding is same for all these three datasets. So, it can generally be concluded that multiple assignment is less sensitive to platooning scenario variation which can lead to different α values.

Fig 4.3 *PFC location (yellow-colored) in Turkey when α value is 0.8 and the number of PFCs is 4 with single assignment*

Fig 4.4 *PFC location (yellow-colored) in Turkey when α value is 0.5 and the number of PFCs is 4 with single assignment*

5. CONCLUSION

For platooning operation, it is very important to strategically locate PFCs for several objectives and one of which includes reduction in total transportation cost, just like any other hub location problems. However, for PFC location problem, it is also very important to include the assumption of cost reduction due to platooning in our PFC location model to better reflect the realistic benefit of the truck platooning, unlike economic scales in other normal hub location models. From our analysis, the conclusions including the following points but not limited to, can be made.

(i) Increasing the number of platooning trucks in each platoon cannot significantly bring down the inter-PFC travel cost between two platooning hubs. Changing the platooning system from completely manned driving to semi-unmanned or totally unmanned driving system can reduce the inter-PFC travel reasonably.

(ii) If trucks from a specific origin can be assigned to more than one single PFC, it can reduce the total travel cost considerably as well. Therefore, it can be summarized that increasing the number of PFCs or allowing multiple PFC assignment system can reduce the total travel cost more than increasing the number of platooning trucks in a platoon.
(iii) Lower inter-PFC discount factor means that truck platoons can enjoy more of the platooning benefit. Therefore, lower inter-PFC discount factor can generally lead to larger inter-PFC distance. This characteristic is more commonly found for single assignment. In other words, optimal PFC location in multiple assignment is less sensitive to discount factor variation or different platooning scenarios.
(iv) Nodes with the larger trade flows tend to appear as PFCs repeatedly in almost all optimization instances, regardless of the spatial distribution pattern of the dataset. Most of the nodes with lower trade flows never appear as PFCs in all optimization instances.
For future study, we need to consider the optimal location model for a large scale model with the actual transport demand and road networks.

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