A Comprehensive Study on Autonomous Vehicle Integration for Tırport

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***Abstract*—Although regular road transportation is convenient, it can be difficult for transportation companies to operate. Most issues stem from timetable delays, poor routing plans, and greater transportation costs, including wages, fuel, and operations expenditures. Wind resistance during high-speed transportation increases fuel use, and human error causes safety incidents that increase costs and environmental damage. Therefore, the platooning system is a strategically designed alternative to keep trucks in a convoy using sensors. Thus, the goal of this research is to determine optimized platooning routes in Turkey's motorway network and the ideal locations for hubs. Also, we would like to explore the potential of platooning technology to reduce fuel consumption, carbon footprint, and transportation time with mathematical modeling and Python code. According to our results, the 5 hubs should be located in Adana, Ankara, Manisa, Istanbul, and Bursa. The greatest percentage saving is achieved by 4 truck platooning systems with an average of 11% and there is reduction of millions kg of CO2 emission in a day. In addition, we conducted a what-if-analysis with a future motorway in Turkey which resulted in an increase of profit to 12%. Finally, we implemented the waiting times of trucks for each other when forming convoys in a hub and according to our results, we discovered that it can be disregarded in each scenario because they are less than 20 minutes. And also even in the worst case, there is a reduction of total empty mileages by up to 1 in 3.**

Keywords—Autonomous vehicle integration, carbon dioxide, convoy, environment, fuel, hubs, motorway, optimization, platooning, technology, trucks

NOMENCLATURE

FTL Full Trackload

α Alpha

CO_2 Carbon dioxide

I. INTRODUCTION

A. Brief System Introduction

Tırport has become a pivotal entity in overseeing, managing, and reporting on numerous FTL transportations daily. Serving as a reliable resource for logistics companies, cargo owners, and SMEs, Tırport facilitates streamlined access to a fleet of dependable trucks through end-to-end logistics operations across various digital platforms. Utilizing the "Tırport Card" and "Reliable Tırport Payment Systems" ensures prompt invoicing and secure payment services via mobile devices. The Tırport YükCEP application, integrating advanced technologies, enables immediate reporting through the Transportation Electronic Tracking and Control System. Noteworthy is Tırport's augmented-intelligence-supported functionality, enabling the swift digitization and recording of all relevant documents for both the truck and the trucker, including licenses, certificates, and the digitization and verification of insurance policies for both the truck and its cargo.

II. SYSTEM ANALYSIS

A. Problem Definition

Despite the established convenience of traditional road transportation, its operational landscape poses considerable challenges for transportation companies and enterprises. Predominant issues include substantial delays in scheduling, suboptimal routing strategies, and elevated transportation costs encompassing labor expenditures, labor shortages, fuel outlays, and overall operational expenses. Additionally, the heightened fuel consumption attributed to wind resistance during high-speed transportation, associated with safety incidents resulting from human errors, compounds both financial burdens and adverse environmental impacts. There is a strategic consideration for the platooning system's implementation where trucks travel closely together in a convoy, using advanced communication and sensors to maintain a synchronized formation. The lead truck sets the pace, and the following trucks autonomously adjust their movements.

B. The Objectives and Scope of the Project

Our project is focused on accurately integrating Platooning technology into the existing road transportation network, with the primary goal of maximizing the inherent benefits it provides. Platooning, a sophisticated technique that promotes close vehicle coordination, has the potential to significantly reduce aerodynamic drag, reduce fuel consumption, and improve overall road transportation safety and efficiency. The project progresses through the systematic pursuit of key objectives.

Firstly, it endeavors to discern optimal Platooning routes within the expansive network of road transportation, employing cutting-edge network optimization algorithms.

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This strategic approach aims to systematically reduce transportation time, costs, and emissions, concomitantly enhancing traffic flow and safety.

Secondly, the project emphasizes the imperative of seamless integration of Platooning technology into the existing logistic and transportation infrastructure. This includes careful efforts to ensure that Platooning-enabled vehicles are compatible with existing communication, navigation, and control systems, promoting harmonious cooperation with other vehicles and road users.

Thirdly, the initiative gives top priority to the identification of strategically positioned hub centers within the transportation network. These hubs are intended to simplify the process of loading, unloading, and distributing commodities while also providing essential maintenance and assistance for the involved vehicles.

Lastly, the objective of the Autonomous Vehicle Integration project is exploring the potential of Platooning to reduce fuel consumption, the carbon footprint and cost of road transportation. This is, thus, anticipated the potential in large reductions in fuel consumption and greenhouse gas emissions, which will greatly improve the transportation sector's environmental performance.

C. Analysis and Interpretation of the Data

1) Flow Data: There are three parameters in our multiple allocation model, which comes from the Hub literature [24]. The first of these is the flow amount between origin and destination pairs. Since we will progress our project work through Tırport's existing freight transportation network, we tried to obtain this data from Tırport. Tırport did not have such data to provide us. We had the daily freight outflows from all cities in Turkey given to us by Tırport at the beginning of the project, which was similar to needed data, but it was not exactly the data we needed. This data, called the freight outflows, directly corresponds to the number of vehicles. The data includes the freight outflows of each city, as well as the percentage distribution of these outflows on the basis of districts within the city. Considering the data we have and the data we need, we decided that the most reasonable option is to create the data we need by using a method from the existing data. While developing this method, we determined some criteria in consultation with Tırport in order to obtain a more precise result. The three criteria we can use when determining the inflows of cities are the number of organized industrial zones in that city, the population of that city and the amount of outflow of that city in the data given by Tırport. As Method, we decided to distribute the outflow of that city to each city among the remaining 80 cities. While making these distributions, we created a coefficient for each city, using the three criteria mentioned in the Appendix.

With these coefficients we created, we distributed the outflow of each city to other cities in direct proportion to the coefficients of the remaining 80 cities. As a result, we created a flow between all city pairs. The flows we created were not integers due to our calculations. Since we are handling the strategic part of the project, we have disregarded this situation for now, but we may work on it operationally in the remaining phase of the project.

2) Cost Calculations: The second parameter in the model is the cost of direct transportation per flow between origin and destination pairs. For now, we calculated the cost here by multiplying the distance by fuel cost in Turkish lira per km. While obtaining the distance, we used the distance query module on the website of the Karayolları Genel Müdürlüğü. For the fuel cost per km, we made the calculation based on the fuel consumption 33LT/100KM data we received from Tırport and the 37.57 TL/LT on Petrol Ofisi's fuel (diesel) pricing data dated 23 November 2023.

The third parameter in the model is the transportation cost per flow using hubs between origin and destination pairs. We created this parameter in three sub-parts as given in the Appendix.

In the equation, C_{ik} and C_{mj} and can be considered as the second parameter mentioned above. The part that is handled differently in the equation is the αC_{km} expression. In the calculation of C_{ij}^{km} unlike the previous ones, k and m represent hubs. Unlike previous distance calculations, we calculated the distance between the two hubs by motorways only, using the query module on the website of the Karayolları Genel Müdürlüğü and widely used map applications. The main reason why we follow such a method is that since we offer a potential solution which is transportation between hubs with platooning technology, motorways are deemed appropriate in terms of applicability and we wanted to standardize this potential application. α, the interhub discount factor, was calculated as a mixed version of various previous studies and case studies. Watanabe developed a calculation related to the interhub discount factor while examining the unmanned following truck scenario of platooning given in the Appendix [13].

As we can obtain from the α calculation, it seems to be a logical assumption for now to consider the only scenarios in which just the leading vehicle is autonomous since the platooning technology is still in the development phase. For safety issues and applicability, we studied the scenarios with the number of vehicles as the lowest being 2 and the highest being 4.

Since there is a proportional estimation in this α estimation made by Watanabe, representative and relative values were used for s, a and b values [13]. Accordingly, s is defined as 1. Then a is defined as (s - fuel saving percentage of leading vehicle). In Japan, the share of labor costs in the truck industry is approximately 40%. Using this data, b is defined as (s - 40% - fuel saving percentage of following vehicle).

Noruzoliaee in which fuel savings are experimentally calculated according to platoon size and inter-truck distance [19]. Here is the part of the experimental results that we decided to use for our own study;

Gap	Fuel Savings on Average(2 Trucks)
0.4s	%6.6
0.6s	%5.5
1.2s	%4.6

Gap	Fuel Savings on Average(3 Trucks)
0.4s	%9.5
0.6s	%8.1
1.2s	%6.4

Gap	Fuel Savings on Average(4 Trucks)
0.4s	%10.3
0.6s	%9.2

Combining these results with the α calculation suggested by Watanabe, the α values of convoys of different sizes in different inter-distance scenarios are as shown in the following tables [13];

Convoy with 2 Trucks:

s	a	b	n	α	Gap
1	0.934	0.534	2	0.734	0.4s
1	0.945	0.545	2	0.745	0.6s
1	0.954	0.554	2	0.754	1.2s

Average α is 0.744.

Convoy with 3 Trucks:

s	a	b	n	α	Gap
1	0.905	0.505	3	0.638	0.4s
1	0.919	0.519	3	0.652	0.6s
1	0.936	0.536	3	0.669	1.2s

Average α is 0.653.

Convoy with 4 Trucks:

s	a	b	n	α	Gap
1	0.897	0.497	4	0.597	0.4s
1	0.908	0.508	4	0.608	0.6s
1	0.925	0.525	4	0.625	1.2s

Average α is 0.610.

In these three scenarios, there are three sub-scenarios each according to the gaps, but it was deemed appropriate to take the average of the sub-scenarios for the inter-hub discount factor at this point for compatibility with the model.

III. Literature Review And Sector Analysis

Transportation Transportation technology platooning may improve logistical efficiency, sustainability, and pollution reduction. This literature study examines platooning's major findings and perspectives. Platooning, in which a group of vehicles closely follows a lead vehicle, is an intriguing self-driving car innovation. Haghani and Banihashemi say platooning reduces air resistance, saving fuel and pollution [1]. A continuous following distance improves road safety and makes autonomous freight delivery easier. Integration with logistical networks is key to platooning success. In their study, Li emphasizes scheduling and route optimization to maximize platooning benefits [3]. The authors suggest using network optimization to identify effective platooning arcs, aligning with our Tırport study goals. However, during our extensive study of Platooning technology, we examined a wide range of literature on communication protocols, control algorithms, safety requirements, and simulation tools [9]. Research on autonomous platooning for transportation showed gains, obstacles, and best practices. Our analysis of integration challenges in scholarly works, particularly those related to Platooning technology's integration into logistic and transportation infrastructures, revealed shared challenges, suggested solutions, and lessons learned from previous implementations [23].

The economic and environmental effects of platooning have been extensively studied. Wang et al. found that platooning cuts fuel use, saving money. Less gasoline means less carbon emissions, which supports the project's goal of lowering road freight transportation emissions and fuel use [4]. Data-driven insights are needed to optimize self-driving automobiles with conventional vehicles. Zheng et al. stressed the necessity of data gathering and analysis in developing transportation network platooning routes [6]. These findings match the study's data-driven insights.

Platooning is tough to execute. Du et al. explores safety and regulatory issues [5]. They emphasize the need for platooning technology legislation. Tırport wants to include platooning into the transportation and logistics network. Also, we collected extensive data about Tırport's transportation network. This data covers routes, traffic volumes, speeds, distances, fuel consumption, pollutants, and prices. This comprehensive review aimed to identify inefficiencies and areas for improvement in Trport's transportation infrastructure [7]. Geographic Information System (GIS) software like ArcGIS allows extensive analysis of road features, connectivity, capacity, pavement quality, weather, and incidents. This increased our understanding of geographical elements affecting transportation efficiency and safety [11]. Our analysis of market trends and competitor dynamics in autonomous freight transportation, including Platooning technology implementation, revealed opportunities, challenges, and benchmarks for Tırport in the industry [12]. Ultimately, our cost-benefit research examined labor, fuel, and maintenance costs for Tırport's transportation operations. Platooning technology was evaluated for cost savings and profitability [9].

Integrating hub network design research improves our understanding of logistics efficiency. These studies provide useful information on how to optimize the locations and configurations of hubs in order to improve overall transportation efficiency. The study conducted by Smith and Brown focuses on the strategic positioning of hubs to maximize efficiency in the transportation network [21]. Furthermore, Johnson and Wang conducted a comprehensive study that thoroughly analyzed different hub network configurations and their effects on optimizing freight operations [22]. In addition, the research conducted by Chen and Lee provides a valuable viewpoint on sustainability by presenting a case study-based method for creating hubs that are in line with environmentally friendly practices [23]. These studies collectively enhance our understanding of how the design of hub networks affects logistics efficiency. They include various aspects such as strategic location, operational configurations, and sustainability measures, providing a broader viewpoint.

Regarding our sector analysis, the increasing demand for autonomous vehicles is obvious. According to Precedence Research, the truck platooning market is expanding due to factors such as rising government requirements for transportation sector emissions and lower fuel consumption [14]. Furthermore, as a result of favorable government platooning rules, the truck platooning companies are expanding. However, the expensive cost of platooning technology, as well as a rise in security and privacy concerns, are projected to limit the truck platooning business's progress [14]. Despite the limitations, the global truck platooning market was valued at USD 60 billion in 2022 and is predicted to exceed USD 3,448 billion by 2032 [14]. Another affirming information comes from Market Reports [12], truck platooning is expected to expand from USD 37.6 million in 2021 to USD 2,728 million in 2030 and the market has grown due to rising road safety and security concerns and transportation cost reduction efforts. Additionally, Turkey is interested in investing in plotting systems for trucks according to the news from Anadolu Ajansı [16]. They stated that the Turkish government and TÜBİTAK has provided significant support for the development of autonomous vehicles. They invested over 20 million euros since 2008 and they plan to reach 30 million euros by year's end Anadolu Ajansı [16]. Therefore, research findings and sector analysis indicate that there is a growing demand for efficient and environmentally favorable platooning trucks for transportation.

In conclusion, the implementation of platooning technology in transportation has the potential to significantly reduce pollution, fuel consumption, and operational inefficiencies. Incorporating platooning into logistics and transportation systems requires making data-driven decisions, optimizing routes, and considering regulatory concerns. The research findings align with the project objectives and the intended scope of Tırport. In addition, the literature network encompasses hub network design, providing a comprehensive comprehension of platooning within the wider logistical context.

IV. System Design

A. System Architecture

The system is designed to optimize road freight transportation for Tırport, integrating platooning technology into existing logistics operations. Utilizing network optimization techniques, it aims to identify the most efficient routes for platooning, balancing efficiency with cost-effectiveness. Our Python script is essential in this system, enabling the effective handling and analysis of a comprehensive dataset. This dataset includes Tırport's information and additional data we have compiled and integrated. The script is designed to efficiently import and process these diverse datasets, converting them into a structured format for our analyses. This process involves handling information like transportation costs and goods flow, along with additional parameters necessary for a complete understanding of the logistics landscape. These parameters include the number of vehicles on specific routes (t_{ij}) and the associated transportation costs (C_{ij}^{km}), key to the strategic integration of platooning into the existing logistics and transportation infrastructure.

a) Inputs and Outputs of the System: Inputs of the system include detailed transportation data, such as direct transportation costs, fuel prices, and fuel consumption for trucks. We also account for direct distances, inter-hub distances, adjusted flows between various cities or hubs, and a comprehensive map of Turkey's national highway exported from ArcGIS. Network parameters, including the number of vehicles (as described in the LP model), transportation costs, the hub discount factor α, and the desired number of hub locations, are considered. The outputs of our system are multifaceted, providing optimized route selection based on cost and distance data, platooning recommendations for effective implementation within the transportation network, and a thorough cost analysis comparing the costs associated with each route, including potential savings from using platooning technology. Additionally, we estimate CO2 emissions for each transportation scenario, utilizing the known emission factor for diesel trucks, to provide an environmental impact analysis alongside economic factors.

Building upon the core outputs, our system delivers analytics and detailed outputs. This includes waiting time

analysis to evaluate and optimize idle times and empty mileage assessments to minimize unladen journeys, and route efficiency metrics that evaluate each route based on distance, fuel consumption, and time. An economic impact analysis offers insights into long-term financial benefits and return of platooning, while sustainability and environmental impact reports highlight the ecological advantages, such as emissions reductions and fuel savings, of the optimized platooning routes.

b) Major Components (Subsystems or Elements): Major components of our system include the Data Processing Module, fundamental to handling the integration and processing of transportation data. This module manages information such as direct costs, distances to inter-hub costs, and adjusted flows. The Optimization Engine employs advanced route optimization algorithms to assimilate platooning technology into logistics, focusing particularly on maximizing cost efficiency. The Modeling Subsystem and Numerical Analysis investigate the performance of platooning across various scenarios, assessing its impact on efficiency and cost. The Output Generation and Reporting component generates route recommendations and provides reports on the costs and potential savings of our platooning technology, focusing on both financial and environmental aspects. We also emphasize Data Quality, ensuring the accuracy and precision of our data for reliable route optimization and cost calculations. Additionally, we consider External Factors and Features, such as changes in fuel prices and the economic situation, which significantly influence the overall cost efficiency of platooning compared to traditional transportation methods. By considering these external elements, we adapt our strategies to be effective and relevant to both current and future operations.

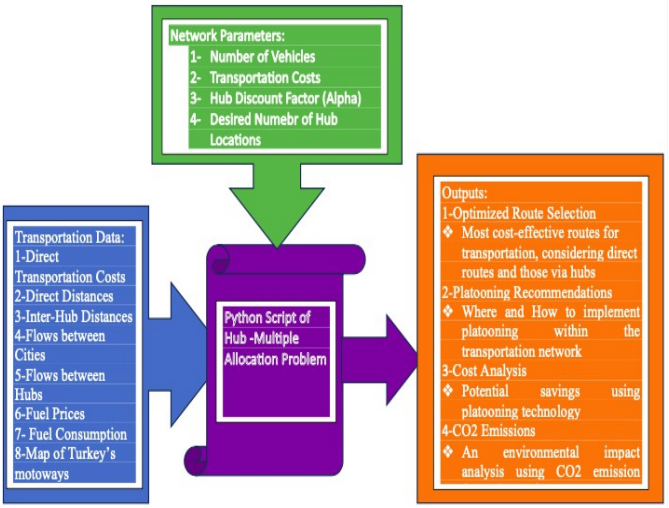

Figure 1: A Simple Flowchart of Our System

The flowchart in Fig. 1. demonstrates an extensive process for integrating platooning technology into the road freight transportation network. The project begins with collecting data and doing an in-depth review of existing literature. Data consists of transportation costs, distances, flows, fuel price, motorway network, and fuel consumption. Then, the project advances through key stages, including the identification of hub centers, route optimization, and the design and implementation of a platooning model conducted by Python Script. The number of trucks, number of hubs, and α values are also given as inputs to our Python model. The experimental step evaluates the performance of the model, whereas validation guarantees its accuracy. The ultimate results encompass enhanced routes and valuable observations, leading to enhanced transportation effectiveness, decreased costs, and ecological sustainability. The flowchart stresses a methodical and data-driven approach, emphasizing the continual evolution of the project to ensure strength and practicality in real-world situations.

c) Description of the Model: Although platooning technology has different advantages than traditional transportation, there are still some barriers in its implementation. The two most important of these are geographical conditions and whether the existing road infrastructures are suitable for platooning. Considering these barriers, it is not currently possible to implement platooning throughout Turkey. Instead, while doing our modeling within the scope of the project, we tried to ensure that the entire flow was transported by using platooning in regions and roads that are geographically and infrastructurally suitable for platooning, and by using traditional transportation in external regions. In order to bring these two different methods together, we decided to place hub locations where platoon convoys are formed and dissolved.

First the flow from different cities are brought to the designated hubs with traditional transportation. Afterwards, platoon convoys are formed in these hubs and these flows are transported to their destination hubs. When the convoys reach the destination hubs, these convoys are dispersed and the loads are delivered to their destination by traditional transportation. Details such as the model's objective, variables, parameters and how these hubs are selected will be explained in detail below.

We created a model by revising the classic multiple allocation model in the hub selection literature within the scope of our own project. We first defined the decision variables and parameters of this MILP model as follows:

Parameters:

t_{ij} = number of vehicles from origin i to destination j

C_{ij} = total cost of direct transportation from origin i to destination j.(per truck)

C_{ij}^{km} = total cost of transportation from origin i to destination j going thragh hubs k and m, respectively. (per truck)

α = interhub discount factor

Q = desired number of hub locations

N = all cities

H= potential hub locations

One of these parameters, t_{ij}, was created from the data given by Tırport with a method explained in detail in the data interpretation section. Similarly, there are detailed explanations on obtaining the parameters C_{ij}, C_{ij}^{km} and α in the same section. There is no restriction regarding Q here, that is, the desired number of hub locations, in the first stage of

the project. In terms of operational feasibility, it may be possible to conduct studies and research on the number of hubs. In the strategic phase, while making analyzes regarding the solution of the model, we used variable Q values as parameters in our model to represent different scenarios. Our N set covers 81 provinces since the project is within the scope of all of Turkey. The critical point here is to determine H, that is, potential hub locations. Since platooning will be carried out between these hubs, the locations of the hubs and the road infrastructure between the hubs must be carefully examined in terms of the applicability of the platooning technology motorways are the type of roads where platooning can be applied. Besides being suitable for platoon convoys due to road infrastructure, motorways are fast-moving and they have boundaries or fences to keep animals and other vehicles out of the path. There are designated areas for entering and exiting on the motorways.

To determine the motorways and potential hub locations depending on these motorways, we created a map as shown in Fig. 2. using OpenStreetMap and ArcMap software.

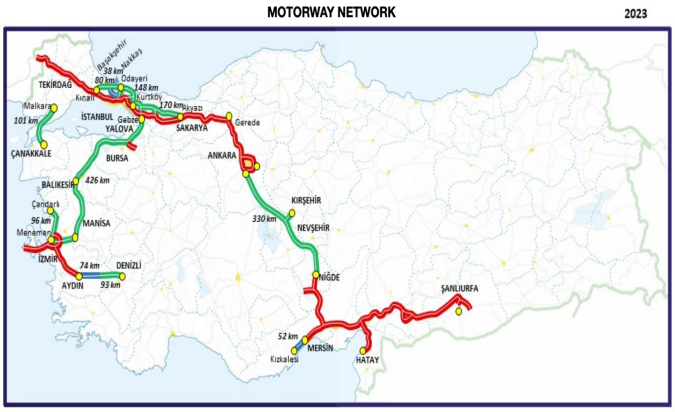

Figure 2: Map of Turkey's Motorway Network

The roads are drawn in red on Fig. 2. represent the existing motorways in Turkey. The nodes marked in yellow represent our 81 cities. While choosing our potential hub points using our map, we assumed that we could establish our hubs in city centers or around that region for simplicity. Therefore, we took the centers of our 81 cities as a basis when determining potential hub points. The cities on the map that the motorways pass directly or close to are selected and 24 cities are selected as potential hub locations. These selected cities also constitute the H set.

Decision Variables:

y_{ij} = if transportation will be carried out without hubs, $y_{ij} = 1$

otherwise, $y_{ij} = 0$

y_{ij}^{km} = if transportation from origin i to destination j carried at through h, b and m, respectively,

$y_{ij}^{km} = 1$

otherwise, $y_{ij}^{km} = 0$

H_k = if potential hub $k \in H$ is selected as hub, $H_k = 1$

otherwise, $H_k = 0$

As defined above, there are 3 decision variables in our model. While two of them decide how the flow will be satisfied, which we call route decisions, the other one decides which of the potential hubs will be opened. As defined, our first variable y_{ij} decides whether transportation is done without hubs, that is, platooning will be performed. This variable is not generally included in classic hub models. The reason we use this variable is if the direct transportation from origin i to destination j is more profitable in terms of cost compared to platooning transportation using hubs, then there should be an option to satisfy the flow directly. Another variable is y^{km}, the variable that decides the route through which hub pair the flow from i to j will take place. The last and third variable, H_k, decides whether potential hubs will be opened as hubs.

Objective Functions:

$$\min \sum_{i,j\in N} \sum_{k,m\in H} \left(t_{ij} c_{ij}^{km} y_{ij}^{km} + t_{ij} c_{ij} y_{ij}\right) \quad where\ C_{ij}^{km} = C_{ik} + aC_{km} + C_{mj}$$

Knowing why platooning is done when creating the model is the beginning and the first step. The first thing that comes to mind is, of course, aerodynamic effectiveness and the amount of savings in gasoline since it is an autonomous system. However, of course, there are also outcomes that we need to consider on the more environmental side, such as carbon emissions. For the integration of a new technology, it is inevitable to consider its environmental effects in order to legalize the existence of this technology. Since we are writing a mathematical modeling and it is also a company's project, we determined the objective as cost minimization along with the gain in gasoline. In the previous sections, the parameters and decision variables of the model were explained in detail. As can be seen here, we divided our total cost into two parts: direct transportation cost and platooning transportation cost.

Constraints:

(I) $\sum_{k\in H} H_k = Q$

(II) $y_{ij} + \sum_{k,m\in H} y_{ij}^{km} = 1 \quad \forall i \in N, \forall j \in N$

(III) $\sum_{m\in H} y_{ij}^{km} \leq H_k \quad \forall i \in N, \forall j \in N, \forall k \in H$

(IV) $\sum_{k\in H} y_{ij}^{km} \leq H_m \quad \forall i \in N, \forall j \in N, \forall m \in H$

(V) $H_k \in (0,1)\ \forall k \in H$

$y_{ij}^{km} \geq 0 \quad \forall i \in N, \forall j \in N, \forall k \in H, \forall m \in H$

$y_{ij} \in (0,1) \quad \forall i \in N, \forall j \in N$

Constraint (I) determines the total number of hubs to be opened. Constraint (II) ensures either direct transportation between origin-destination pairs or platooning transportation using hubs. Constraint (III) and (IV) state that k and m hubs must be opened in order for flows to pass through k and m hubs, respectively. Finally we have (V) nonnegativity constraints for the decision variables.

d) Python Implementation: After preparing our model, we wrote it using Gurobi via Jupyter, as shown in Fig. 3.

```
def modeltry(file):

    cost       = pd.read_excel(file, sheet_name = 0)
    flow       = pd.read_excel(file, sheet_name = 4)
    flow2  = pd.read_excel(file, sheet_name = 4)
    cost_interhub = pd.read_excel(file, sheet_name = 2)

    I=np.arange(1,82).tolist()
    J=np.arange(1,82).tolist()
    K = [1, 6, 9, 10, 14, 16, 17, 20, 22, 27, 33, 34, 35, 39, 40, 41, 45, 51, 54, 59, 68, 77, 80, 81]
    L = [1, 6, 9, 10, 14, 16, 17, 20, 22, 27, 33, 34, 35, 39, 40, 41, 45, 51, 54, 59, 68, 77, 80, 81]
    Q = 10 # desired number of hub
    alpha = 0.744

    Routes=[(i,j,k,l) for i in I for j in J for k in K for l in L]
    DirectAssignment=[(i,j) for i in I for j in J]

    flow         = dict(((i,j,k,l),flow[j][i]) for i in I for j in J for k in K for l in L)
    fuelcost     = dict(((i,j),cost[j][i]) for i in I for j in J)
    flowdirect   = dict(((i,j),flow2[j][i]) for i in I for j in J)
    fuelcostinterhub = dict(((k,l),cost[l][k]) for k in K for l in L)

    HubRouteCost=dict(((i,j,k,l),(flow[i,j,k,l])*(fuelcost[i,k]+ alpha*fuelcostinterhub[k,l]+ fuelcost[l,j]))
                  for i in I for j in J for k in K for l in L)
    DirectRouteCost= dict(((i,j),(flowdirect[i,j])*(fuelcost[i,j]))
                  for i in I for j in J )

    m = gp.Model("cfl")
    m.ModelSense = GRB.MINIMIZE

    xk=m.addVars(K,name="City Nodes",vtype=GRB.BINARY,obj=0)
    yijkl=m.addVars(Routes,name="Hub Used Routes",obj=HubRouteCost)
    yij=m.addVars(DirectAssignment,name="Direct Routes",obj=DirectRouteCost)

    desiredhub = m.addConstr((quicksum(xk[k]
                            for k in K ) <= Q ), "Desired Hub")

    directorhub = m.addConstrs(( yij[i,j]+ quicksum(yijkl[i,j,k,l]
                            for k in K for l in L) == 1
                            for i in I for j in J), "Direct or Hub Decision Constraint")

    hub1 = m.addConstrs((quicksum(yijkl[i,j,k,l] for l in L) <= xk[k] for i in I for j in J for k in K), "Hub1")

    hub2 = m.addConstrs((quicksum(yijkl[i,j,k,l] for k in K) <= xk[l] for i in I for j in J for l in L), "Hub2")

    m.optimize()

    for v in m.getVars():
        if v.x > 0:
            print(f"{v.varName}: {v.x}")

    return(m.objVal)
```

```
modeltry("temporary data (1).xls")
```

Figure 3: The Python Code for Our Model

e) Results: As we mentioned before, we had 3 different α values that we can take as inputs while running the model. Similarly, the desired number of hubs in the model is also a parameter. In the part of our project so far, we have worked on 8 different scenarios with the number of hubs as minimum 3 and maximum 10. With 3 different α values and 8 different hub numbers, there are 24 different scenarios in total. After running each scenario in our model, our resulting optimal objective values, that is, our total costs, can be seen in TABLE I and Fig. 4.

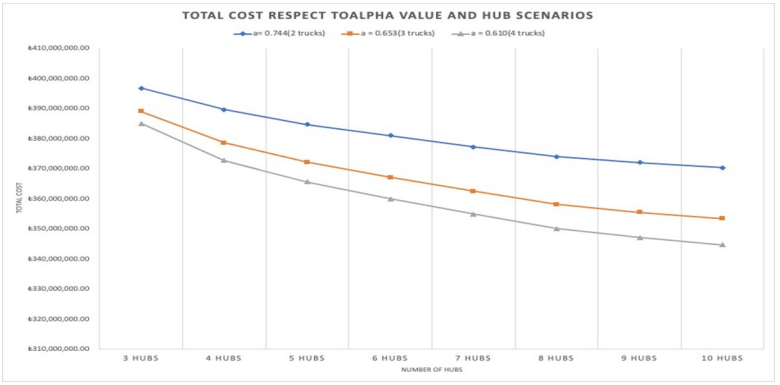

Figure 4: The Graph of Total Costs to Alpha and Hub Scenarios

TABLE I
TOTAL COST OF DIFFERENT HUB AND ALPHA SCENARIOS

Number of Hubs	a= 0.744(2 trucks)	a = 0.653(3 trucks)	a = 0.610(4 trucks)	Total Average
3 Hubs	₺ 396.620.678,00	₺ 388.966.148,00	₺ 384.965.574,00	
4 Hubs	₺ 389.531.633,00	₺ 378.463.731,00	₺ 372.651.736,00	
5 Hubs	₺ 384.607.595,00	₺ 372.035.413,00	₺ 365.553.370,00	
6 Hubs	₺ 380.913.131,00	₺ 366.998.049,00	₺ 359.907.058,00	
7 Hubs	₺ 377.089.297,00	₺ 362.431.019,00	₺ 354.875.292,00	
8 Hubs	₺ 373.885.092,00	₺ 358.033.648,00	₺ 349.977.389,00	
9 Hubs	₺ 371.995.064,00	₺ 355.452.027,00	₺ 347.027.410,00	
10 Hubs	₺ 370.284.569,00	₺ 353.344.657,00	₺ 344.552.831,00	
	₺ 380.615.882,38	**₺ 366.965.586,50**	**₺ 359.938.832,50**	**₺ 369.173.433,79**

As seen in the Table I and Fig. 4, there is a decrease in our total costs as our α value decreases. Similarly, as the number of hubs increases, there are decreases in total cost at different rates. It is expected that our cost will decrease as the α value decreases, because a lower α value means platooning is done more effectively, which should be more cost effective. It is also expected that the cost will decrease as the number of hubs increases, because more number of hubs means more transportation opportunities through more hubs, which increases the application of platooning and creates a lower cost with platooning.

On Fig.4., we visually observe that as the number of hubs increases, the amount of decrease in total cost decreases. This means that after a certain number of hubs are opened, the contribution of the hubs that will be opened/wanted to be opened to cost reduction will actually decrease. Although there is no hub opening cost in the current model, opening a hub may still be unnecessary in operational terms.

Comparing the scenarios with each other, cost reductions are clearly visible. But we need to examine what exactly the cost reductions in the entire scenario tell us. While preparing our freight transportation model using platooning, our goal is actually cost minimization. We minimize the cost, but we do not have the current scenario without platooning. In order to understand the effectiveness of platooning, the current scenario also needs to be analyzed. To do this, we modified our model. The only thing we did for this was to force the model to direct transportation. With a new constraint we added, we forced direct shipment between all origin destinations.

$$y_{ij} = 1 \quad \forall i \in N, \forall j \in N$$

After we run the model with this constraint, our calculated cost for the current system is around 409 million Turkish liras. After calculating the current cost, we compared it with the costs of the scenarios in the model we created and the cost reduction percentages for each scenario were as shown in TABLE II.

These reductions have a cost saving of up to 19 percent. We conclude from the results that, on average, all scenarios have a gain of around 11 percent. If we express the 11 percent gain in different ways, it means a daily gain of approximately 40 million Turkish liras, which corresponds to a saving of approximately 1 million liters of diesel. When we consider all the trucks in the flow in one day, this means a gain of
21.76 liters of diesel per truck. From an environmental perspective, approximately 58 kg of CO_2 emissions are reduced per truck.

TABLE 2
PERCENT SAVINGS OF DIFFERENT HUB AND ALPHA SCENARIOS

Number of Hubs	a= 0.744(2 trucks)	a = 0.653(3 trucks)	a = 0.610(4 trucks)	Total Average
3 Hubs	3,32%	5,36%	6,45%	
4 Hubs	5,20%	8,28%	9,97%	
5 Hubs	6,55%	10,15%	12,10%	
6 Hubs	7,58%	11,66%	13,86%	
7 Hubs	8,68%	13,07%	15,48%	
8 Hubs	9,61%	14,46%	17,09%	
9 Hubs	10,16%	15,29%	18,09%	
10 Hubs	10,67%	15,98%	18,94%	
Averages	**7,72%**	**11,78%**	**14,00%**	**11,17%**

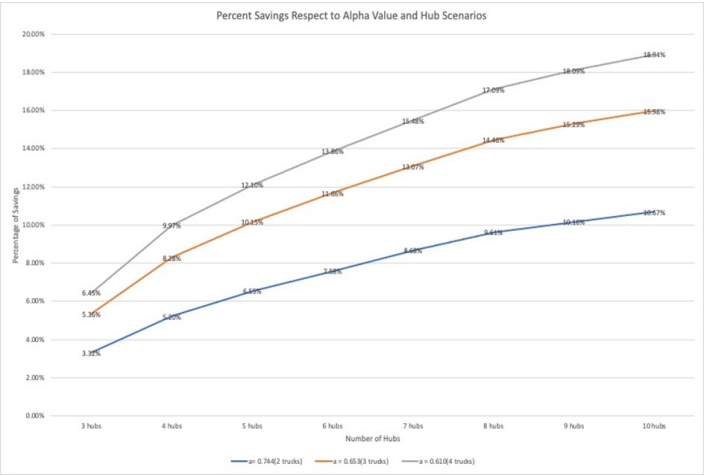

Figure 5: The Graph of Percent Savings to Alpha and Hub Scenarios

Again , as we saw and commented in the previous graph, as we increase the number of hubs, the increase in our savings percentage decreases.

B. Model Development and Validation

While interpreting and analyzing the results of the model we created, we proceeded based on the total transportation cost that we set as an objective. After this, we decided to analyze the challenging points of the project in a more operational sense and its adaptability to real life. First, we decided to simulate the waiting times of trucks that set off from different origins and arrived at the same hub point while forming a convoy. While doing this analysis, we examined the worst cases.

During our meeting with TIRPORT, we could not obtain any data regarding the departure times of the trucks and we decided that the most reasonable and realistic approach was to determine the departure times by making a triangular distribution. We created the triangular distribution, thinking that trucks could set off randomly, but that this would be more intense towards noon hours. Our method in calculating waiting times is to calculate the arrival time of each truck to the first hub, list the arrival times of the trucks with the same destination hubs in ascending order, and then group them into two, three or four groups according to the scenario we will examine respectively. Since the maximum waiting time in the convoy for each convoy group is the waiting time of the earliest arriving truck in the convoy for the last arriving truck, we assumed the difference between the arrival times of the first and last arriving trucks as waiting time. Then, we prepared the simulation by integrating it into our model using Python.

Let's establish a simple logic regarding the worst cases mentioned above. If we compare our scenarios according to convoy lengths, the longer the convoy, the longer the waiting times because the first vehicle in the convoy will wait for more vehicles. Likewise, as the number of hubs we use in the model increases, the amount of flow carried by platooning will be divided more. Accordingly, the average flow amount between any two hubs will decrease as the number of hubs increases. We predict that decreasing flow amounts will reduce the frequency of convoys and cause an increase in waiting times. Therefore, we decided to conduct our analysis in a scenario with 10 hubs and 4 trucks in length, where we predicted that waiting times would be highest. In the worst case scenario, where the maximum convoy length is 4 in convoys between two hubs, the average waiting time for the first truck in the convoy to the last truck is 10,59 minutes on average. When we examined the waiting times in each convoy one by one, we noticed a few extreme waiting times that would seriously increase the average. In these specific cases, for example, instead of waiting for the 5th truck, it can be divided into two convoys in the form of 3-2, or instead of the first truck of a convoy waiting for the other trucks, where we predict that the waiting time will be high, it can be included in the previous convoy and a convoy of 5 trucks can be formed. If this is done, there will be a significant decrease in the average waiting time which we can disregard.

Another issue is empty mileage, which is when trucks return to the origin city they came from after carrying loads to the hubs, with empty loads. While the trucks leave their loads at the hubs, it is also possible that there are loads brought to that hub from another hub via platooning. Freights arriving at the hubs can also be transported to their destination

points with trucks returning to the same point. Our empty mileage analysis here focuses on the worst case, as in waiting time, since in some cases there is a possibility that trucks will return empty after arriving at the hubs. As a worst case, we thought of an extreme scenario such as all the trucks coming to the hubs returning empty. On the other hand, when we make the worst case calculation, we need to consider the current system for comparison. Since TIRPORT's current system is focused on full truck load, empty mileage is not actually an issue. But as a reference, in our meeting with them, they suggested taking the empty mileage rate as 30%. When we simulated the empty mileages in our own model in Python, we saw that among our different hub and α scenarios, the empty mileage was at least approximately 1/3 of the current system.

C. Consideration of Alternatives

In the comprehensive analysis of alternative platooning applications, we discerned three discrete systems: Scheduled Platooning, Opportunistic Platooning, and Orchestrated Platooning. Opportunistic Platooning manifests as the spontaneous formation of platoons among trucks in close proximity, while Orchestrated Platooning entails centralized management by Platooning Service Providers (PSPs). In light of the persistent imperative for substantial infrastructure development to facilitate expansive business operations and accommodate spontaneous platoon formations, coupled with limited data provided by TIRPORT, our predilection converges towards the Scheduled Platooning system.

This proclivity emanates from the strategic alignment of the Scheduled Platooning alternative with our operational exigencies. Specifically, this system adeptly leverages premeditated travel information and platoon management, thereby engendering a structured and meticulously organized framework for platooning applications. The predilection for Scheduled Platooning is predicated upon its capacity to mitigate uncertainties and enhance the predictability of platoon logistics, thereby catering to the requisites of a sophisticated operational landscape. This preference is substantiated by the discerned harmony between the methodological precision afforded by Scheduled Platooning and the imperatives of our operational milieu. Additionally, we encountered various alternatives regarding potential hub selection. Our first alternative was to identify central points in the regions of Turkey and determine them as potential hubs, but we did not use this because not every central point was on roads suitable for platooning. Secondly, we thought of choosing hubs according to the flows of each city in Turkey, but the most appropriate method for choosing potential hubs was to proceed through roads suitable for platooning. That's why we took advantage of the existing motorway map in Turkey and determined the cities on it as potential hubs.

Finally, after creating our model, we examined the discount factor, or α, in our model in 3 different scenarios. These were the α values chosen based on the presence of 2, 3 and 4 trucks in convoy in the platooning system. As we stated in section 2.c, as a result of our research, we found the average α value to be 0.744 in the platooning system containing 2 trucks, 0.653 in the platooning system containing 3 trucks, and 0.610 in the platooning system containing 4 trucks. According to the results, the most advantageous value seems to be the platooning system containing 4 trucks, because as the number of trucks in the convoy increases, air resistance decreases and thus fuel consumption decreases significantly. However, apart from the numerical results, the disadvantage is that as the number of trucks increases, it becomes practically difficult to create a platooning system. In terms of creating a platooning system with a length of 4 trucks in each convoy, it becomes unrealistic and almost impossible.

D. Solution Methodologies

a) Collection and Analysis of Data for Existing Transportation Network: This comprehensive examination encompasses various critical parameters, such as routes, flow amounts, speeds, distances, fuel consumption, emissions, and associated costs. To facilitate a thorough understanding of the current state of the transportation infrastructure, an attentive investigation into the geographic information system software is proposed. To determine the motorways and potential hub locations depending on these motorways, OpenStreetMap and ArcMap software have been used in this project.

b) Developing a Model & Conducting Experiments: The implementation of the model (see 4.1) was executed through the utilization of the Python programming language. Python was used as the main coding framework for creating and implementing the model because of its widespread adoption and large library ecosystem. In order to simulate the application of hub-based platooning technology in Turkey, the behavior and performance of convoys on selected routes were investigated. Under this review, different scenarios helped determine which cities could be designated as hubs.

c) Comparing Hub and Truck Scenarios in Current System and Suggested New Motorway: 24 distinct scenarios arise as if combining the scenarios of 3–10 hubs with 2, 3, and 4 trucks in both scenarios. These scenarios' cost amounts were evaluated. Based on the collected data, it was shown that the overall cost decreased with an increase in hub count. However, the cost increment eventually decreased as the number of hubs rose. There is a parallel situation with truck numbers. The new motorway opening scenario provides a significant total cost reduction for the same truck numbers.

E. Scenario and What-If Analysis

The most limiting situation in the current scenario is that we cannot choose our potential hubs from the east of

Figure 6: Map of Turkey with Future Gerede-Gürbulak Motorway

Turkey and the Black Sea region. The main reason for this is that there are no motorways we need for platooning in those regions. We know that the Karayolları Genel Müdürlüğü aims to increase Turkey's total motorway length in the long term. However, the Gerede-Gürbulak motorway project, which has news and speculation even though it has not become official yet, caught our attention (see Fig. 6). This motorway, starting from Bolu and extending to the Ağrı Gürbulak border gate, is an important project that can be an international logistics corridor. Therefore, in addition to the current system, we wanted to examine the difference that the scenario in which the Gerede-Gürbulak motorway would exist would affect our model and results, in the form of a What-If analysis

During integrating this new scenario into our model and code, the parts that required changes were our hub locations set and inter-hub distances. We made these changes and solve different α and different number of hub scenarios in our model.

TABLE 4
TOTAL COST AND PERCENTAGE REDUCTION OF FUTURE GEREDE-GÜRBUKAK MOTORWAY MODEL

Number of Hubs	a= 0.744(2 trucks)	a = 0.653(3 trucks)	a = 0.610(4 trucks)	Total Average
3 hubs	₺ 396.620.678,00	₺ 388.966.148,00	₺ 384.965.574,00	
4 hubs	₺ 389.321.912,00	₺ 378.023.444,00	₺ 372.164.083,00	
5 hubs	₺ 383.386.301,00	₺ 368.911.283,00	₺ 361.434.275,00	
6 hubs	₺ 378.818.575,00	₺ 363.289.759,00	₺ 355.405.696,00	
7 hubs	₺ 374.837.653,00	₺ 358.237.330,00	₺ 349.723.725,00	
8 hubs	₺ 371.009.394,00	₺ 353.057.626,00	₺ 344.049.855,00	
9 hubs	₺ 367.362.049,00	₺ 348.278.434,00	₺ 338.542.412,00	
10 hubs	₺ 364.312.288,00	₺ 344.167.976,00	₺ 333.832.375,00	
	₺ 378.208.606,25	**₺ 362.866.500,00**	**₺ 355.014.749,38**	**₺ 365.363.285,21**

Number of Hubs	a= 0.744(2 trucks)	a = 0.653(3 trucks)	a = 0.610(4 trucks)	Total Average
3 hubs	3,32%	5,36%	6,45%	
4 hubs	5,26%	8,41%	10,11%	
5 hubs	6,89%	11,08%	13,38%	
6 hubs	8,18%	12,80%	15,31%	
7 hubs	9,33%	14,39%	17,18%	
8 hubs	10,46%	16,07%	19,11%	
9 hubs	11,55%	17,67%	21,05%	
10 hubs	12,49%	19,07%	22,76%	
	8,43%	13,11%	15,67%	12,40%

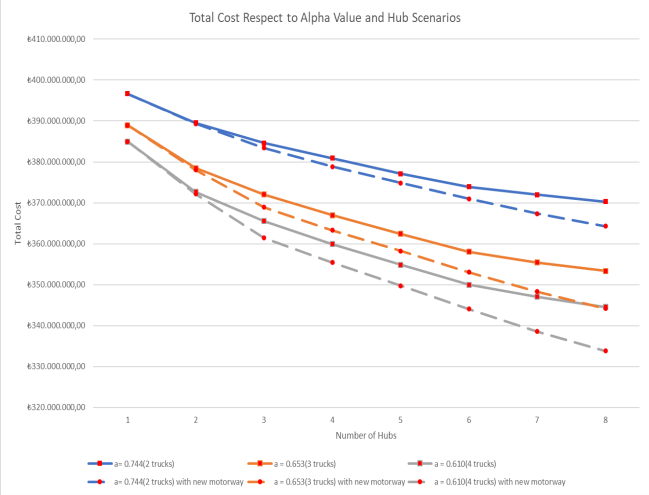

Figure 7: The Graph of Total Costs to Alpha and Hub Scenarios with New Motorway

As can be seen in TABLE III, while the average profit percentage in the current model is 11.17, it rises to 12.40 here. And again, the profit from 21.76 liters per truck increases to 23.80. Also, the plot of the current system's and What-if system's total costs can be seen in fig. 3.

The new motorway opening scenario provides a significant total cost reduction for the same α values shown in Fig. 7. There are similar gains in other numerical analyses. This numerical analysis actually shows us how much potential the Gerede-Gürbulak highway has and how cost minimization can be improved in this way.

V. IMPLEMENTATION

The project delivers an integrated hub-based platooning system within Tırport's logistics operations. First of all, we identified and optimized platooning routes within the road transportation network, employing network optimization methods with hub-based methodology. As a result, there were concrete benefits such as reduced travel duration, reduced empty mileages, and cost savings. The implementation of platooning arcs in the road freight transportation network has resulted in a notable reduction in fuel consumption and accordingly a significant reduction in CO2 emission, in line with objectives for environmental sustainability. The widespread implementation of platooning technology has not only complied with safety rules but has also yielded comprehensive data-driven insights to enhance decision-making in the transportation network. The organization can successfully achieve significant cost reductions by reducing fuel consumption and empty mileages, thereby improving its overall profitability.

Integrating platooning technology into the current logistics and transportation infrastructure required guaranteeing compatibility with communication, navigation, and control systems. The identification of suitable hub centers strategically located for platooning has been a crucial achievement. The project predominantly employed Python as the programming language and ArcGIS Desktop for acquiring comprehensive data on highways and freight routes. The platooning model was created, executed, and confirmed through a sequence of trials and tests, taking into account several criteria such as platooning convoy size, or number of hubs. After concluding our model for choosing appropriate hubs for platooning, we upgraded our model for the operational phase which included the incorporation of waiting times of trucks for each other when combining a convoy in a hub and the calculation of empty mileages. According to our upgraded model, we discovered that the waiting times are negligible and even in the worst case, there is a reduction in total empty mileage.

The implemented model utilizes advanced algorithms for hub decisions and platooning decisions to optimize the load flows through motorways in Turkey. This integrated approach has contributed to the effectiveness of the transportation network. Future plans for Tırport can cover the initiative plans to further improve and extend the routes used for platooning within Turkey's transportation network. The emphasis will be on incorporating innovative technology and innovations that improve the effectiveness and security of platooning operations. In other words, they can work on the infrastructure of Turkey's motorway to integrate the platooning systems for trucks with a safety prioritization. Continuous communication with relevant parties and

ongoing analysis of data will be crucial for improving the platooning model and adjusting to changing transportation requirements. The project's objective is to remain up-to-date with regulatory breakthroughs in platooning technology and to predict prospective obstacles or advancements in the field. Since one of the objectives was to reduce the fuel consumption and CO2 emissions to the environment, Tırport can also consider adding the existing railroad networks into the transportation equation to further optimize the system. The efficient incorporation of platooning technology into the current logistics and transportation infrastructure represents a significant accomplishment.

The implementation of platooning technology can have a profound effect on the organization. The optimized platooning routes have led to a potential of significant reductions in transportation time, costs, emissions, and empty mileages. Also, the enhanced traffic flow and safety may contribute to a more efficient logistics network. Therefore, the company may achieve substantial financial savings by reducing fuel use and operational expenses. Furthermore, the adoption of platooning technology may position the organization as an industry leader on platooning technology, embracing innovation and sustainability.

In a nutshell, the project has effectively achieved its objectives, demonstrated a beneficial influence on the organization and environment, and laid the groundwork for continuous enhancements and progress in platooning technology inside the road transportation network.

VI. Acknowledgements

We would like to express our sincere gratitude to our academic supervisor and Industrial Engineering Professor Barış Yıldız from Koç University for his invaluable advice and support throughout the development of this article. His wisdom and guidance has significantly enriched the content and quality of this work. Also, we are deeply thankful to our industrial supervisor Emre Çapoğlu from Tırport for his collaboration during the process. Their constructive feedback and insightful suggestions have played a pivotal role in shaping the final outcome.

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