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Mixed Integer Programming Formulation for Time-Dependent Petrol Station Replenishment Problem: A Real-Life Case in İstanbul

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Abstract

Limited resources must be used effectively, precisely, and damage-free considering the increase in the consumption of petroleum and petroleum-derived products. Therefore, the accurate and effective distribution of petroleum and related problems with petroleum distribution have attracted much attention among practitioners and optimization working researchers over the years. The petroleum distribution problem, as a version of the vehicle routing problem (VRP), deals with the planning of petroleum distribution from the depot(s) to the petrol stations safely and quickly. In this study, the petrol station replenishment problem (PSRP) is handled and a case study is presented for a public company located in Istanbul. The problem is considered as a time-dependent VRP with time windows. To handle the proposed time-dependent problem in a more realistic way, variable tanker speeds are considered based on traffic density. In this study, a novel mixed integer mathematical model to solve time dependent PSRP with time windows is proposed. The optimum route is determined in which risks such as environment and marine pollution may occur in case of possible accidents, and these risks are minimized by the proposed mathematical model considering factors such as traffic, vehicle speed, road structure, the road's proximity to the sea, and living areas.

1. INTRODUCTION

Distribution operations are a part of the goods and service industries. The corporation uses distribution operations as one of its marketing strategies to get its goods in front of buyers. Distribution channels are a group of individuals or organizations that carry out all the tasks required to convey goods or services from a business to the final consumers [1]. In today's world, petroleum and petroleum products are indispensable resources in meeting energy needs [2]. These resources are used in almost every area such as manufacturing, transportation, energy, and service. The demand for petroleum is increasing day by day with the rapid development of technology in recent years as a consequence [3]. The adverse effects of petroleum and petroleum products on both human life and the environment in which the usage increases in all areas of life are not also negligible. Petroleum and petroleum products create more pollutants and greenhouse gases than renewable energy sources since it is an exhaustible and non-renewable fossil fuel [4]. Greenhouse gases affect the environment and they may cause climate change [5]. In addition, some important problems with marine environmental pollution are caused by leaks during petroleum product distribution, especially at the time of accidents. Therefore, petroleum and petroleum products should be distributed with minimum risk and in the most convenient way to protect the environment and human health. With the increase in the consumption of petroleum and petroleum products, limited resources around the world must be provided efficiently, accurately, and with minimal damage. In the current literature, such problems are addressed under the title of hazardous material transportation problem (HMTP).

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The HMTP is a current research topic that has been focused on by many different scholars and practitioners for a long time. Mathematical modeling techniques, such as mixed integer programming, stochastic programming, and robust modeling, are the most frequently applied methods to solve many different variations of HMTPs. However, many scholars use multi-criteria decision-making (MCDM) approaches to deal with HMTPs and challenges associated with them. For different objectives, including risk assessment, location selection, and strategy selection, many MCDM methodologies are used. The prominent of these studies can be summarized as given below.

Erkut & Ingolfsson (2000) propose catastrophe-avoidance models for three different scenarios considering accidents during the hazardous material distribution. The first model minimizes the number of exposed population, the second model integrates route into the final solution, and explicit disutility function is used in the third model [6]. Kara & Verter (2004) develop a bilevel optimization model to solve network design problems with respect to the risk of hazardous material transportation consists of environmental and social risks associated with the carrier route [7]. Erkut & Gzara (2008) focus on the hazardous materials network design problem considering government rules. The problem is modeled as a variation of the bilevel network flow optimization problem and solved using heuristic optimization techniques [8]. Zografos & Androutsopoulos (2008) develop a decision support model to determine the best route(s) for hazardous materials transportation with minimizing the risks and costs. They determine the evacuation route for victims and emergency unit locations to minimize the damage caused by accidents [9]. Leonelli et al. (2000) formulate the HMTP as a variation of a minimum-cost flow network problem. The cost of each arc is determined considering the social risk, individual risk, and the cost [10]. Samanlioglu (2013) develops a multiobjective location-routing model to determine the most suitable locations of treatment centers and disposal centers. The proposed model determines the transportation of best route for the hazardous materials while minimizing the risks related to population exposure along with transportation and, around disposal centers and treatment centers [11]. Saat et al. (2014) present a comprehensive analyzes for hazardous material transportation by rail. The risks per car-mile per ton-mile are calculated annually using historical accident data to compare the risks among different hazardous materials [12]. Bonvicini et al. (2015) specify the environmental risk indexes to use in the risk analysis for the risk assessment of onshore pipelines [13]. Lam & Zhou (2016) present statical analyzes that focus on accident data from onshore pipelines and provide onshore pipeline risk assessment methodology [14]. Zarei et al. (2017) propose a comprehensive dynamic risk analysis based on different accident scenarios for a natural gas station using Failure mode and effect analysis (FMEA), Bayesian networks, and bow tie diagram [15]. Ma (2018) uses constraint programming techniques to design a hazardous material transportation network in an uncertain environment, and solve the model with a multi-objective genetic algorithm [16]. Yang et al. (2018) group risks under the titles of environment, human, material, and management and aims to minimize these risks for the HMTP by fuzzy quality function deployment (QFD) [17]. Hu et al. (2018) focus on three-level HMTP among suppliers, manufacturers, and retailers and balance the cost with risk under fuzzy environment [18]. Hu et al. (2019) determine safe routes for HMTP by considering the traffic restrictions [19]. Ghaderi & Burdett (2019) determine the best strategy for the transportation of hazardous materials through a bimodal transportation network [20]. Li et al. (2019) present a systematic framework for the management of hazardous materials risk. They firstly define risk factors and determine the weight of factors by the fuzzy analytic hierarchy process (F-AHP), then, they analyze these risks by fuzzy FMEA, and risks are combined with QFD. They also develop a non-linear goal programming to determine the levels of risk measures [21]. Chiou (2020) develops a resilience-based signal control system to manage maximum risk over arcs in the network for HMTP and the maximum risk over the network is reduced by stochastic programming [22]. Hu et al. (2020) determine the plan for production and routes for transportation routes within a fixed period for multi-period HMTP [23]. Ziaei and Jabbarzadeh (2021) propose a robust location and route for hazardous materials by incorporating carbon emission and hazardous materials transportation risks [24]. Zhou et al. (2021) focus on HMTP and develop a multi-depot heterogeneous VRP model to minimize both risks and costs [25]. Ayyildiz and Taskin Gumus (2021) specify the risk factors for hazardous material transportation and determine the weights of these factors using Pythagorean fuzzy AHP [26]. Jinkun et al. (2022) develop a multi-objective pareto-based network design model to mitigate hazardous material transportation risks [27]. Additionally, some remarkable studies on this subject are summarized in Table 1 according to the objective functions and method used. Table 1 summarizes the different extensions of HMTP. As can be seen from the table, different problem structures, objective functions are used to deal with HMTP extensions. Also different mathematical models proposed to solve different objectives.

Table 1. *The remarkable studies based on HMTP*

Source	***Problem***	***Method***	***Objective Function***
[28]	*Traditional HMTP*	*Mixed integer programming*	*Minimum distance*
[29]	*Multi-objective stochastic dynamic HMTP*	*Heuristic algorithm*	*Optimum route*
[30]	*Multi-objective HMTP*	*Multi-objective modeling*	*Minimum risk, cost, exposed population*
[31]	*Split delivery HMTP*	*Bi-level modeling*	*Minimum cost*
[32]	*Multi product HMTP*	*Mixed integer programming*	*Minimum distance*
[33]	*HMTP focused on vehicle*	*Multi-objective modeling*	*Minimum risk of vehicle*
[34]	*Hazardous waste routing problem*	*Goal programming*	*Minimum cost*

The HMTP and its extensions are a popular research area among academics and researchers. These extensions deal with certainty (deterministic) and uncertainty (i.e., stochastic, fuzzy, or robust) in accordance with the problem structures. These problems can include a variety of real-life constraints related to risk, cost, distance and vehicle factors, security conditions, environmental, marine and energy issues, traffic density, and more [35]. There are different objective functions for HMTPs, as can be seen in Table 1. Minimizing total traveling time is the aim that we determine in this study, as the time spent on the road decreases, the risk of environmental and marine pollution decreases. In the following, the petrol station replenishment problems (PSRP) in the literature are discussed and summarized in Table 2.

Table 2. *The remarkable studies based on PSRP*

Source	***Problem***	***Method***	***Objective Function***
[36]	*Multi stage PSRP*	*Mixed integer programming*	*Maximum profit*
[37]	*Multi stage PSRP*	*Heuristic algorithm*	*Maximum service level*
[38]	*Traditional PSRP*	*Multi-objective modeling*	*Minimum service level*
[39]	*Multi product and stage PSRP*	*Mixed integer programming*	*Maximum profit*
[40]	*Multi product and depot PSRP*	*Mixed integer programming*	*Minimum cost*
[41]	*Trip packing PSRP*	*Mixed integer programming*	*Maximum profit*
[42]	*Multi product, stage and depot PSRP*	*Heuristic algorithm*	*Maximum profit*
[43]	*Periodic PSRP*	*Bi-level modeling*	*Minimax service level*
[44]	*Multi stage PSRP*	*Heuristic algorithm*	*Minimum distance*
[45]	*Multi product and stage PSRP*	*Mixed integer programming*	*Minimum cost*
[46]	*Multi product, stage and depot PSRP*	*Mixed integer programming*	*Minimum distance*
[47]	*Multi product and stage PSRP*	*Mixed integer programming*	*Minimum distance*
[48]	*Periodic PSRP*	*Mixed integer programming*	*Minimum distance*
[49]	*Heterogeneous fleet PSRP*	*Mixed integer programming*	*Minimum distance*
[50]	*PSRP with forecasted demand*	*Bi-level modeling*	*Minimum loss and distance*
[51]	*Multi product PSRP*	*Mixed integer programming*	*Minimum cost*

There are different extensions and approaches for PSRP in the literature, as can be seen in Table 2. Based on the research in the literature, the problem addressed in this study is considered a novel PSRP problem because it first takes into account traffic density. In addition to other studies, this article deals with time dependency and time window with a realistic objective function and also includes a real-life application for Istanbul.

This study aims to prepare a decision support system for the transportation of petroleum supplied from a refinery to petrol stations in different regions, with minimum risk in terms of environmental and marine pollution. Furthermore, the proposed mathematical model aims to decrease the total travel distance of tanker in order to reduce carbon emission because of the future emission space would be extremely strict [52]. The current study fills the following literature gaps:

- ✓ This study deals with time dependency and time window with a realistic objective function.
- ✓ This study considers environmental risks in the event of an accident.
- ✓ Environmental risk factors are determined by the HMTP literature and then the most appropriate factors for the PSRP are determined by consulting experts.
- ✓ The Delphi technique is used to determine the risks.
- ✓ This study is the first time-dependent vehicle routing problem application to petroleum transportation.
- ✓ This study also has a real-life application in Istanbul.

Within the scope of the study, the PSRP of a public company that distributes petroleum to petrol stations is discussed. Minimum marine and environmental pollution is the purposes of this problem. The rest of the paper is organized as follows: Section 2 gives the proposed mathematical model. Detailed problem definition and data collection are given in Section 3. Section 4 includes the application of the real case for petroleum transportation and the sensitivity analysis of the proposed methodology. Finally, Section 5 presents the conclusions and future projections for this study.

2.THE PROPOSED MATHEMATICAL MODEL

The steps of methodology to solve the considered time dependent PSRP with time windows are introduced in this section. The basic steps of the proposed methodology are data collection, mathematical modeling, and sensitivity analysis phases. The data to be collected to solve the model include traffic data, distances, service times, and time windows.

Traffic data is collected from traffic density map prepared by the Istanbul Metropolitan Municipality, distances between petrol stations are obtained by Google Maps, and service time for petrol stations is determined by experts. Time windows are determined according to the company's distribution strategy. Then, the proposed mathematical model to designate the time dependent PSRP with time windows is structured and solved using the collected data. The mathematical model is solved by IBM ILOG Cplex OPL Optimization Studio 12.8. Finally, the results are presented as routes and travel times and measured via sensitivity analysis. Details of these steps are presented in the following sections.

In the PSRP, it is aimed to minimize the total risk taking into consideration environmental concerns. Less travel time means less risk for the tankers in the distribution network. This fact highlights the practical potential of real-life practice. Accordingly, related information for a realistic approach to the PSRP is described below.

- ➢ The PSRP of a public company serving in Istanbul has been addressed.
- ➢ Petroleum is distributed to petrol stations through a tanker from a refinery.
- ➢ The refinery and most of the petrol stations are located by the sea.
- ➢ The stations do not have the infrastructure to supply petroleum by ships and some stations can only be reached by highway. So, petroleum must be distributed by land.
- ➢ It is assumed that the demands of the stations should be met at once.
- ➢ Petroleum distribution should be done within the time window that each station is suitable for service.
- ➢ Tanker speed varies according to traffic density.

During the determination of the risk of the route to be used by the tanker, many factors such as transportation time, distance to sea, and structure of the road (i.e. number of lanes, slope, type of road, etc.) are taken into account.

It is assumed that there is no contamination in the sea because the tanker that returns to the refinery will not carry petroleum.

Based on the information given above, a mathematical model is prepared for the problem. In this mathematical model, it is defined on a directed graph that is expressed as $G = (N, A)$, where N represents the set of nodes and A represents the set of arcs between nodes. The locations of each petrol station and refinery are represented as a node. The index "1" represents the refinery node. The set of arcs is defined on $A = \{(i, j): \forall i, j \in N, i \neq j\}$ and d_{ij} means distance between node i and node j, and it is nonnegative; also $d_{ij} = d_{ji}$. Each petrol station has a service time S_i and time window m_i, n_i. Arrival time to the petrol station A_i must be $m_i \leq A_i \leq n_i$. If the arrival time of the vehicle is earlier than m_i, it must wait (W_i) until the start of service is possible. The time intervals defined on T have starting time B_t and ending time E_t. The speed V_t varies on this time interval. Traveling time (t_{ij}) of the tanker between nodes i and j is calculated taking into account the speed V_t and distance d_{ij}. If the travel begins in the time interval "t" and ends in the next time interval "u", then the traveling distance is calculated via $(E_t - D_i)V_t + (A_j - B_u)V_u$ using leaving and arrival times. It is assumed that the tanker leaving the refinery must return to the depot by completing the operations within working hours. It is also assumed that the tanker must deliver petroleum to the petrol stations between 06:00 a.m.-18:00 (starting at 06:00 a.m. and ending at 18:00) and these delivery periods vary according to the time windows of the stations. The traffic density is examined for each 60-minute period (for example between 06:00-07:00, 7:00-8:00, etc.) and these data are used in the model. The tanker originates at the refinery, services the petrol stations, and returns to the refinery. The objective of the problem is to service all petrol stations while minimizing the total risk.

Sets

T Set of time intervals

I Set of nodes

Parameters

d_{ij} The distance between nodes (i, j)

R_{ij} The risk between nodes (i, j)

V_t The speed of tanker (t)

B_t Beginning time of time interval (t)

E_t Ending time of time interval (t)

S_i Service time for the node (i)

$[m_i, n_i]$ Time window for the node (i)

D_i Demand of the node (i)

C Capacity of tanker

M Big number

Decision Variables

A_i Arrival time to node (i)

L_i Leaving time from node (i)

t_{ij} Traveling time of tanker between nodes (i, j)

W_i Waiting time at node (i)

$$X_{ij} \begin{cases} 1, & \text{if arc (i, j) is used by tanker;} \\ 0, & \text{otherwise} \end{cases}$$

$$Y_{ij}^{tu} \begin{cases} 1, & \text{if tanker leaves from node (i) at time interval (t), arrives to node (j) at time interval (u)} \\ 0, & \text{otherwise} \end{cases}$$

Formulation

$min\ \sum_{i\in I}\sum_{j\in I/1} t_{ij}\, R_{ij}$ (1)

subject to

$\sum_{t\in T}\sum_{u\in T} Y_{ij}^{tu} = X_{ij}$ $(\forall i, j \in I)$ (2)

$t_{ij} \le MX_{ij}$ $(\forall i, j \in I)$ (3)

$t_{ij} \le A_j - L_i + M(1 - X_{ij})$ $(\forall i, j \in I)$ (4)

$t_{ij} \ge A_j - L_i + M(X_{ij} - 1)$ $(\forall i, j \in I)$ (5)

$d_{ij} - M\left(2 - X_{ij} - Y_{ij}^{tt}\right) \le (A_j - L_i)V_t$ $(\forall i, j \in I),\ (\forall t \in T)$ (6)

$d_{ij} - M\left(X_{ij} + Y_{ij}^{tt} - 2\right) \ge (A_j - L_i)V_t$ $(\forall i, j \in I),\ (\forall t \in T)$ (7)

$d_{ij} - M\left(2 - X_{ij} - Y_{ij}^{tu}\right) \le (E_t - L_i)V_t + \sum_{t<\rho<u}\left(E_\rho - B_\rho\right)V_\rho + (A_j - B_u)V_u$ $(\forall I, j \in I),\ (\forall t, u \in T), u > t$ (8)

$d_{ij} - M\left(X_{ij} + Y_{ij}^{tu} - 2\right) \ge (E_t - L_i)V_t + + \sum_{t<\rho<u}\left(E_\rho - B_\rho\right)V_\rho + (A_j - B_u)V_u$ $(\forall i, j \in I),\ (\forall t, u \in T), u > \mathrm{t}$ (9)

$\sum_{j\in I}\sum_{t,u\in T} Y_{ij}^{tu} E_t \ge L_i$ $(\forall i \in I)$ (10)

$\sum_{j\in I}\sum_{t,u\in T} Y_{ij}^{tu} B_t \le L_i$ $(\forall i \in I)$ (11)

$\sum_{i\in I}\sum_{t,u\in T} Y_{ij}^{tu} E_u \ge A_j$ $(\forall j \in I)$ (12)

$\sum_{i\in I}\sum_{t,u\in T} Y_{ij}^{tu} B_u \le A_j$ $(\forall j \in I)$ (13)

Li =Ai +Si+Wi $L_i = A_i + S_i + W_i$ $(\forall i \in I)$ (14)

$\sum_{j\in I} X_{ij} = 1$ $(\forall i \in I)$ (15)

$\sum_{i\in I} X_{ij} = 1$ $(\forall j \in I)$ (16)

$A_i + W_i \ge m_i$ $(\forall i \in I)$ (17)

$L_i \le n_i$ $(\forall i \in I)$ (18)

$\sum_{i,j\in I} R_{ij}X_{ij} \le R_{max}$ (19)

$\sum_{i,j\in I} D_i X_{ij} \le C$ (20)

$L_1 \le L_i$ $(\forall i \in I)$ (21)

$\mathrm{A_1} \ge \mathrm{A_i}$ $(\forall \mathrm{i} \in \mathrm{I})$ (22)

$A_i, L_i, t_{ij}, W_i \ge 0$ $(\forall i, j \in I),\ (\forall t \in T)$ (23)

$X_{ij}, Y_{ij}^{tu} \epsilon \{0,1\}$ $(\forall i, j \in I),\ (\forall t, u \in T)$ (24)

The objective function (1) minimizes the total risk. Constraint (2) is for each arc; if the arc is used, it ensures that the vehicle starts on a journey and ends in the same or a different time period. The traveling time can take values based on the usage of arc according to the constraint (3). The constraints (4) and (5) ensure that the arrival time of tanker to nodes and leaving times of tanker from nodes are related to the traveling times between nodes, and they also prevent the formation of subtours by following the arrival times of nodes, respectively. Constraints (6), (7), (8) and (9) allow the transitions between time intervals to the speed of the be linked to tanker and distance traveled. Constraints (6) and (7) are valid when the entire journey takes place in the same time interval. Constraints (8) and (9) are applied when the journey begins at the time interval "t" and ends at the next time interval "u". Constraints (10) and (11) ensure that the lower and upper limits of the time interval are linked to the time of leaving the tanker from each node. Constraints (12) and (13) also ensure that the lower and upper limits of time intervals are linked to the arrival time of the tanker to each node. Constraint (14) ensures that the leaving time of the tanker is equal to the sum of arriving time to the node, the waiting time at the node and the service time spent at the node. Constraints (15) and (16) are balance constraints for nodes. Constraints (17) and (18) consider that every petrol station must be supplied within a certain time window. If the tanker arrives too early, it must wait until the start of service is possible. Total risk cannot exceed maximum risk according to constraint (19). Constraint (20) ensures that the total demand of serviced stations can not exceed the capacity of the tanker. Leaving time from refinery must be less than leaving times of all nodes. So, the vehicle leaves the refinery first, according to constraint (21). The arrival time to the refinery must be greater than the arrival times of all nodes. So, the vehicle arrives at the refinery last, according to constraint (22). Node 1 denotes the refinery. Constraints (23) and (24) are non-negativity constraints and binary constraints for the decision variables.

3.REAL LIFE APPLICATION FOR ISTANBUL

Within the scope of the study, the PSRP is handled for Istanbul. Istanbul is the city where most of the energy consumption is seen in Turkey due to the high population [53]. Environmental and marine pollution is also increasing in the city. The problem of a public company that distributes petroleum to petrol stations in the target region is addressed here. Figure 1 shows the locations of the refineries and petrol stations in the supply network of this company. The company distributes petroleum between these points.

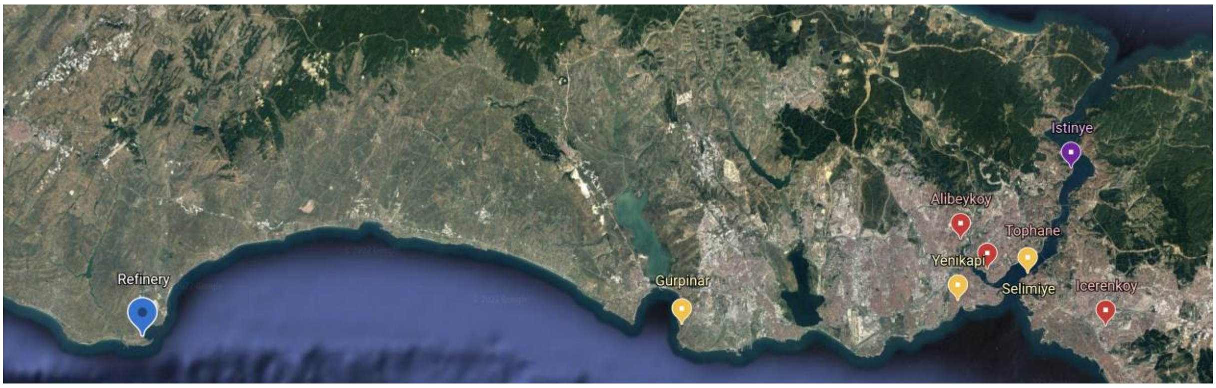

Figure 1. *Locations of the petrol stations and the refinery [26]*

The company supplies petroleum products from the refinery (shown with a blue pin in Figure 1) and distributes them to seven stations in Istanbul. There are three types of stations in the company's distribution network. The company's own petrol stations are represented with yellow pins, the petrol stations rented by the company to operate for other companies are represented with red pins, and lastly, the purple pin shows the station that provides petroleum to sea vehicles passing through the Bosphorus. The company's petroleum tanker is assumed to be distributed to the stations every day between 06:00 a.m.-18:00 and returns to the refinery after completing the distribution. It is assumed that the tanker can deliver to the stations indicated in yellow pins at any time during the day, to the stations indicated in red pins only between 06:00 a.m. and 12:00, and to the station indicated with purple pin only between 12:00 and 18:00. In addition, it is assumed that the service times of the tanker are different for stations. Table 3 shows the distances between the points indicated with pins in the company's petroleum distribution network.

Table 3. *Distances between petrol stations and refinery (km.)*

	Refinery	Gürpınar	Yenikapı	Selimiye	İçerenköy	Tophane	Alibeyköy	İstinye
Refinery	-	66.8	105	123	130	106	109	113
Gürpınar	66.8	-	40.3	57.8	55.4	41.5	47.6	52.1
Yenikapı	105	40.3	-	18.5	23.9	6	11.8	24.8
Selimiye	123	57.8	18.5	-	13.9	17.8	18.3	19.1
İçerenköy	130	55.4	23.9	13.9	-	18.5	30.4	23.2
Tophane	106	41.5	6	17.8	18.5	-	8	21.7
Alibeyköy	109	47.6	11.8	18.3	30.4	8	-	14.4
İstinye	113	52.1	24.8	19.1	23.2	21.7	14.4	-

The risk factors are determined by a comprehensive literature review, and then the most appropriate factors are specified by consulting with anonymous experts that study transportation operations for the petroleum transportation problem handled in this study. As a result, critical risk factors for petroleum transportation are determined in five main titles as road, environment, traffic, vehicle and material [26].

Road factors are important in determining the risks of HMTPs [54]. Traffic, road conditions can cause accidents that can have dangerous consequences [55]. The capacity can be determined according to the number of lanes on the road. The road material (gravel, asphalt, etc.) is also taken into consideration to determine the risks. In addition, deteriorated roads can cause an accident. Therefore, the road condition plays an important role in the transportation of hazardous materials.

The risk values of the factors are very crucial and should be considered for a possible accident for the tanker, which carries petroleum from the refinery to the petrol stations. It is obvious that petroleum leaking from the tanker in case of an accident can cause marine and environmental pollution. In this study, the risks of the roads the tanker uses on the distribution network are determined by expert interviews. Experts determine road risk values of the roads between 1 and 10 considering the proximity of the road to the sea and living areas, traffic density, the structure of the road, etc.

In this study, the Delphi technique is adopted while determining risks, and interviews with five different experts are carried out face-to-face and via email during the assessment of risks within the scope of this approach. Three of these experts work in petroleum transportation operations for public company. In addition, the opinions of two different academicians taking part in academic studies and projects on similar subjects are also taken, and the first meeting is held with the experts and ideas are collected in order to better understand the current situation and the problem. These negotiations are repeated until consensus is reached and expert opinions are obtained again and again. At the end of the process, the experts share a comprehensive common opinion about the risks. As a result of the evaluations by the experts on the risks, it is concluded that the experts had the same opinions on the risk values. Thus, the identified risks are integrated into the study. The risk values between nodes are given in Table 4

Table 4. *The risk values of arcs*

	Refinery	Gürpınar	Yenikapı	Selimiye	İçerenköy	Tophane	Alibeyköy	İstinye
Refinery	-	2	4	8	9	5	5	10
Gürpınar	0	-	1	5	4	1	1	5
Yenikapı	0	1	-	2	2	1	1	3
Selimiye	0	5	2	-	1	2	2	4
İçerenköy	0	4	1	1	-	3	3	5
Tophane	0	1	1	2	3	-	1	2
Alibeyköy	0	1	1	2	3	1	-	2
İstinye	0	5	2	4	5	2	2	-

The time-dependent VRP consists of the optimum routing of vehicles. In the time-dependent VRP, the traveling times between nodes may vary depending on the hours of the day [56]. When determining the travel time between nodes in the problem, the time period in which the travel begins on that arc is important. The planning period is divided into time intervals and different speeds are defined in these intervals. Usually, the solution aims to minimize the total travel time. The arrival time of the vehicle leaving from one node to the next node is determined by the departure time from the first node and the time spent on the route it uses. In this type of problem, the travel time is calculated using the departure time from each node and the average speed varying depending on that time. This is important in terms of structuring a realistic approach in traffic-intensive city centers. For example; while the speeds of the vehicles decrease due to very busy traffic during the morning hours, their speeds increase when the traffic density decreases at noon. In this study, the tanker speeds are determined taking into account the traffic density.

Risk is related to the time spent on the road, the density of traffic, and the speed of the vehicle. The proposed model for PSRP, which takes into account changing vehicle speeds ensures a more realistic approach than the traditional approaches. The travel time of the tanker depends on the moment it leaves the petrol station/refinery. Therefore, the planning period of petroleum distribution is divided into time intervals; then the different speeds are determined in these time intervals according to traffic density. By this way, a novel mixed integer programming formulation is developed to solve this time dependent VRP problem which minimizing the risk.

The traffic density in Istanbul, the largest and crowded city in Turkey, is one of the biggest problems. At the end of the year 2018, traffic density starts on business days in the morning and lasts approximately 2 hours, from 07:00 a.m. to 09:00 a.m., and then decreases in the middle of the day [57]. The petroleum distribution process must be completed between 06:00 a.m. and 18:00 in the problem handled in the study.

The speed of the tanker is reduced due to traffic density and so petrol distribution to the stations takes a longer time. The traffic density graph between 06:00 a.m.-18:00 in Istanbul can be seen in Figure 2.

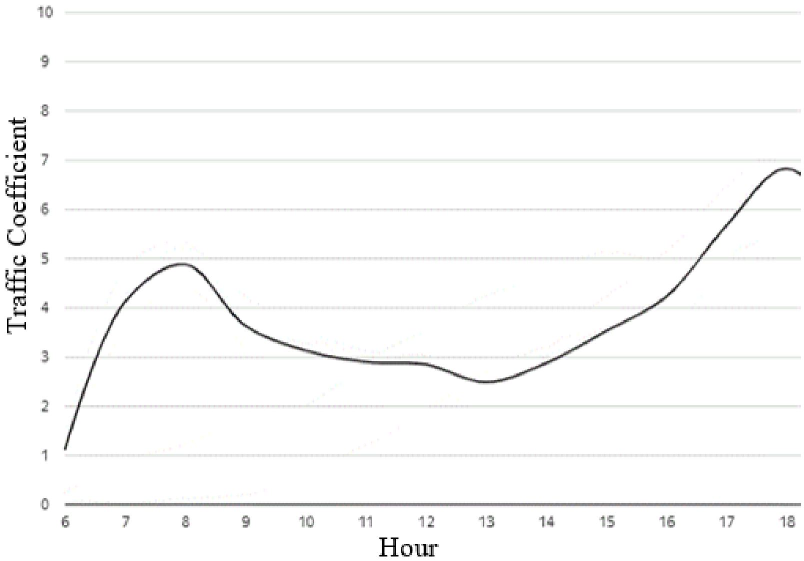

Figure 2. *Traffic density graphic between 06:00 a.m.-18:00 p.m.*

As can be seen in Figure 2, the traffic density varies between 06:00 a.m. and 18:00. To better express this variability in the proposed model, 60 minutes of time intervals are taken into consideration. Vehicle speeds varying according to traffic density levels in these time periods are determined using Equation 3.1 and are given in Table 5. Equation 25 is formed using historical data given in the 3-Year Traffic Analysis for Istanbul by Yandex [57]. The average traffic coefficients in an hour are determined using Figure 2.

$$Speed(km/h) = 100 - 10(Average\ Traffic\ Coefficient\ in\ Hour) \quad (25)$$

Table 5. *Tanker speeds according to the time interval*

Time Interval	**Density**	**Speed (km/h)**
06:00-07:00	2.50	70
07:00-08:00	4.25	57.5
08:00-09:00	4.30	57
09:00-10:00	3.30	67
10:00-11:00	2.95	70
11:00-12:00	2.75	70
12:00-13:00	2.50	70
13:00-14:00	2.75	70
14:00-15:00	3.10	69
15:00-16:00	3.50	65
16:00-17:00	5.00	50
17:00-18:00	6.50	35

The maximum speed limit in urban use in Istanbul is 70 km/h [58]. So, the speeds in time intervals of 06:00 a.m.-07:00 a.m. and 10:00 a.m.-14:00 are fixed at 70 km/h.

4.APPLICATION OF THE PROPOSED MODEL

The route of distribution of petroleum with minimum risk is obtained using the proposed mathematical model as shown in Figure 3. The objective function value that shows the risk degree is determined as 261.381. The proposed mathematical model is solved on a computer with Intel(R) Core(TM) i7-9750-H CPU @ 2.60 Ghz processor, 16.00 GB RAM, using IBM ILOG CPLEX Optimization Studio 12.8 package program. The central processing unit (CPU) time for this problem is 6.06 seconds.

Figure 3. *Optimum route for petroleum distribution*

The route in which the tanker delivers petroleum by supplying from the refinery is shown in yellow. The route by which the tanker returned to the refinery after the last arrival of the Istinye Petrol Station is shown in red. For the problem handled in the study, it is assumed that the tanker would be empty after the petrol station in İstinye, which is the last served node. Therefore, it is assumed that there is no risk on the route shown in red. Therefore, even if the route determined by the proposed mathematical model for the return to the refinery is located close to the sea, it does not pose any risk. The arrival time, service time and waiting time for each petrol station are given in Table 6.

Table 6. *Arrival time, service time and waiting time for each petrol station*

Petrol Station	Arrival	Service (min)	Waiting (min)	Departure	Traveling (min)
Refinery	-	-	0	06:00	57
Gürpınar	06:57	30	0	07:27	44
Tophane	08:11	33	3	08:47	18
Selimiye	09:05	32	0	09:37	12
İçerenköy	09:49	31	0	10:20	21
Yenikapı	10:41	40	0	11:21	10
Alibeyköy	11:31	29	0	12:00	12
İstinye	12:12	20	148	15:00	118
Refinery	16:58				

The tanker distributes petroleum during the time period between 06:00 a.m.-16:58 by taking into account the traffic density. As can be seen from Table 6, to minimize travel time, the vehicle completes the entire distribution process at time intervals where the traffic density is less than in the other intervals. The tanker leaving the refinery at 06:00 a.m. follows the route Gürpnar-Tophane. It arrives in Tophane at 08:11 a.m. and completes the petroleum loading process at 08:44 a.m. considering 33 minutes of service time. Due to the high traffic density, the tanker waits for 3 minutes at Tophane, until 08:47 a.m. The vehicle leaves Tophane at 08:47 a.m. and follows the route Selimiye-çerenköy-Yenikap-Alibeyköy-stinye, respectively, without waiting. It arrives at İstinye at 12:12 and completes the petroleum loading process at 12:32, considering 20 minutes of service time. Due to the high traffic density, the tanker waits for 148 minutes in

İstinye. Lastly, the tanker departs from İstinye at 15:00 and arrives refinery at 16:58. And so on tanker spends 292 minutes as total traveling time on the road.

4.1. Sensitivity Analysis

The proposed model for PSRP that takes into account changing vehicle speeds ensures a more realistic approach than the mathematical models with traditional PSRP. By solving the mathematical model, accurate and efficient results are obtained. Sensitivity analysis is also performed to show and prove the accuracy and efficiency of the proposed mathematical model by presenting a comparison with the traditional PSRP solution.

The traditional PSRP where variable vehicle speed based on traffic density is not considered is applied to the network. The tanker distributes petroleum to the stations at an average speed. This average speed is assumed to be 60 km/h. according to Table 5. The optimum distribution route obtained by the mathematical model for the traditional PSRP is determined as shown in Figure 4.

Figure 4. *Optimum route for petroleum distribution according to the results of sensitivity analysis*

The arrival time, service time and waiting time for each petrol station according to the results of the sensitivity analysis are given in Table 7.

Table 7. *The results of the sensitivity analysis*

Petrol Station	Arrival	Service (min)	Waiting (min)	Departure	Traveling (min)
Refinery	-	-	0	06:00	57
Gürpınar	06:57	30	0	07:27	42
Yenikapı	08:09	40	0	08:49	6
Tophane	08:55	33	0	09:27	17
İçerenköy	09:44	31	0	10:15	12
Selimiye	10:27	32	0	10:59	16
Alibeyköy	11:15	29	0	11:44	12
İstinye	11:56	20	4	12:20	97
Refinery	13:57				

In traditional PSRP with time windows where variable vehicle speeds based on traffic density are not taken into account, the tanker spends a total of 259 minutes on the road. This route has a risk value of 281.321. The tanker spends 292 minutes on the road in the proposed mathematical model, and the route has the risk value of 261.381. Compared to the result of the proposed mathematical model, the total risk on the road by tanker increases approximately 7.63% in the traditional model. As can be seen, traditional PSRP model has less traveling time, but also it has a bigger risk. The proposed mathematical model reduces the risk while increasing travel time.

4.CONCLUSIONS

The well-known PSRP with time windows, which calls for the determination of optimal routes by operating a fleet of tank trucks to serve a set of petrol stations over a specific planning horizon, is one of the most significant difficulties in the petroleum business. This problem is extended in this study by taking variable tanker speed into account. So, time-dependent PSRP with time windows is handled and novel mixed integer programming formulation is developed to solve problem. In this study, the PSRP for a public company located in Istanbul is handled. The problem is considered as a time-dependent vehicle routing problem with time windows. A novel mathematical model is proposed for the problem. The optimum route is determined by minimizing risks such as environment and marine pollution. The risk is determined by considering factors such as traffic, vehicle speed, road structure, proximity to the sea, and living areas and is used in the proposed mathematical model.

The contributions of the study to the literature can be defined as follows: (1) The petrol station replenishment problem for a public company located in Istanbul is discussed; (2) In order to handle the proposed time-dependent problem in a more realistic way, variable tanker speeds are considered based on traffic density; (3) Transportation times of the tanker from the refinery to the stations are determined; (4) A study that considers the risks of marine and environmental pollution is presented to the literature; (5) A real case is applied to show the applicability and reliability of the methodology; (6) The proposed method would be used for the organizations' objectives of improving their petroleum distribution strategies.

As future directions, larger and/or combined regions can be selected as the application area for the PSRP. Heuristic or metaheuristic algorithms can be used to handle more complex problems. Besides, the problem can be modeled as a robust model or a stochastic model.

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