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AUTOMATIC LICENSE PLATE RECOGNITION SYSTEM LOCATION SELECTION

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ABSTRACT

AUTOMATIC LICENSE PLATE RECOGNITION SYSTEM LOCATION SELECTION

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With the help of advancements on sensor and data transfer technologies, the usage area of Automatic License Plate Recognition (ALPR) Systems has been enlarged. Both public and private sectors implement ALPR applications for their respective needs. Public safety ALPR applications aim to monitor and control traffic data at both individual and collective levels. For this reason, to build an efficient sensor network number and location of ALPR systems should be determined optimally. This study focuses on determining optimal number and location of ALPR systems in order to maximize network coverage that consists of vehicle coverage and road coverage. The study provides numerical experiments designed for two cities in Turkey. Centralized and decentralized decision-making processes are compared and it is suggested that determining number and location of ALPR systems in a centralized manner would provide better network coverage. The relative importance of vehicle and road coverages that constitutes the network coverage is considered and optimal solutions for number and location of ALPR systems under various configurations are presented.

Keywords: Location selection, Public Safety, License Plate Recognition, Centralized, Network Coverage,

ÖZ

OTOMATİK PLAKA TANIMA SİSTEMİ YER SEÇİMİ

Gör, Buğra

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Sensör ve veri aktarımı alanlarındaki teknolojik gelişmeler neticesinde Otomatik Plaka Tanıma (OPT) sistemlerinin kullanım alanı genişlemiştir. Hem özel hem de devlet kurumları OPT uygulamalarını kendi ihtiyaçları doğrultusunda kullanmaktadır. Kamu güvenliği alanında kullanılan OPT sistemleri, bireysel ve kolektif seviyelerde trafik bilgisini gözlemlemeyi ve yönetmeyi amaçlamaktadır. Bu amaçla, etkin bir sensör ağı oluşturmak için OPT sistemlerinin sayı ve yerleri optimal olarak belirlenmelidir. Bu çalışma, OPT sistemlerinin optimal adet ve yerlerinin bulunarak araç kapsaması ve yol kapsamasından oluşan ağ kapsamasını eniyilemeyi amaçlamaktadır. Çalışma, Türkiye'deki iki şehir için tasarlanmış sayısal deneyleri sunmaktadır. Merkezi ve lokal karar verme süreçleri bu deneyler kapsamında karşılaştırılmış ve OPT sistemlerinin adet ve yerlerinin merkezi olarak belirlenmesinin daha yüksek ağ kapsaması sağladığı görülmüştür. Ağ kapsamasını oluşturan araç ve yol kapsamalarının birbirlerine göre önem ağırlıkları göz önüne alınarak, farklı konfigürasyonlar için en iyi OPT sistemi yer ve adetleri konusunda çözümler sunulmuştur.

Anahtar Kelimeler: Yer seçimi, Kamu güvenliği, Plaka Tanıma Sistemi, Merkezileştirilmiş, Ağ Kapsaması

This thesis is dedicated to my parents and my love.

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LIST OF ABBREVIATIONS

ITS	Intelligent Transportation System
SLP	Sensor Location Problem
ALPR	Automatic License Plate Recognition
SCLP	Set Covering Location Problem
MCLP	Maximum Coverage Location Problem
MALPR	Mobile Automatic License Plate Recognition
OD	Origin-Destination
VC	Vehicle Coverage
RC	Road Coverage
NC	Network Coverage

CHAPTER 1

INTRODUCTION

Less than 4 years after the Wards Auto's report (2011) on world vehicle population topping 1 billion units in 2010, it surpasses 1.2 billion units in 2014 and it is forecasted that 2 billion vehicles will be on roads by 2035 (Voelcker, 2014). Growing number of vehicles necessitates efficient intelligent transportation system (ITS) solutions to plan and manage traffic. ITS, as defined by European Parliament directive (European Parliament & The Council of the European Union, 2010), integrates telecommunications, electronics and information technologies with transport engineering in order to plan, design, operate, maintain and manage transport systems. Traffic surveillance, one of the major application areas of ITS, has become more popular with the advancements on computer technology for the past few decades. This in turn makes it necessary to collect real time traffic data by building sensor networks for managing and analyzing transportation systems.

Various sensor technologies such as surveillance cameras, speed detecting sensors, image sensors and magnetic sensors are used to collect traffic data. It is suggested that the collected data can be used to obtain the number of vehicles on a lane or road, and to identify vehicles and predefined paths used by those vehicles (Mitsakis et al, 2017). The real-time traffic data collected from road networks is used by both public and private sectors for different purposes. For instance, the governmental agencies that are responsible for managing traffic utilize the traffic information obtained from the sensor networks to develop strategic plans concerning traffic flow and traffic safety. This information including but not limited to traffic congestion, origin-destination patterns, vehicle identification, tracking and tracing specific vehicles provides policy makers a wide variety of application areas.

Monitoring and controlling traffic through sensors require building and maintaining an efficient and effective network system. Such a system should ensure a certain level of coverage as well as accuracy. Coverage of a network can be associated with distribution of sensors throughout the network and volume of the traffic flow captured by those sensors. On the other side, accuracy can be described as the rate of true detection of vehicles. Accuracy can be improved with high technology and high-quality sensors while coverage can be improved by implementing large number of sensors in the network. The number of sensors in a network should be determined with respect to required level of traffic information. The density and distribution of those sensors should be determined according to the needs. It would be impractical to place sensors to cover all roads or links in a network due to the accompanying costs, complexity of road networks, and data handling problems. Hu et al. (2009) argue that deploying a large number of sensors on an urban network of a moderate size causes substantial costs.

The problem of decision on the number and location of sensors to be deployed under limited budget attracts attention of researchers as well as traffic managers. The tradeoff between cost and coverage of the sensor network form the basis of a so called Sensor Location Problems (SLP). In this context, the aim of our study is to define a method to locate automatic license plate recognition (ALPR) systems to maximize coverage in a road network. The method is tested on real life settings, Ankara and Kırıkkale, two neighbor cities in Turkey where an integrated ALPR network system is already in use. The study addresses two different cases: decentralized and centralized. In the decentralized case, the sensor location problems for Ankara and Kırıkkale are solved independently. On the other hand, in the centralized case, the two-city network is examined as one and thus, instead of two separate problems a single problem with a larger network is solved. To test the performance of the method, the results for the two cases are compared with those in the existing system. Although the tests are conducted on two cities as a pilot study, our approach can easily be extended for the location of ALPR systems over a nation-wide road network.

The rest of this study is organized as follows: Chapter 2 discusses the previous studies about sensor location problems and methods used to determine optimal sensor location on a road network. In Chapter 3, information on ALPR technology and its applications are presented. Chapter 4 develops the approach and demonstrates it on a toy example. In Chapter 5, experiments conducted on two cities in Turkey are presented. In this section, Ankara and Kırıkkale cities are selected for conducting numerical examples. First, decentralized cases are examined separately for both cities. Later, a single network of two cities is considered in centralized case. Lastly, current state of the two cities are compared with decentralized and centralized cases. Chapter 6 provides the analyses and the results of numerical experiments designed in previous chapter. Finally, future study issues and conclusive remarks are presented in Chapter 7.

CHAPTER 2

LITERATURE REVIEW

Determining a facility location has a crucial impact on strategic planning for both public and private sectors. There is an extensive research on facility location problems and various methods and models are suggested to satisfy different needs. One of the most popular subject in facility location model is covering problems. Francis, McGinnis and White (1992) suggest that, determining the number and the location of schools, police stations, libraries, parks and waste disposal facilities can be formulated as covering problems.

In literature, covering problems are divided into two major categories with respect to the objectives of the problems: the set covering location problem (SCLP) first introduced by Hakimi (1964) and the maximal coverage location problem (MCLP) studied by Church and ReVelle (1974). The objective of SCLP is to find the minimum number of facilities while meeting all the demand, covering the set. Objective function of SCPL minimizes the total number of facilities and constraints ensure that each customer zone is covered by at least one facility located on a possible site in the network. In MCLP, the aim is to maximize the demand satisfied with the limited number of facilities available. MCLP problems put a limit on the budget and investigate optimal locations of facilities to be located in order to maximize network coverage. It is shown that both SCLP and MCLP are NP-hard problems and various heuristics and methods are developed to solve these problems (Current and Schilling, 1990).

Enhancements in sensor technology and the usage of sophisticated sensors on road networks to collect real time traffic information give rise to a specific type of coverage problems, SLP. Since implementation of sensors over a road network to observe real time traffic information requires high investment, in SLP it is aimed to achieve high accuracy and high coverage which are considered to be the major requirements of an effective sensor network. The tradeoff between cost and effectiveness of sensor networks motivates researches to find optimal number and location of sensors over a network.

A set of SLP studies focuses on determination of the number and the location of sensors to optimize traffic flow estimation. In literature, there are various approaches developed to estimate Origin-Destination (OD) matrices. An OD matrix contains information on number of vehicles that are travelling between origin and destination nodes of a network. Obtaining the true OD matrix for a network is costly and time consuming. However, with the help of traffic count stations located on specific links or nodes, good estimates can be achieved (Abrahamsson, 1998).

Yang et al. (1991) examine the reliability of OD matrix using maximal possible relative error between true OD matrix and estimated OD matrix as a measure of variability according to number of sensors and their locations. Yang and Zhou (1998) introduce four different rules while determining sensor locations in a network: OD covering rule, maximal flow fraction rule, maximal flow intersecting rule, and link interdependence rule. They use these rules to develop different models for determining optimal sensor number and locations. While OD covering rule emphasizes selection of locations observing all OD pairs, maximal flow intersecting rule promotes the sensor locations with maximum observed flow.

Chung (2001) includes purchase and installation cost of sensors and proposes two models with different objectives: cost minimization problem with complete OD coverage constraint and OD coverage maximization under limited budget. Bianco et al. (2001) develop two-stage procedure for OD matrix estimation. First, they solve the cost minimization of sensor installation problem to find sensor locations. Then they use flows obtained from the locations determined in the first stage to construct OD matrix estimation models. Ehlert et al. (2006) develop a software that contributes to the literature with several practical aspects. In their study, preexisting sensors on the network are taken into account while locating additional sensors under budget limitation. In the same study, relative weights can be assigned to OD flows and by doing so; links carrying more informative data than others can be favored. Yang et al. (2006) propose a model to determine the location of traffic count stations in order to separate as many OD pairs as possible. In their study, an OD pair is said to be separated if trips between this OD pair are entirely intercepted by the current traffic counting stations.

All the studies mentioned above are based on counting sensor locations in links that provides information only from those observed links. Castillo et al. (2008b) propose a model to determine the optimal locations of license plate scanning sensors for path flow construction. Path flow or route flow terms concern with alternative ways to travel between an origin and a destination. They suggest that plate scanning sensors lead to better estimations for OD and route flows since they provide more information than counting sensors. In the same study, they provide a method for selecting minimum number of links to observe exact route flows. Castillo et al. (2010) present full observability approach by incorporating license plate scanners. They state that a subset of unobserved flows is observable if its flow can be calculated in terms of the observed flows. They use this approach to find the optimal location of sensors that enables full observability of links in the network.

Gentili and Mirchandani (2011) provide a comprehensive review on sensor location problems. They present a framework for different sensor types (counting sensors, image sensors and license plate recognition sensors). Ten different models are constructed with respect to sensor location determination rules, showing that certain SLP models can be relaxed to MCLP or its variants.

In a more recent study, Mitsakis et al. (2017) present a methodological approach and application on a SLP. They propose a quadratic programming model for maximizing the traffic flow passing by Bluetooth sensors over a network. They provide a numerical example on a road network in Thessaloniki, Greece. The network had already Bluetooth sensors installed, so the authors try to improve the network coverage by additional installations. They introduce the neighboring intersections where Euclidian distances between any intersection node pair is less than predefined unit distance. The model used in the study does not allow to select two neighboring intersection. It is stated that identification of intersections with high traffic volume and intersections through which the drivers can follow alternative routes are important for building an efficient sensor network.

Most studies on SLP aim to find or estimate certain traffic flow information by using prior information on links, nodes, and OD matrices. In our study, we also use prior link flow information to determine optimal automatic license plate recognition sensor locations. However, rather than estimating OD matrix or route flows, our study aims to maximize the network coverage that consists of vehicle coverage and road coverage by determining automatic license plate recognition sensor locations on nodes in the network. We incorporate the close neighbor constraint similar to that of Mitsakis et al. (2017).

According to experts, an efficient sensor location methodology needs to address sensor locations with high traffic volume and intersection of links that drivers can follow alternative routes. In our study, we refer these issues as vehicle coverage and road coverage in such a way that vehicle coverage stands for maximum traffic volume to be captured by an ALPR sensor and road coverage stands for how many directions or links that a sensor can serve at that location.

CHAPTER 3

AUTOMATIC LICENSE PLATE RECOGNITION

In this chapter, information on ALPR system network applications will be provided. ALPR application areas, purposes, capabilities and requirements of ALPR systems will be discussed. Lastly, public safety ALPR system application used in Turkey will be illustrated.

3.1. Historical information of ALPR Technology

As an ITS solution, ALPR can be defined as a process of capturing images or video of license plates and transforming those visual data to alphanumeric plate numbers through certain algorithms. ALPR technology is developed in UK in 1976 by The British Police Scientific Development Branch (Qadri and Asif, 2009). At that time, lack of digital cameras, and limited computational capacity and data transfer technology suffice lower accuracy and functionality. Thus, first practices were performed under laboratory conditions as ALPR system was impractical for real life applications.

Technological developments on the related areas help improving the capability while enlarging the area of use of ALPR systems. Today, APLR systems can be used to satisfy various needs of commercial and governmental stakeholders. As it is illustrated in Figure 1, practices include parking lot plate reading, gas station vehicle recognition, toll collection systems, customs control, traffic control and public safety applications. Purposes and capabilities of an ALPR system differ with respect to usage area. For a parking lot, for example, plate numbers of vehicles, entering and leaving times of those vehicles are required. On the other hand, for toll collection systems, type of vehicle should be obtained to differentiate price on trucks and cars.

Figure 1. *ALPR applications (retrieved and collated from the Internet)*

According to Roberts and Casanova (2012), the European Secure Vehicle Alliance notes that terrorist attacks in London in 1993 resulted in the “ring of steel”, a surveillance and security cordon supported by closed-circuit television and ALPR cameras. Law Enforcement Management and Administrative Statistics surveys in 2007 and 2013 provide insights on the usage rate of ALPR systems in the US. The rate of the law enforcement agencies that use ALPR systems in the US has increased from 19% to 34% for the period 2007-2013 indicating that ALPR system usage for public safety applications is increasing.

In our study, a country-wide ALPR system network used by law enforcement units is examined. In this sense, aim of the ALPR system is to help law enforcement agencies to implement public safety practices by increasing investigative capabilities. These safety practices include searching for vehicles that are unregistered, stolen, involved in criminal or terrorist activities or owned by wanted people. Such an ALPR system is expected to identify, trace, track, and analyze traffic behavior at both individual and collective levels. Specifically, tracing, tracking and analysis require a network of multiple ALPR system installations dispersed over a network of concern.

The data to be collected from an ALPR system may include plate number, passing time, direction, brand, model, color and so on. Collection of such data from separate ALPR locations can be aggregated on a central database for further analysis or it can be kept at local databases. Establishing a central database enables network-wide analysis, while local database provides node-based information for authorities.

In Turkey, law enforcement agencies, Turkish Gendarmerie and Turkish Police Forces, use ALPR system networks for public safety purposes. Both agencies' goal is to ensure public order. However, they utilize technically and administratively different nation-wide plate recognition systems with respect to their needs and area of responsibility. Simply, police forces are located in city centers and public areas while gendarmerie operates in rural context.

3.2. ALPR System Public Safety Applications

In study, the ALPR system used by Turkish Gendarmerie will be examined. With more than 300 ALPR systems located on city and state roads, Gendarmerie collects huge amount of traffic data for public safety applications nation-wide. The flow of data is illustrated in Figure 2 below:

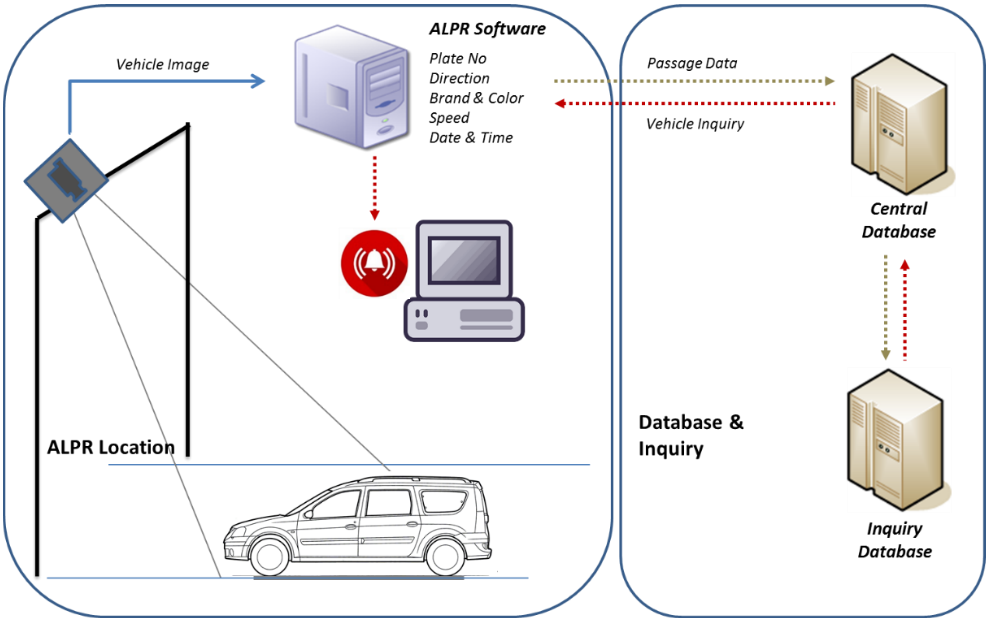


Figure 2. *Data flow illustration of the Turkish Gendarmerie ALPR system*

The data is collected by the ALPR system located on a road. Cameras mounted on overhead poles take images of passing vehicles and send them to computer in the nearby office. The ALPR software on the computer detects plate number, direction, brand, color and speed of the vehicle. With date and time information, the data package is transferred to central database to be recorded. Central database then sends passage data to another database for inquiry to get information about the vehicle status. The vehicle status information is sent back to central database. Then, central database sends back the vehicle status to the related office. After passing by an ALPR location it takes several seconds to obtain vehicle status information at the office. Finally, gendarmerie uses this information for law enforcement purposes.

Simply, the purpose of the ALPR system used by Turkish Gendarmerie is to monitor and control traffic in the responsibility area. Controlling traffic in this sense starts with capturing maximum possible traffic volume. Ability to inspect a large portion of the traffic volume helps law enforcement units not only to solve more judicial cases but also to create a larger database for big data applications. Second step in controlling traffic can be considered as tracing back and tracking forward of individual vehicles to achieve individual traffic information. Information related to plate and direction of a vehicle passing by successive or neighbor ALPR systems in a specific period of time helps law enforcement units in fighting against terrorism, trafficking, auto theft and so on.

If located on an intersection of multiple nearby road-links, the data collected by ALPR cameras are aggregated in a single office. With the help of data connection between cameras and the ALPR software, the office can detect which vehicle is directed which way. According to expert opinion, two important measures of effectiveness of the ALPR system network are daily number of vehicles identified and number of different road-links covered by the network. Therefore, it can be inferred that efficiency of the network is highly dependent on number and location of ALPR systems.

While determining location of an ALPR system, technical constraints and administrative decisions should be addressed. For technical dimension, presence of a nearby Gendarmerie office, availability of Internet, data transfer infrastructure, formal permissions from General Directorate of Highways and municipalities should be considered. Technical constraints determine whether a candidate location is appropriate for installation and system integration or not.

Administratively, the number and location of ALPR systems to be installed on a network of concern can be determined by *central office* or *local authorities of the city*. In our study, if local authorities in cities give number and location decisions for ALPR systems, then it is called *decentralized case*. In other case called *centralized case*, the number of ALPR systems allocated to each city and their locations are determined by the central office.

The centralized or decentralized location selection of ALPR systems have an impact on the efficiency of the network. In decentralized case, local authorities only consider the city-wide road network and do not pay attention to other cities' decisions. In centralized case, nation-wide road network is considered as a whole and administrative decisions are given accordingly. In this study, this impact will be analyzed in later parts.

CHAPTER 4

THE APPROACH

In our study, we seek to propose a mathematical model for determining optimal location of ALPR systems to be deployed over a network by maximizing the network coverage. We want to address the differences between centralized and decentralized decision-making setting and their impact on the network coverage under different parameters.

We aim to compare the efficiency of centralized and decentralized cases in terms of number and location of ALPR systems suggested by those settings. Locations of ALPR systems can be determined by local authorities (city-wide authorization) or central office (nation-wide authorization) as mentioned in the previous chapter. Local authorities include their experience and knowledge about the region of concern while determining location of ALPR systems. Central authorities can supervise the whole country and analyze the possible locations for a geographically dispersed network system connecting cities each other.

The models used in our study lie within covering problems which are divided into two major categories as SCLP and MCLP. In the SCLP, the objective is to minimize the facility location cost while ensuring specified level of coverage. In the MCLP, the objective is to maximize the coverage under limited number of facilities. Both the SCLP and MCLP model variants are incorporated in our study. MCLP is used to observe the differences in maximum network coverage under limited number of ALPR systems whereas SCLP is used to minimize the number of ALPR systems required to ensure certain level of network coverage.

Expert opinions are referred about the coverage information requirements to include the right dimensions of network coverage data during model construction. According to experts, both daily number of vehicles detected and the number of road-links monitored that drivers can change their course of trip are important for a suitable analysis. In other words, an ALPR system location should be selected such that it captures highest possible traffic volume and largest possible number of road-links.

Experts also address the relative importance of these two metrics. It is stated that their relative importance to each other may vary depending on region and time of interest. For regions subjected to trafficking, auto theft or terrorism activities, the number of road-links covered may be more important than daily number of vehicles detected. Assuming that vehicles associated with such illegal activities follows more secluded and low-density roads, it may be reasonable to locate ALPR systems on low-density locations that can monitor multiple road-links to control the region. On the other hand, for urban regions with large roads or highways accompanying with high traffic density, the number of vehicles detected per day may be more important. In such regions, the main concern of the ALPR system is to monitor the traffic flow and to capture minor crimes as vehicles with unregistered/unsuitable license or attachment order.

In our study, network coverage is divided into two distinct parameters to reflect the coverage requirements of the system: *vehicle coverage (VC)* and *road coverage (RC)*. VC is the ratio of the number of vehicles passed by an ALPR location in a day to total number of vehicles passed by all possible ALPR locations in a day. For an ALPR location, the vehicle coverage represents the percentage of vehicles that could be captured by all possible ALPR locations. In a similar sense, road coverage is the ratio of the number of different road-links covered by an ALPR location to total number of roads that can be covered by all possible ALPR locations.

An ALPR location that has large VC may cover only one road-link and a junction point may have low VC while collecting data on 5 different road-links. To exemplify the tradeoff between VC and RC, consider the possible ALPR locations for a sample network in Table 1.

Table 1. *ALPR location parameters for a sample network*

ALPR Location	# of Vehicles Covered	# of Road-Links Covered	VC	RC	Average Coverage
1	10,000	4	10%	40%	25%
2	20,000	3	20%	30%	25%
3	30,000	2	30%	20%	25%
4	40,000	1	40%	10%	25%

From Table 1, it can be observed that location 1 has the highest RC and lowest VC. In contrast, location 4 has the highest VC and lowest RC. All possible locations have 25% average coverage values. At this point, a question arises: If only one ALPR system is available, where should it be located? To represent the relative importance of VC and RC, a weight coefficient p for VC and 1- p for RC are introduced. If the example above is reviewed under p=0.8, where the VC is much more important than RC, the results are as follows in Table 2:

Table 2. *Weighted parameters for ALPR locations, p=0.8*

ALPR Location	VC	RC	Weighted VC (0.8xVC)	Weighted RC (0.2xRC)	Weighted Sum
1	10%	40%	8%	8%	16%
2	20%	30%	16%	6%	22%
3	30%	20%	24%	4%	28%
4	40%	10%	32%	2%	34%

It is obvious that, giving more importance to VC would favor the locations with higher VC values. However, as mentioned before it is not easy to find a unique *p* value that is valid for all regions to differentiate the importance of VR and RC. To address this issue, we examine our results under different *p* values ranging from 0.1 to 0.9 and observe their effect on the problem.

An important issue in determining ALPR locations is the dispersion of available ALPR systems over the network. If there are few numbers of ALPR systems available over a small network, it would be preferable to locate these ALPR systems far from each other. When ALPR locations are selected according to weighted sum values calculated by VC, RC, and p parameters; ALPR systems may be located too close to each other that may lead to duplication of collected vehicle data in short distances.

Additionally, if two ALPR systems are located on the same road-link, that is, they are neighbor locations located either end of that road-link, then duplication of traffic data in a short time would be inevitable. Combining the close-distance and on-the-same-road-link conditions, close neighbor ALPR locations are defined. Close neighbor ALPR locations are on the same road-link and distance between those locations is less than a predefined distance.

Vehicle license plate data collected by an ALPR location would be duplicated at its close neighbor location if there are any. Duplicated vehicles cause overestimating the VC of the network if close neighbor locations are utilized. The same vehicles detected by close neighbor locations in short distances are included in VC calculation for both locations. On the other side, cumulative RC of close neighbors are not affected since both locations may capture different directions or road-links even though they are on the two ends of the same road-link.

Experts stated that close neighbor location pairs should not be selected together as ALPR locations. This limitation may lead important differences between decentralized and centralized cases on ALPR location selection. In terms of decentralized setting, local authorities would decide on ALPR locations in each city separately while eliminating selection of close neighbor locations only for those cities. For centralized case, consider a network of two neighbor cities connected by an inter-city road. The inter-city road may contain two or more ALPR locations on the same road-link that are close to each other but in different cities. In this sense, the close neighbor condition should be revised to include not only inner-city ALPR locations but also inter-city ALPR locations. That is, some decentralized optimal ALPR locations determined for multiple neighbor cities would result in inter-city close neighbor ALPR locations in centralized terms.

We next introduce our model and then demonstrate close neighbor condition and its impact on decision-making setting on an example.

4.1. Optimization Model

Sets

- i, j ε I, possible ALPR location set.

Decision Variables

- ALPR location variable set, x_i

$$x_i = \begin{cases} 1, & \text{if ALPR system is located on } i \\ 0, & otherwise \end{cases}$$

Parameters

- *Close neighbor parameter (*$\boldsymbol{d_{ij}}$*).* Close neighbor locations are on the same road-link and the minimum distance between those locations is less than predefined distance.

$$d_{ij} = \begin{cases} 0, & \text{if i and j are close neighbor locations} \\ 1, & otherwise \end{cases}$$

- *Daily average number of vehicles passed by location i*, ($\boldsymbol{V_i}$)
- *Number of road-links that can be observed by location i*, ($\boldsymbol{R_i}$)
- *Vehicle coverage of location i* ($\boldsymbol{VC_i}$), the rate of number of vehicles passed by an ALPR location in a day to total number of vehicles passed by all possible ALPR

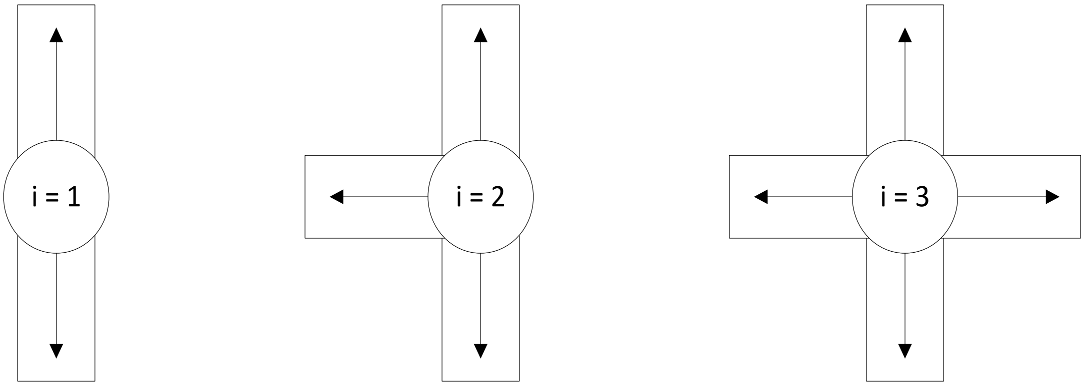
locations in a day. VC is calculated using the following formula where VC_i represents a measure of vehicle flow percentage of any location i:

$$VC_i = \frac{V_i}{\sum_i(V_i)}$$

- *Road coverage of location i* ($\boldsymbol{RC_i}$), the rate of number of road-links covered by an ALPR location to total number of road-links that can be covered by all possible ALPR locations. RC_i is calculated using the formula given below:

$$RC_i = \frac{R_i}{\sum_i(R_i)}$$

RC calculation is illustrated in Figure 3 below: (Consider 3-location network with total number of road-links is 9. $\sum_{\boldsymbol{i}}(\boldsymbol{R_i}) = \mathbf{9}$)



$\boldsymbol{R_1}$ = 2 road-links

$\boldsymbol{RC_1}$ = 2/9 = **22.22%**

$\boldsymbol{R_2}$ = 3 road-links

$\boldsymbol{RC_2}$ = 3/9 = **33.33%**

$\boldsymbol{R_3}$ = 4 road-links

$\boldsymbol{RC_3}$ = 4/9 = **44.44%**

Figure 3. *Road coverage calculation illustration*

- *Weight coefficient,* ***(p** and **1-p)*** is used to differentiate the importance of VC_i and RC_i. Value of p is between 0 and 1. The coefficients p and 1-p are defined as the weights of VC and RC, respectively.

- *Total number of ALPR systems available,* ***k***

Model MaxCover

Maximize network coverage $Z = p * \sum_{i=1}^{I} (x_i * VC_i) + (1\text{-}p) * \sum_{i=1}^{I} (x_i * RC_i)$ (1)

Subject to:

$$\sum_{i=1}^{I} x_i \leq k \qquad (2)$$

$$x_i + x_j \leq d_{ij} + 1 \qquad \forall \text{ i, j} \in \text{I and i} \neq \text{j} \qquad (3)$$

$$x_i \in \{0, 1\} \qquad \forall \text{ i} \in \text{I} \qquad (4)$$

- (1) maximizes the objective value Z that calculates the weighted sum of VC and RC of selected locations from elements of I, the possible ALPR location set.

- (2) is the budget constraint and it limits the maximum number of ALPR systems available to k.

- (3) is used to disable the model to select close neighbor locations together in the solution. When i and j are close neighbors, d_{ij} will be equal to 0 and the sum of decision variables on the LHS will be enforced to be less than or equal to 1. This constraint checks every location pair and allows selecting at most one location when i and j are close neighbors. If i and j are not close neighbors, then d_{ij} will be 1 and RHS of (3) will be 2. In this case, there is no limitation, i.e., both location i and location j can be selected.

- (4) states that decision variables are binary.

4.2. A Toy Example

To illustrate how the model behaves, a toy example is introduced below:

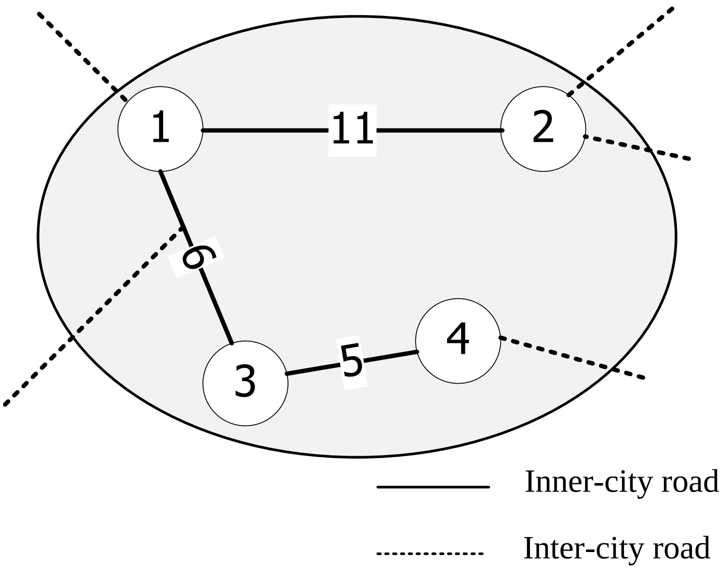


Figure 4. *The toy example network illustration*

Consider the 4 possible locations for ALPR installations that are connected through a road network illustrated in Figure 4. Let the numbers on the links represent the distance between locations. Assume that the minimum acceptable distance between nodes is 10 units (i.e., close neighbor threshold level) and total number of ALPR systems available is 2. The weight coefficient for VC, *p,* is set to 0.8.

Table 3. *The toy example parameters and close neighbor matrix, p=0.8*

i	VC_i	RC_i	$p * VC_i$	$(1-p) * RC_i$	Weighted Sum
1	10%	30%	8%	6%	14%
2	20%	30%	16%	6%	22%
3	30%	20%	24%	4%	28%
4	40%	20%	32%	4%	36%

Table 4. *Close Neighbor Matrix for the Example Problem*

d_{ij}	1	2	3	4
1	1	1	1	1
2	1	1	1	1
3	1	1	1	0
4	1	1	0	1

According to d_{ij} matrix given in the Table 4 above, only location 3 and 4 are considered as close neighbors with $d_{34} = d_{43} = 0$. The distance between locations 3 and 4 is 5 units and they are on the same road-link. In the network illustration, it can be seen that the minimum distances between 1 and 3 is 6 units. However, the 1-3 location pair is not considered to be close neighbors even the distance between those locations are less than 10 units. This is because 1 and 3 are not on the same road-link. The link between 1 and 3 is divided by another link creating an intersection. At this point we cannot claim that there is a complete duplication in vehicles detected at locations 1 and 3 since we do not know the turning ratios. It is possible that certain percentage of the vehicles passing through 1 and directed to 3 can turn to the inter-city road-link, simply eliminate a duplicate data in 3 vice versa.

VC and RC of locations are given in the Table 3. Weighted coverage values are calculated with p = 0.8 and added up to obtain weighted sum column. This column indicates the individual contributions of the locations in the objective. Recall that k = 2 and top two scored locations belong to 3 and 4 indicating that they should be selected. However, considering 3 and 4 are close neighbors, next best solution with respect to weighted sum is comprised of locations 4 and 2. The objective function value, called network coverage in our study, is just weighted sum of VC and RC of locations in the optimal and is calculated as 58%.

In the toy example, there are four possible ALPR locations. Now assume that k = 4 and we want full network coverage. Note that our model does not allow us to select locations 3 and 4 together since they are close neighbors. In this case, locations 1, 2, and 4 are selected with a total network coverage of 72%. It can be stated that in the presence of close neighbor locations, the network cannot be fully covered. However, if close neighbor constraint is omitted as a whole or close neighbor locations are eliminated beforehand, then the setting provided in this study can result in 100% network coverage. As stated before whether being close neighbors or not is an important issue in real life settings, thus, we keep this constraint in our models and report the corresponding network coverage as it is. In our toy example, 72% of network coverage is the best value under close neighbor constraint and to emphasize this, a new scale can be introduced where the best value is represented with 100%. However, we prefer to use original network coverage values to make a fair comparison between different settings (i.e., decentralized, centralized and current state settings).

If close neighbor constraint is ignored and 4 out of 4 locations are selected for ALPR installations, VC is assumed to be duplicated on locations 3 and 4. While calculating network coverage, maximum VC of the close neighbor pair is taken into account while minimum is considered lost. It is assumed that two close neighbor locations can have a VC that is maximum VC of those locations. However, the RC of both locations should be included in calculation. Table 3 is updated to illustrate this case:

Table 5. *Parameters under close neighbor constraint violation, p=0.8*

i	VC_i	RC_i	$p * VC_i$	$(1-p) * RC_i$	Weighted Sum
1	10%	30%	8%	6%	14%
2	20%	30%	16%	6%	22%
3	**0**%	20%	**0**%	4%	**4**%
4	40%	20%	32%	4%	36%

In Table 5, it is shown that VC_3 is taken as 0% since $VC_4 > VC_3$ as given in the Table 3. Also, note that RC_3 stays the same. Even though close neighbor constraint is violated and fourth ALPR system is used on location 3, total network coverage is calculated as 76% which is 4% higher than 3-location optimal. It can be inferred that the 4% increase comes from the weighted RC of location 3. So far we discuss the example for *p* = 0.8 meaning that VC is more important than RC. Now, consider the toy example parameters recalculated with p= 0.2 where RC is more important than VC:

Table 6. *Parameters under close neighbor constraint violation, p=0.2*

i	VC_i	RC_i	$p * VC_i$	$(1-p) * RC_i$	Weighted Sum
1	10%	30%	2%	24%	26%
2	20%	30%	4%	24%	28%
3	**0%**	20%	**0%**	16%	**16%**
4	40%	20%	8%	16%	24%

For *p* = 0.2, the lost network coverage due to close neighbor constraint is 16% since we cannot use location 3 in optimal solution. Violation of a close neighbor constraint have a greater impact on network coverage where weight coefficient favors RC. It should be noted that if a location has a high VC, then close neighbor of that location may have high VC also as they are close to each other and on the same road-link.

When there are three or more locations that are all close neighbors to each other, we use a similar idea. Let A, B, and C be three locations where A-B, B-C, and A-C be close neighbor pairs. In this case, again only the maximum VC of those locations are taken into account while calculating NC. Now assume that there are three locations with vehicle coverages $VC_A > VC_B > VC_C$ and A-B and B-C are close neighbors, but A-C are not. In such a case where a location has more than one close neighbor, VC of location B should be compared to the close neighbor location with the highest NC first. Since $VC_A > VC_C$, VC of location B should be compared with location A first. When compared, VC_A is larger than VC_B and VC_B should be omitted and assumed to be 0.

After, VC_B=0 is compared to VC_C and it is decided that VC_C should be included in VC calculation. If A-B and A-C are close neighbors and B-C are not, then VC_A is first compared to VC_B and VC_B is omitted since $VC_A > VC_B$. Later, VC_A is compared to VC_C and VC_C is also omitted since $VC_A > VC_C$. In this case, only VC_A should be included in VC calculation while VC_B and VC_C should be considered lost.

The further analysis on the impact of close neighbor locations on network coverage is presented in later sections.

CHAPTER 5

EXPERIMENTS

In this section, numerical experiments for two cities in Turkey, Ankara and Kırıkkale, are presented. Ankara, the capital of Turkey, is the geographical hub of road network in Turkey. Kırıkkale is a relatively small town but it connects Ankara to eastern Turkey. There are three main reasons to select these two cities for the experiment:

First, the appropriate ALPR locations have been predefined for both cities. Typically, the ALPR technical installation requirements, work permits, and interrelations of stakeholders as Turkish Gendarmerie and General Directorate of Highways make it hard to determine suitable locations for the ALPR systems. Having information on suitable ALPR locations increase the applicability of results of experiments providing a foundation for current state analysis.

Second, both cities have been using ALPR systems located throughout the city and state road network. It provides a base for comparing the results of the experiments and the current state. This comparison will enable us to comment on if the locations of ALPR systems are selected optimally according to the network coverage maximization objective.

Third and finally, Ankara and Kırıkkale are neighbor states and they are connected by several inter-city roads. For both cities, the ALPR installation locations had been determined by local authorities. It provides us a benchmark for decentralized ALPR location determination. We will also perform experiments for centralized case and compare decentralized and centralized solutions as well as the current situation. In summary, the reasons to select Ankara and Kırıkkale in our study are listed below:

1. Technically approved ALPR locations are known – applicable for real life implications
2. ALPR systems in use – base for comparison between current state and experiment results
3. Neighbor cities with multiple inter-city roads – base for analysis of decentralized and centralized solutions

The experiment is divided into three main parts: *Decentralized* case, *Centralized* case and *Current State Scenarios*.

In decentralized case, optimal ALPR locations and network coverage will be examined for both cities separately. Model MaxCover given in the approach section will be used to find optimal locations and coverage of the network. In this part, the problem is solved as if there are no active ALPR systems installed on any city. Decentralized solutions will provide independent solutions for Ankara and Kırıkkale. We solve the MaxCover model for different values of number of available ALPR systems for each city. We denote the number of available ALPR systems for Ankara and Kırıkkale as $\boldsymbol{k^A}$ and $\boldsymbol{k^K}$, respectively.

In centralized case, Ankara and Kırıkkale are considered as a single road network and problem is solved accordingly. Again, Model MaxCover is used for solving the problem and cities share the total number of available ALPR systems ($\boldsymbol{k^C}$) according to network coverage objective. In this part, weight coefficient for VC is not differentiated among cities and the whole network will have a single p value.

In current state scenarios, the network coverage of the two cities are calculated according to present locations of ALPR systems. These values are compared to suggested optimal solutions found in decentralized and centralized cases. Afterwards, Model MaxCover is modified to find minimum number of ALPR systems required to reach different service levels. This new model, Model MinInstall, is used to discuss how many ALPR systems are required for ensuring specified network coverage for both in the presence of existing ALPR systems or over an empty network. An analysis is presented on minimum number of ALPR installations needed for improving network coverage.

The setting of the experiment is summarized below:

1. Decentralized Setting
    a. Ankara Case
    b. Kırıkkale Case
    c. Decentralized Case Review
2. Centralized Setting
    a. Centralized solution
    b. Centralized and decentralized comparison
3. Current State Scenarios

We next provide the assumptions of our experiments.

Assumption 1: In a road network, there may be different road paths between location pairs. In our study, it is assumed that any vehicle should select the shortest path between any two nodes. While examining if two locations are close neighbors, minimum road distance between those nodes are considered.

Assumption 2: In a centralized problem, there is only single *p* value associated with VC parameter- considering two cities. Even though weight coefficient can be differentiated among cities in the centralized setting, it would be impractical while comparing centralized and decentralized solutions. In other words, setting a single *p* value enables us to easily compare network coverage values of centralized and decentralized problems for the corresponding *p* value.

Assumption 3: VC and RC parameters of an ALPR location are estimated from the Traffic Volume Map (2016) issued by General Directorate of Highways. Maps for provincial roads and state roads includes daily average number of vehicles detected by traffic counting stations on road-links. These values and road-links specified in the traffic volume maps are used to calculate VC and to deduce RC for suitable ALPR locations.

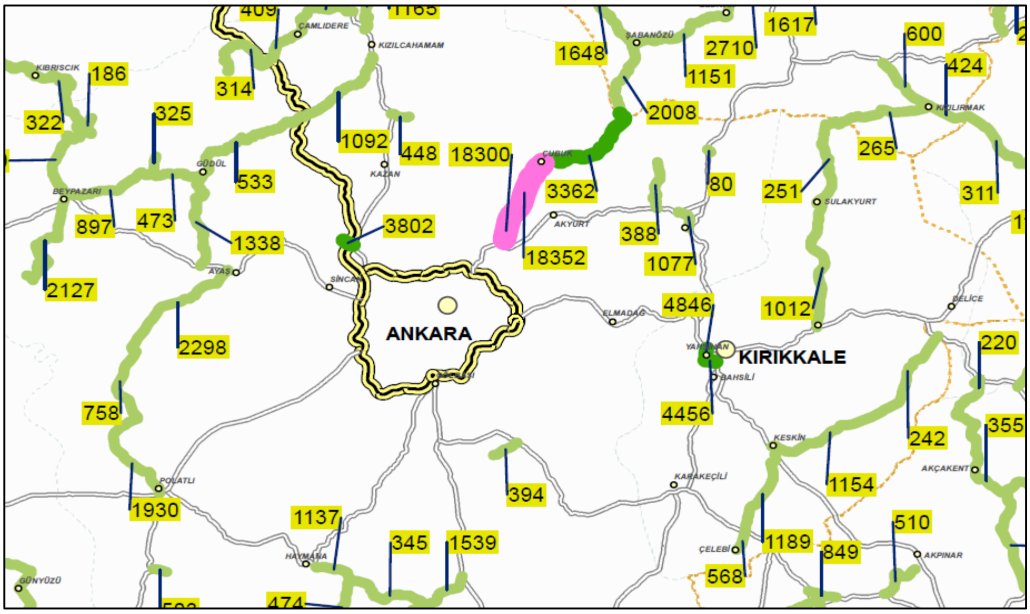


Figure 5. *Traffic volume map, provincial road volumes and road-links, 2016*

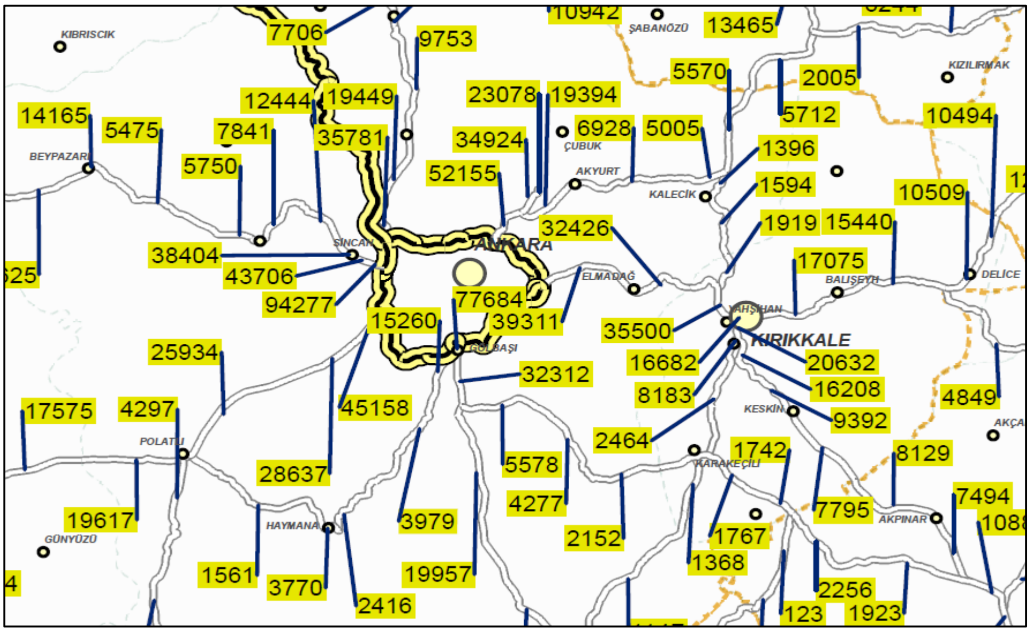


Figure 6. *Traffic volume map, state road volumes and road-links, 2016*

We provide the steps of the approach used to find VC and RC values on Polatlı location example:

1. Traffic volume maps for *provincial roads* and *state roads* are combined for each location.

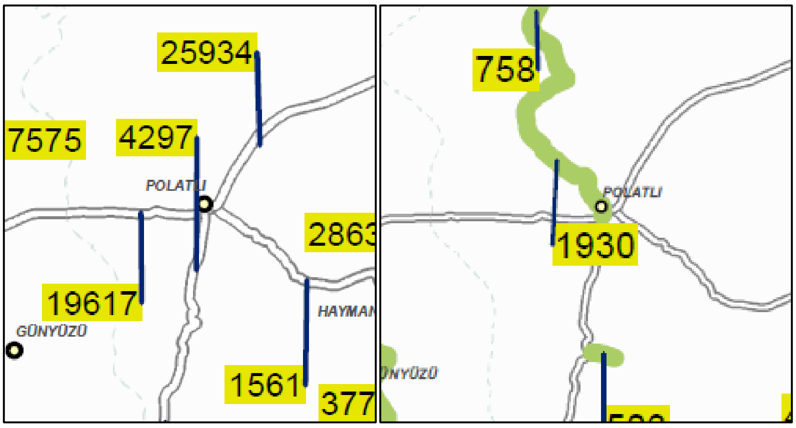


Figure 7. *Provincial roads (left) and state roads (right) for Polatlı location*

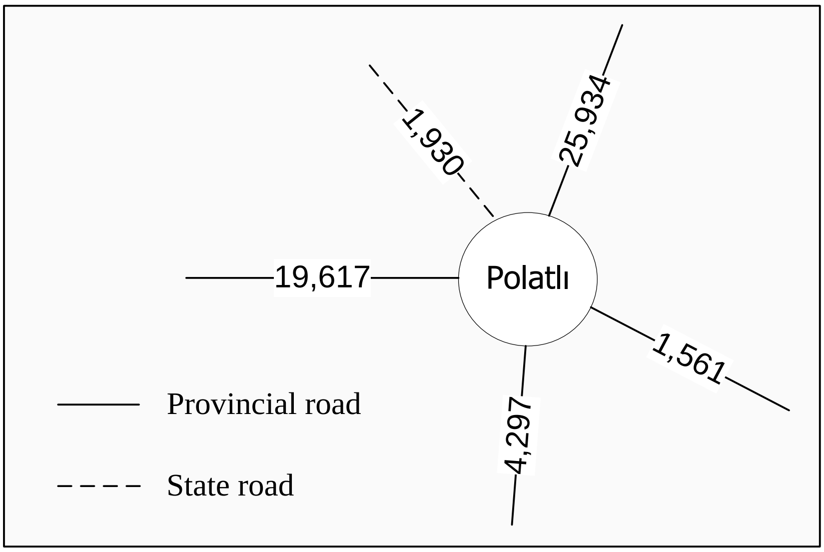


Figure 8. *Provincial and state roads combined for Polatlı location*

2. The number of road-links covered by each location is counted. For Polatlı location, the number of road-links covered, $R_{\text{Polatlı}}$, is 5 as it is seen in Figure 8.

3. The number of vehicles detected by nearest counting stations for all road-links connected to the location are added up. For Polatlı, total number of vehicle is 53,339 as illustrated in Figure 9 below.

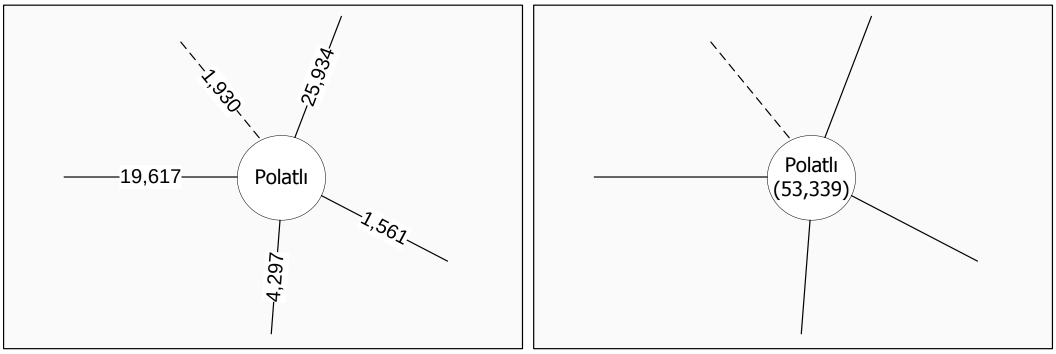


Figure 9. *Total vehicle counts on all road-links connected to Polatlı*

4. The total vehicle count is divided to 2. The vehicle counts observed on links are bidirectional. It is assumed that half of the vehicles detected on links are directed to Polatlı location while other half are directed the opposite direction. As a result, the daily number of vehicles passing by Polatlı location, $V_{\text{Polatlı}}$, is calculated as 26,670.
5. For all possible ALPR locations in the network, first 4 steps are followed and total number of vehicles (ΣV) and total number of road-links (ΣR) that can be covered by all possible ALPR locations are found for the network.
6. VC and RC for any location i is calculated according to the formulas given below:

$$VC_i = \frac{V_i}{\sum_I (V_i)} \qquad\qquad RC_i = \frac{R_i}{\sum_I (R_i)}$$

Let ΣV and ΣR values are 100,000 vehicles and 20 road-links respectively for a network containing Polatlı location. Then, $VC_{Polatlı}$ and $RC_{Polatlı}$ are calculated as 26.67% and 25%, respectively.

Assumption 4: The VC values obtained from traffic volume maps are assumed to be stationary values. In 2018, the 2016 VC and RC data may have changed due to change in road network and drivers' decisions.

CHAPTER 6

RESULTS AND DISCUSSIONS

In this section, results of experiments will be presented in accordance with the experiment section. First, parameters of the related problem will be introduced. Then, network coverage value matrix with respect to total number of available ALPR systems (k), and weight coefficient (p) will be presented. Comments on the solutions will be given in each subsection. The problems are solved as Mixed Integer Problem (MIP) with mathematical optimization tool GAMS® v23.9.

6.1. Decentralized Setting

6.1.1. Ankara Case

In Ankara, there are 13 available ALPR locations. In total, 176,132 vehicles in a day and 37 road-links can be monitored by those 13 locations. V and R values are obtained by the method explained in Assumption 3 for all locations. VC and RC values are calculated by the formulas provided in the optimization model section. Parameters of Ankara city are listed below:

Table 7. *Vehicle and road coverages for Ankara locations*

i	V_i	R_i	VC_i	RC_i
1	14,165	5	8%	14%
2	7,895	3	4%	8%
3	19,681	3	11%	8%
4	1,172	3	1%	8%
5	27,615	2	16%	5%
6	8,707	2	5%	5%

Table 7 (cont'd)

7	10,857	2	6%	5%
8	13,161	2	7%	5%
9	36,869	2	21%	5%
10	3,662	3	2%	8%
11	26,670	5	15%	14%
12	3,215	2	2%	5%
13	2,463	3	1%	8%
Total	176,132	37	100%	100%

From Table 7, it can be seen that highest VC is observed in location 9. Highest RC is observed in locations 11 and 1. A location with highest VC does not need to have highest RC as in this case. We wanted to check if VC and RC parameters are positively correlated. VC and RC parameters should not be positively correlated in order to depict tradeoff between the parameters. If correlation coefficient between VC and RC is positive and high, then impact of weight coefficient p on the optimal solution would be low.

Recall that p is used to differentiate the importance of VC and RC. If these two parameters are positively correlated, then a location with high VC is expected to have high RC as well. In this case, p cannot depict relative importance of the two parameters and optimal solutions may not change at all even p changes dramatically. The correlation coefficient between VC and RC is calculated as 0.06 suggesting that there is no strong positive correlation between those parameter sets for Ankara.

The Decentralized Ankara problem is solved under 5 different p (0.1, 0.3, 0.5, 0.7, and 0.9) and 13 different k^A (from 1 to 13) values. Maximum network coverage (NC), the objective function value, for different parameters are provided in the table below:

Table 8. *Optimal network coverage values for decentralized Ankara case*

k^A	$p=0.1$	$p=0.3$	$p=0.5$	$p=0.7$	$p=0.9$
1	14%	14%	14%	16%	19%
2	27%	26%	28%	31%	34%
3	35%	36%	38%	44%	49%
4	43%	45%	49%	54%	60%
5	50%	54%	59%	64%	69%
6	57%	60%	65%	70%	76%
7	63%	66%	71%	76%	82%
8	69%	72%	76%	80%	85%
9	75%	78%	81%	84%	87%
10	80%	82%	84%	86%	89%
11	80%	82%	84%	86%	89%
12	80%	82%	84%	86%	89%
13	80%	82%	84%	86%	89%

NC values given in the Table 8 should be interpreted as percentage coverage values for the corresponding p values. For p = 0.5 case in which both VC and RC have the same weight, 65% network coverage can be achieved with 6 ALPR locations. In other words, to ensure 65% coverage under p=0.5, at least 6 ALPR systems must be used. 65% coverage is comprised of 78% VC and 51% RC This result indicates that roughly 137,000 of 176,000 vehicles daily and 19 of 37 road-links can be monitored with 6 ALPR systems.

Table 9. *Optimal ALPR locations for decentralized Ankara case, $k^A=3$*

p	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	*NC*
0.1	1		1								1			35%
0.3	1								1		1			36%
0.5	1								1		1			38%
0.7					1				1		1			44%
0.9					1				1		1			48%

In Table 9, optimal ALPR locations for $k^A=3$ under different p values are presented. For p = 0.1, $x_1 = x_3 = x_{11} = 1$ with network coverage of 35%. When solved for p = 0.3, $x_1 = x_9 = x_{11} = 1$ with slightly higher network coverage of 36%.

Table 10. *Weighted scores of ALPR locations in Ankara, for different p*

i	*p=0.1*			*p=0.3*			*p=0.5*			*p=0.7*			*p=0.9*		
	VC_i (%)	RC_i (%)	NC_i (%)	VC_i (%)	RC_i (%)	NC_i (%)	VC_i (%)	RC_i (%)	NC_i (%)	VC_i (%)	RC_i (%)	NC_i (%)	VC_i (%)	RC_i (%)	NC_i (%)
1	1	12	**13**	2	9	**12**	4	7	**11**	6	4	10	7	1	9
2	0	7	8	1	6	7	2	4	6	3	2	6	4	1	5
3	1	7	**8**	3	6	9	6	4	10	8	2	10	10	1	11
4	0	7	7	0	6	6	0	4	4	0	2	3	1	1	1
5	2	5	6	5	4	8	8	3	11	11	2	**13**	14	1	**15**
6	0	5	5	1	4	5	2	3	5	3	2	5	4	1	5
7	1	5	5	2	4	6	3	3	6	4	2	6	6	1	6
8	1	5	6	2	4	6	4	3	6	5	2	7	7	1	7
9	2	5	7	6	4	**10**	10	3	**13**	15	2	**16**	19	1	**19**
10	0	7	8	1	6	6	1	4	5	1	2	4	2	1	3
11	2	12	**14**	5	9	**14**	8	7	**14**	11	4	**15**	14	1	**15**
12	0	5	5	1	4	4	1	3	4	1	2	3	2	1	2
13	0	7	7	0	6	6	1	4	5	1	2	3	1	1	2

In Table 10, VC, RC and NC of all locations with respect to different p values are presented. The values in the table are called weighted scores for each location and represents the contribution of a location in the network coverage if they are selected. For each p, optimal locations are selected according to their rank in the weighted score table unless close neighbor constraint is violated. According to Table 10, for p = 0.5, if k^A is increased to 4, x_5 with the highest NC will be in the optimal solution as a 4th location if there are no close neighbors among the new solution set.

In Table 10, numbers in bold represents the top three locations in terms of NC for each p. Notice that optimal solutions in Table 9 correspond to the locations in bold in Table 10 respectively. As p increases from 0.1 to 0.3 location 3 is replaced with location 9 in the optimal solution. When weighted scores of these locations are compared, NC of location 9 increases from 7% to 10% since high VC is multiplied by higher p, while

NC of location 3 increases from 8% to 9%. Similarly, as p changes from 0.5 to 0.7, location 1 is dominated by location 5 in terms of NC.

It is observed that while p increases from 0.3 to 0.5, optimal solution does not change. However, network coverage is improved from 36% to 38%. Locations 9 and 11 have higher VC than their respective RC. Thus, weighted score of these location increases as p increases. We note that, increase in location 11 cannot be observed due to round-off. Score of location 1 decreases since VC is less than RC for this location. Main reason behind changing weighted scores with respect to p is the difference between VC and RC for any location i. If VC is higher than RC, then NC of that location will increase as p increases and vice versa.

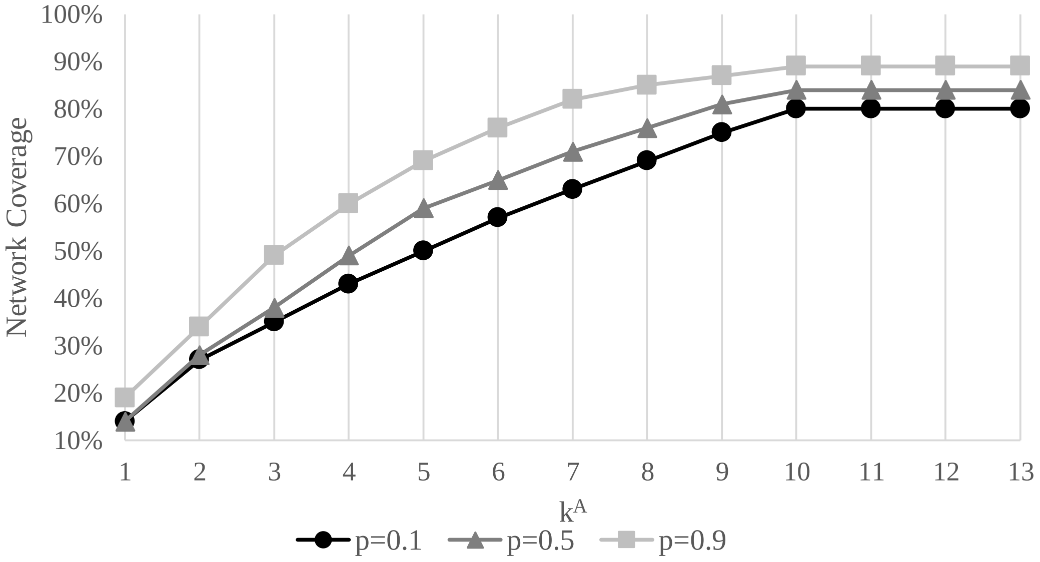


Figure 10. *Optimal network coverage illustration for different p values, Ankara*

From Figure 10, it can be noticed that, increase in the network coverage diminishes as the k^A gets larger. Due to close neighbor constraint, at most 10 out of 13 ALPR locations can be utilized and network coverage cannot reach 100%. For $k^A > 10$, the optimal solution and the network coverage do not change for any p.

From the graph in Figure 10, it can be inferred that for any k^A, network coverage is higher for larger p. It can be also observed in Table 10 that as p increases, the range between NC of locations is increasing. Since the range of VC is 0.20 (between 0.01 and 0.21) while range of RC is 0.09 (between 0.05 and 0.14) for Ankara locations, as the weight of the VC increases, the magnitude of additional network coverage provided by higher VC locations is larger than the lost due to giving up RC. In other words, as p increases, the NC differences between locations become more apparent.

In example, for p=0.1, the maximum NC is 14% and there are only 2 locations that have NC larger than 10%. Besides, the minimum NC is 5% for p=0.1. On the other side, for p=0.9, the maximum NC is 19% and there are 4 locations that have a NC larger than 10%. The minimum NC of a location is 1% for p=0.9. All optimal locations with respect to k^A and p for decentralized Ankara case are given in the APPENDIX A. The close neighbor matrix for Ankara is provided in the APPENDIX B.

6.1.2. Kırıkkale Case

In Kırıkkale, there are 6 available ALPR locations. In total, 72,058 vehicles in a day and 20 road-links can be monitored by those 6 locations. V_i and R_i values are obtained by the method explained in Assumption 3 for all locations. VC and RC values are calculated by the formulas provided in the optimization model section. Parameters of Kırıkkale city are listed in Table 11 given below:

Table 11. *Vehicle and road coverages for Kırıkkale locations*

i	V_i	R_i	VC_i	RC_i
1	20,632	4	29%	20%
2	16,764	3	23%	15%
3	12,934	2	18%	10%
4	8,087	3	11%	15%
5	9,765	4	14%	20%
6	3,876	4	5%	20%
total	72,058	20	100%	100%

Correlation between VC and RC is calculated as -0.11 indicating that there is no strong positive correlation between location parameters for Kırıkkale. The Decentralized Kırıkkale problem is solved under 5 different p (0.1, 0.3, 0.5, 0.7, and 0.9) and 6 different k^K (from 1 to 6) values. Maximum network coverage, the objective function value, for different parameters are provided in Table 12.

Table 12. *Optimal network coverage values for decentralized Kırıkkale case*

k^K	$p=0.1$	$p=0.3$	$p=0.5$	$p=0.7$	$p=0.9$
1	21%	23%	24%	26%	28%
2	40%	41%	41%	42%	45%
3	59%	56%	55%	57%	59%
4	73%	70%	68%	69%	71%
5	84%	83%	81%	79%	78%
6	84%	83%	81%	79%	78%

Optimal ALPR locations for $k^K=3$ under different p values are presented in Table 13.

Table 13. *Optimal ALPR locations for decentralized Kırıkkale case,* $k^K=3$

p	x_1	x_2	x_3	x_4	x_5	x_6	*NC*
0.1	1				1	1	59%
0.3	1				1	1	56%
0.5	1		1		1		55%
0.7	1		1		1		57%
0.9	1		1		1		59%

For p=0.1 and p=0.3, optimal solution consists of locations 1, 5 and 6. For $p \geq 0.5$, location 6 with highest RC and lowest VC is replaced with location 3. Changing optimal solutions can be examined through weighted score table provided below:

Table 14. *Weighted scores of ALPR locations in Kırıkkale, for different p values*

i	*p=0.1*			*p=0.3*			*p=0.5*			*p=0.7*			*p=0.9*		
	VC_i (%)	RC_i (%)	NC_i (%)	VC_i (%)	RC_i (%)	NC_i (%)	VC_i (%)	RC_i (%)	NC_i (%)	VC_i (%)	RC_i (%)	NC_i (%)	VC_i (%)	RC_i (%)	NC_i (%)
1	3	18	**21**	9	14	**23**	14	10	**24**	20	6	**26**	26	2	**28**
2	2	14	16	7	11	**17**	12	8	**19**	16	5	**21**	21	2	**22**
3	2	9	11	5	7	12	9	5	14	13	3	**16**	16	1	**17**
4	1	14	15	3	11	14	6	8	13	8	5	12	10	2	12
5	1	18	**19**	4	14	**18**	7	10	**17**	9	6	15	12	2	14
6	1	18	**19**	2	14	16	3	10	13	4	6	10	5	2	7

In Table 14, numbers in bold represents the top three locations in terms of NC for different p values. For p = 0.1 notice that optimal solution in Table 13 is consistent with the scores given in Table 14. For other p values, location 2 should be in the optimal solution according to the Table 14. However, in Table 13 it is shown that location 2 is not in optimal solution.

This is because locations 1 and 2 are close neighbors. They are on the same road-link and the minimum road distance between those locations are less than the predefined limit, minimum allowed distance for Kırıkkale. The reason location 1 is preferred over location 2 is that the former has an absolute advantage with higher VC and higher RC than the latter.

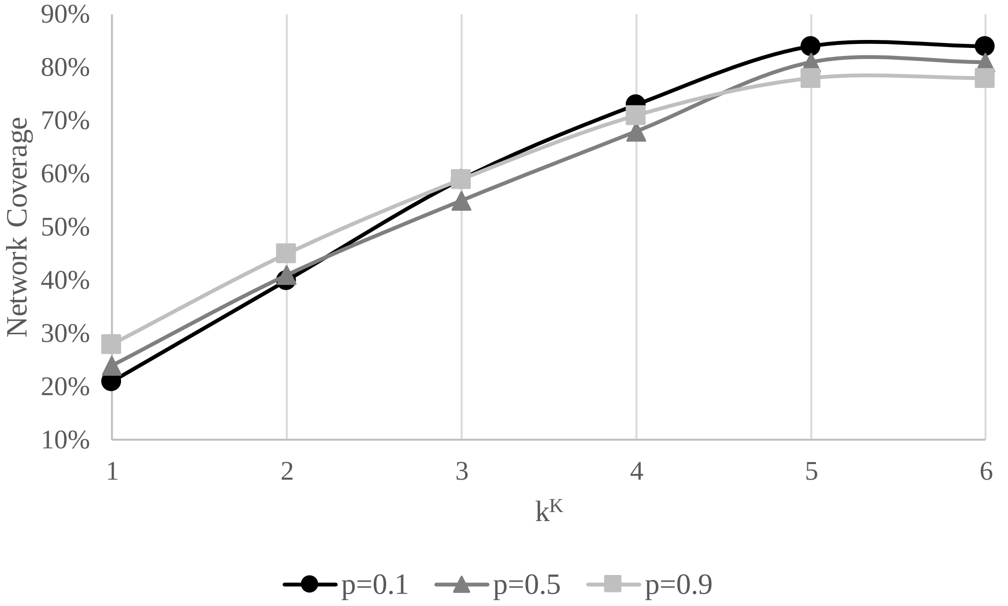


Figure 11. *Optimal network coverage illustration for different p values, Kırıkkale*

Kırıkkale case depicts a different picture than Ankara in terms of maximum NC with respect to p. In Ankara, for any k^A, higher p indicates higher network coverage always. In Kırıkkale, for $k^K \leq 2$, network coverage is larger when p is larger as it is in the Ankara case. However, for $k^K \geq 4$, network coverage is highest for $p = 0.1$.

Since locations 1 and 2 are close neighbors, they cannot be selected together in the optimal solution. Therefore, out of six available locations, at most five can be selected. Notice that location 1 has an absolute advantage over all other locations including location 2 in terms of both VC and RC. Therefore, location 1 will always be selected as an optimal location for any k and p values. Consequently, location 2 can never be in optimal. NC values of locations 1 and 3 increase by a total of 13% as p increases from 0.1 to 0.9 since these locations’ VC values are higher than their respective RC values. On the other hand, NC values of locations 4, 5, and 6 decrease by 20% as p increases from 0.1 to 0.9 since these locations’ RC values are higher than their respective VC values. Especially, NC decrease of location 6 that has a considerably low VC and high RC turns out to be 12%.

For $k \leq 2$, NC increase of location 1 compensates the NC decrease of location 5 in optimal and generates higher NC as p increases. For $k=3$ and $p<0.5$, location 6 is added among locations 1 and 5 in the optimal solution. Due to the rapid NC decrease of location 6, the overall NC decreases for as p increases from 0.1 to 0.3. For $k=3$ and $p \geq 0.5$, location 6 is replaced with location 3 which has an increasing NC as p increases. So, for p increasing from 0.5 to 0.9 the overall NC increases. The $k=4$ case is similar with the $k=3$ case and NC first decreases and then increases as p increases from 0.1 to 0.9. For $k=5$, NC decrease resulted due to selecting locations 4, 5, and 6 cannot be compensated with the increase of selecting locations 1 and 3, thus overall NC decreases while p increases from 0.1 to 0.9.

Optimal solutions for all k^K and p values are given in APPENDIX C. The close neighbor matrix for Kırıkkale is provided in APPENDIX D.

6.1.3. Decentralized Case Review

Decentralized solutions for Ankara and Kırıkkale give insights on how to select ALPR locations with respect to VC and RC of locations for each city under different k and p values. In decentralized setting, k and p values are treated independently for each city. Within each city, close neighbor constraint is applied in order to avoid duplication of vehicles detected. If close neighbor locations were selected for ALPR locations, it is assumed that vehicles detected on the road-link that connect the two locations would be same and it would cause inefficiency in terms of cost and information requirements of the system. An illustration is given below:

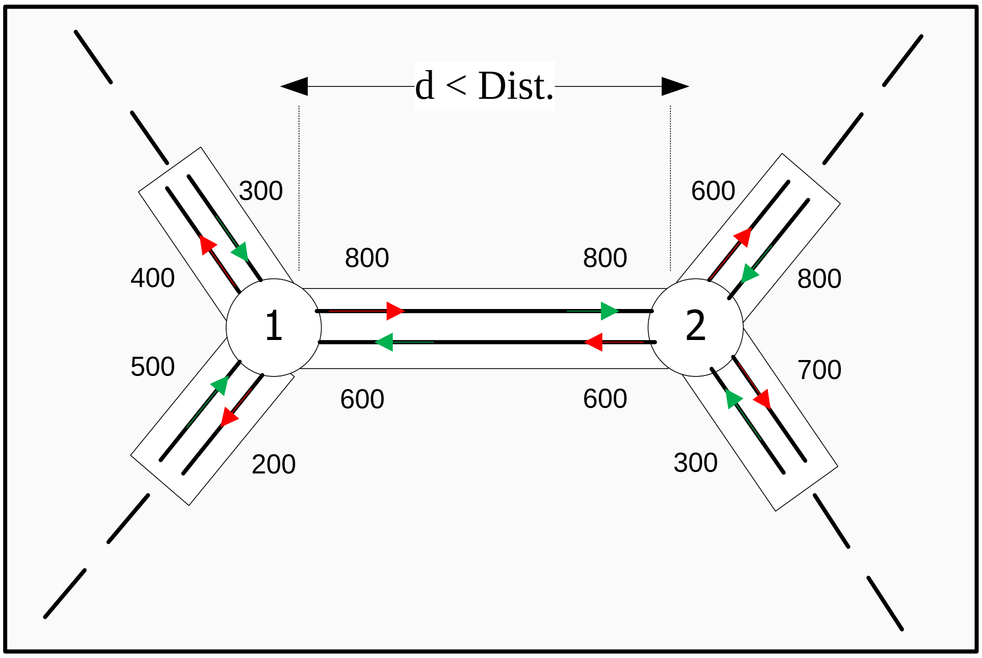


Figure 12. *Close neighbor locations with bidirectional vehicle counts on links*

The partial road network is represented in Figure 12. In this network there are two locations and both locations monitor three road-links. Number of vehicles are represented in numbers outside the road and direction of vehicles are also given. Number of vehicles going in and out is 1,400 and 1,900 for locations 1 and 2, respectively. These numbers correspond to the number of vehicles passing by ALPR locations.

Recall the VC and RC calculation method given in the Assumption 3 in Experiments Chapter. Since provincial and state road volume maps do not indicate the direction of vehicles on any road, the illustration in Figure 12 can be reorganized as follows:

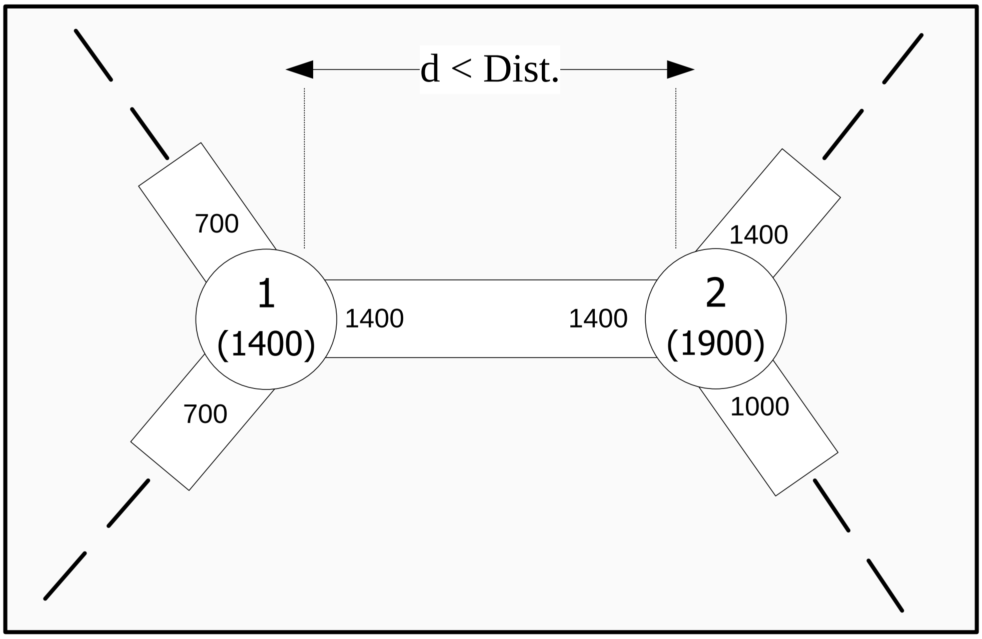


Figure 13. *Calculation of number of vehicles passing by ALPR locations*

For any location i, V_i is calculated by adding up the vehicle volumes in the road-links that are connected to that location and then divided by 2. From Figure 13, V_1 and V_2 can be calculated as 1,400 and 1,900, respectively. Note that locations 1 and 2 are directly connected via the same road-link and the minimum distance between them is less than the predefined limit, *Dist.*, making them *close neighbor* locations. If locations 1 and 2 are in the same city, then close neighbor constraint does not allow the model to select both locations in the optimal solution. However, decentralized solutions overlook the condition that these two locations may exist in two neighbor cities and the road-link connecting two locations may be one of the inter-city roads connecting two cities.

Assume that locations 1 and 2 are in the responsibility area of City A and City B, respectively. If both cities solve their own problems separately and find out that location 1 and 2 are optimal for the corresponding cities, then VC of the A-B network would be overstated and the number of vehicles passing by the two ALPR locations will be taken as 3,300. In fact, total number of vehicles passing by locations 1 and 2 is

1,900. 1,400 vehicles counted in City A would be considered as duplication and should be kept out of VC calculation. Knowing that location 2 is selected by City B, City A should revise their decision on locating the ALPR system on location 1. In the centralized case, a solution to the inter-city close neighbor problem is addressed.

6.2. Centralized Setting

6.2.1. Centralized Solution

In this section, Ankara and Kırıkkale cities will be considered as a single network and the problem will be solved accordingly. Parameters of both cities are combined. However, it is expected that network coverage value would differ even the optimal ALPR locations among the network do not change since VC_i and RC_i calculations are based on percentages of V_i and R_i with respect to city totals. Considering the centralized network, the VC_i and RC_i for all locations will be smaller compared to decentralized values as both the total number of vehicles passing by all ALPR locations and total number of road-links that can be covered by all ALPR locations increase.

The main difference between decentralized and centralized location decisions is that in decentralized case cities determine the number and location of ALPR systems independently. The optimal allocation of ALPR systems among cities is not considered. In centralized setting, on the other hand, the total number of ALPR systems available, k^C, can be shared in any configuration by the two cities according to VC and RC of the locations in the network.

As mentioned before, neighbor cities can be connected via multiple common road-links that may include close neighbor locations. Selection of those locations would create duplication of vehicle data and cause overvaluation of VC, consequently network coverage value. Illustration of inter-city close neighbor locations is given below:

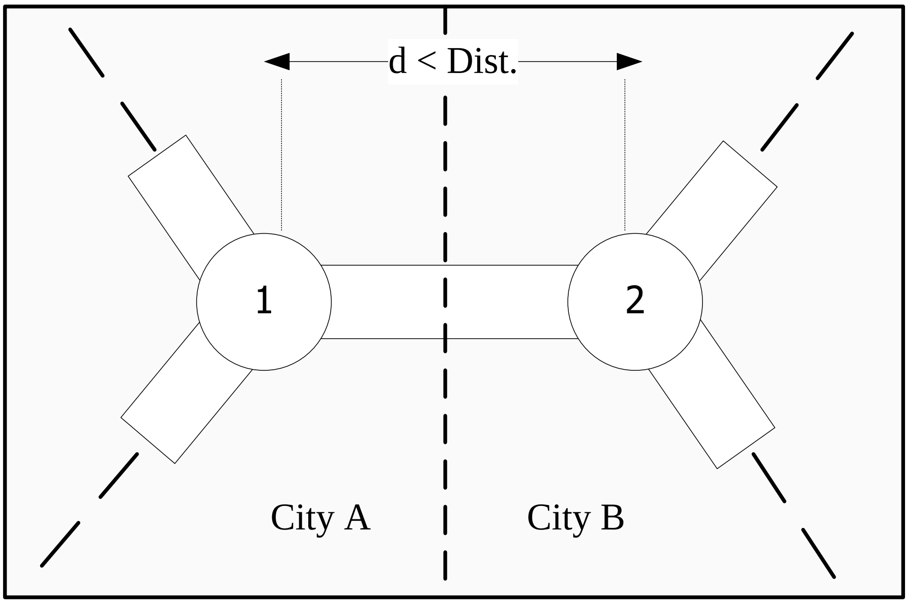


Figure 14. *Inter-city close neighbor locations*

In the centralized case, it is assumed that network has a single *p* coefficient. Although different *p* values can be used for each city in the network, for the sake of completeness, we use a common *p* in centralized setting and compare decentralized and centralized problems accordingly. Parameters of the centralized problem are given in the table below:

Table 15. *Vehicle and road coverages for centralized network*

City	*i*	V_i	R_i	VC_i	RC_i
Ankara	1	14,165	5	5.7%	8.8%
Ankara	2	7,895	3	3.2%	5.3%
Ankara	3	19,681	3	7.9%	5.3%
Ankara	4	1,172	3	0.5%	5.3%
Ankara	5	27,615	2	11.1%	3.5%
Ankara	6	8,707	2	3.5%	3.5%
Ankara	7	10,857	2	4.4%	3.5%
Ankara	8	13,161	2	5.3%	3.5%

Table 15 (cont'd)

Ankara	9	36,869	2	14.9%	3.5%
Ankara	10	3,662	3	1.5%	5.3%
Ankara	11	26,670	5	10.7%	8.8%
Ankara	12	3,215	2	1.3%	3.5%
Ankara	13	2,463	3	1.0%	5.3%
Kırıkkale	14	20,632	4	8.3%	7.0%
Kırıkkale	15	16,764	3	6.8%	5.3%
Kırıkkale	16	12,934	2	5.2%	3.5%
Kırıkkale	17	8,087	3	3.3%	5.3%
Kırıkkale	18	9,765	4	3.9%	7.0%
Kırıkkale	19	3,876	4	1.6%	7.0%
Ankara total		176,132	37	71%	65%
Kırıkkale total		72,058	20	29%	35%
Total		248,190	57	100%	100%

In centralized setting, VC and RC of individual locations recalculated according to the total number of vehicles and road-links in network. In decentralized Ankara problem, VC$_1$=8% and RC$_{1=}$ 14%. However, in centralized problem VC$_1$= 6% and RC$_1^=$ 9%. To compare centralized and decentralized optimal network coverages, centralized VC and RC values will be used as comparison base.

Table 16. *Optimal network coverage values for centralized case*

k^C	*p=0.1*	*p=0.3*	*p=0.5*	*p=0.7*	*p=0.9*
1	9.0%	9.4%	9.8%	11.5%	13.7%
2	17.4%	17.2%	18.9%	21.6%	24.3%
3	24.6%	24.6%	26.3%	30.4%	34.6%
4	31.3%	30.7%	33.5%	37.6%	42.3%
5	37.8%	36.8%	40.1%	44.2%	48.9%
6	43.3%	42.6%	46.1%	50.5%	54.9%
7	48.4%	48.0%	51.6%	55.4%	60.0%

Table 16 (cont'd)

8	53.2%	53.2%	56.0%	60.1%	65.1%
9	58.1%	57.8%	60.3%	64.8%	69.4%
10	62.3%	62.0%	64.6%	68.9%	73.6%
11	66.0%	66.0%	68.9%	72.8%	77.1%
12	69.7%	70.0%	72.8%	76.0%	79.2%
13	73.3%	74.0%	76.2%	78.6%	81.0%
14	76.2%	77.8%	79.3%	80.9%	82.5%
15	76.2%	77.8%	79.3%	80.9%	82.5%
16	76.2%	77.8%	79.3%	80.9%	82.5%
17	76.2%	77.8%	79.3%	80.9%	82.5%
18	76.2%	77.8%	79.3%	80.9%	82.5%
19	76.2%	77.8%	79.3%	80.9%	82.5%

In Table 16, the network coverage values represent the overall coverage of the network containing Ankara and Kırıkkale locations. 14 out of 19 locations can be utilized in optimal solution. After 14, close neighbor locations within or between cities prevent more locations to be included in the optimal solution. In other words, network coverage value cannot be improved after k^C= 14.

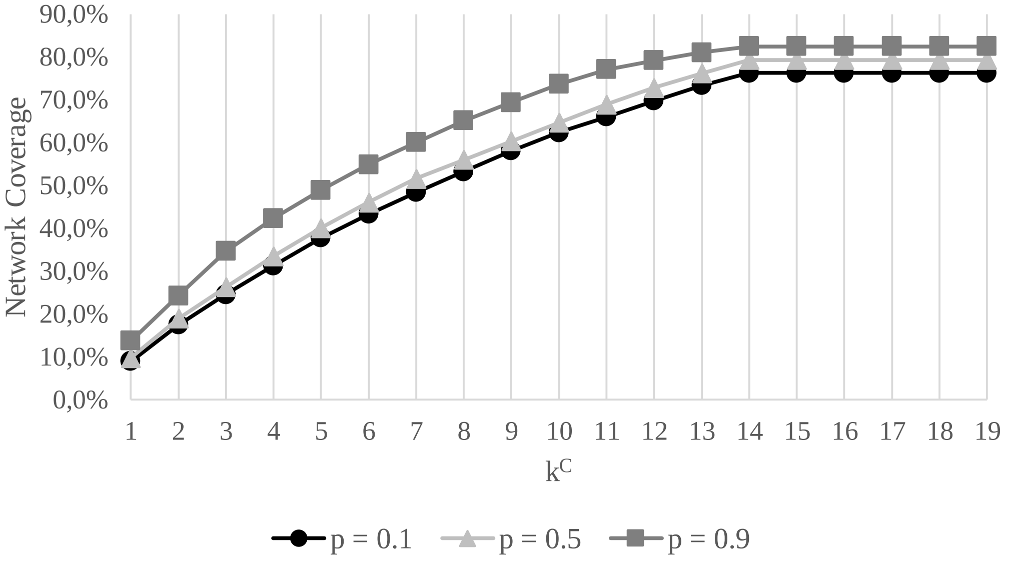


Figure 15. *Optimal NC illustration for different p values, centralized*

Network coverage values with respect to k^C for different p values are represented in Figure 15. It can be observed that for the same k^C, higher p results in higher network coverage as it is in the Decentralized Ankara case. Centralized optimal solutions for all k^C and p are given in APPENDIX E. The close neighbor matrix for the centralized network is provided in the APPENDIX F.

6.2.2. Centralized and Decentralized Comparison

In this section, centralized and decentralized optimal solution comparison will be provided. In decentralized case, cities determine their k values independently from each other. For both cities, assume that $k^A = k^K = 3$. The total 6 ALPR systems available on the network corresponds to $k^C = 6$ for centralized problem. The number of ALPR systems allocated to Ankara or Kırıkkale in centralized solutions are denoted by k'^A and k'^K respectively. Optimal solutions for centralized (C) and decentralized (D) solutions are given in the table below:

Table 17. *Decentralized and centralized optimal solution comparison*

D	*Ankara*													*Kırıkkale*					
p	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_1	x_2	x_3	x_4	x_5	x_6
0.1	1		1								1			1				1	1
0.3	1								1		1			1				1	1
0.5	1								1		1			1		1		1	
0.7					1				1		1			1		1		1	
0.9					1				1		1			1		1		1	
C	*Ankara*													*Kırıkkale*					
p	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	x_{19}
0.1	1		1								1			1				1	1
0.3	1		1		1						1			1				1	
0.5	1		1		1				1		1				1				
0.7	1		1		1				1		1				1				
0.9	1		1		1				1		1				1				

Notice that, for $p = 0.1$, centralized and decentralized optimal ALPR locations are the same. In centralized solution, both cities share 6 ALPR systems evenly in this case. For $p>0.5$, $k'^{A}=5$ meaning that Ankara captures 5 locations out of 6 in centralized solution. While p changes from 0.3 to 0.5, location 14 is excluded from the optimal solution since location 9 of Ankara and location 14 of Kırıkkale are close neighbors. Location 15 is replaced by location 14 which has the highest coverage values in Kırıkkale.

Notice that, for $p \geq 0.3$, both location 9 of Ankara and location 1 of Kırıkkale (location 14 in the centralized case) that are inter-city close neighbors, are included together in their respective decentralized optimal solutions. In this case, to eliminate duplicated vehicles detected, maximum VC of the close neighbors are included in network coverage calculation. Since location 9 has higher VC than location 1, only VC of the 9 will be counted while calculating network coverage value of decentralized case. RC of the two close neighbor locations are calculated as it is for any pair of location.

It is important to keep in mind that in decentralized case, number of available ALPR systems for Ankara and Kırıkkale can be set in various settings. The total 6 ALPR systems can be selected by 6 different ways. Notice that maximum ALPR systems used in Kırıkkale is 5 as it is not possible to utilize 6 locations due to close neighbor constraint. See the following table for possible ALPR system configurations for $k^{C}=6$:

Table 18. *ALPR system allocation configurations for* $k^{C} = 6$

k^{C}	k^{A}	k^{K}
6	6	0
6	5	1
6	4	2
6	3	3
6	2	4
6	1	5

For k^C ranging from 2 to 13, all possible city configurations are examined, and results are compared with centralized setting under different p weights. For each p, 62 different k^A *and* k^K configuration is compared and reported in APPENDIX G. A partial table is given below:

Table 19. *Partial network coverage comparison table for p = 0.1*

k^A	k^K	ΣVC (%)	ΣRC (%)	NC (%)	k^C	ΣVC^C (%)	ΣRC^C (%)	NC^C (%)	ΔVC (%)	ΔRC (%)	ΔNC (%)
2	0	16.5	17.5	17.4	2	16.5	17.5	17.4	0.0	0.0	0.0
1	1	19.1	15.8	16.1	2	16.5	17.5	17.4	-2.6	1.8	1.3
0	2	12.2	14.0	13.9	2	16.5	17.5	17.4	4.2	3.5	3.6
3	0	24.4	22.8	23.0	3	24.8	24.6	24.6	0.4	1.8	1.6
2	1	24.8	24.6	24.6	3	24.8	24.6	24.6	0.0	0.0	0.0
1	2	23.0	22.8	22.8	3	24.8	24.6	24.6	1.8	1.8	1.8
...	...	...	...	...	...	...	...	...	...	...	...
3	2	36.6	36.8	36.8	5	30.3	38.6	37.8	-6.4	1.8	0.9
2	3	30.3	38.6	37.8	5	30.3	38.6	37.8	0.0	0.0	0.0
1	4	27.8	35.1	34.4	5	30.3	38.6	37.8	2.4	3.5	3.4
0	5	22.3	29.8	29.1	5	30.3	38.6	37.8	8.0	8.8	8.7
6	0	41.7	36.8	37.3	6	38.2	43.9	43.3	-3.5	7.0	6.0
5	1	35.2	40.4	39.8	6	38.2	43.9	43.3	3.0	3.5	3.5
...	...	...	...	...	...	...	...	...	...	...	...
7	4	61.6	66.7	66.2	11	60.3	66.7	66.0	-1.2	0.0	-0.1
6	5	55.7	66.7	65.6	11	60.3	66.7	66.0	4.7	0.0	0.5
10	2	67.7	64.9	65.2	12	65.6	70.2	69.7	-2.2	5.3	4.5
9	3	68.0	68.4	68.4	12	65.6	70.2	69.7	-2.4	1.8	1.3
8	4	66.9	70.2	69.8	12	65.6	70.2	69.7	-1.3	0.0	-0.1
7	5	66.8	70.2	69.8	12	65.6	70.2	69.7	-1.2	0.0	-0.1
...	...	...	...	...	...	...	...	...	...	...	...

In the comparison table, k^C denotes total number of available ALPR systems for centralized network while k^A and k^K represent the number of available ALPR systems for Decentralized Ankara and Kırıkkale cases respectively. ΣVC and ΣRC represent the sum of VC and sum of RC of decentralized optimal locations with respect to k^A and k^K. NC is the network coverage value for decentralized case calculated by ΣVC, ΣRC, and p weight. Similarly, ΣVC^C and ΣRC^C represent total VC and RC in centralized optimal solution with respect to k^C. VC and RC differences between decentralized and centralized optimal solutions are given as ΔVC and ΔRC, respectively. Last column, ΔNC, denotes the difference between network coverage values of respective decentralized and centralized solutions and calculated by the formula provided below:

$$\Delta NC = NC^C - NC = p * \Delta VC + (1-p) * \Delta RC$$

For each possible k^A, k^K, and k^C combination, ΔNC indicates how much the centralized optimal NC is higher than the decentralized optimal NC generated by decentralized Ankara and decentralized Kırıkkale solutions. To exemplify, let's take the row with $k^C = 12$, $k^A = 10$ and $k^K = 2$. Network coverage of decentralized solutions with $k^A = 10$ and $k^K = 2$ is 65.2%. In centralized case, optimal solution for $k^C = 12$ consists of 7 locations from Ankara and 5 locations from Kırıkkale with a network coverage value of 69.7%. For network, VC decreases 2.2% while RC increases 5.3% in centralized setting. Under $p = 0.1$, ΔNC is calculated as 4.5% which indicates that centralized optimal is better than the decentralized optimal network coverage.

For 65 out of total 310 cases, decentralized k^A and k^K configurations are same with the optimal allocation in centralized case. Only in 21 out of those 65 cases, decentralized and centralized solution yields the same network coverage value. For 40 cases, network coverage of centralized optimal is higher than the decentralized ones due to inter-city close neighbor locations even though they have the same allocation of ALPR systems in each city. In the remaining 4 cases, decentralized network coverage is higher than the centralized.

When all possible combinations of k^A and k^K are compared with corresponding k^C's, an overall difference between centralized and decentralized optimal solutions are summarized as in the table below:

Table 20. *Best, average and worst coverage differences*

p	*Difference*	$\Sigma V^C - \Sigma V$	$\Sigma R^C - \Sigma R$	ΔVC (%)	ΔRC (%)	ΔNC (%)
0.1	Best	-21,841	7.0	-8.8%	12.3%	10.2%
	Average	-2,417	1.7	-1.0%	3.0%	2.6%
	Worst	16,764	-1.0	6.8%	-1.8%	-0.9%
0.3	Best	35,739	4.0	14.4%	7.0%	9.2%
	Average	13,795	0.7	5.6%	1.2%	2.5%
	Worst	0	0.0	0.0%	0.0%	0.0%
0.5	Best	69,741	0.0	28.1%	0.0%	14.0%
	Average	25,114	-0.5	10.1%	-0.8%	4.6%
	Worst	0	0.0	0.0%	0.0%	0.0%
0.7	Best	90,338	0.0	36.4%	0.0%	25.5%
	Average	26,572	0.1	10.7%	0.2%	7.5%
	Worst	0	0.0	0.0%	0.0%	0.0%
0.9	Best	92,937	-2.0	37.4%	-3.5%	33.4%
	Average	27,544	-0.6	11.1%	-1.0%	9.9%
	Worst	0	0.0	0.0%	0.0%	0.0%

In the summary table given above, three different cases for each p is provided. Best and worst difference cases address the cases where the subtraction of decentralized network coverage from centralized optimal is highest and lowest respectively. In average difference, 62 different configurations are averaged for each p. $\Sigma V^C - \Sigma V$ represents the difference of total number of vehicles that can be detected under centralized and decentralized optimal solutions. Similarly, $\Sigma R^C - \Sigma R$ represents the difference in total number of road-links covered in centralized and decentralized optimal solutions.

It can be inferred from the Table 20 that for almost all cases centralized solution generates better network coverage than decentralized solution. There are two major reasons explaining why centralized solution is better than decentralized solution. First, in decentralized setting cities may not find the best configuration for k^A and k^K by themselves. Second, decentralized solution ignores the existence of inter-city close neighbors while most of the cases implement those. Notice that as the importance of VC increases, the difference become more visible as it is seen in the graph below:

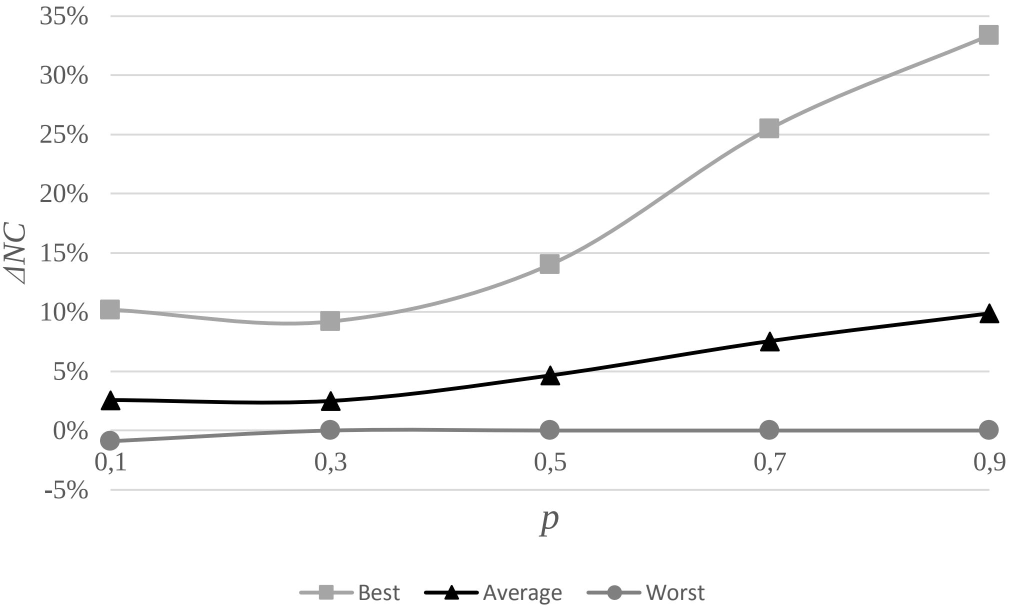


Figure 16. *Impact of p on network coverage differences*

Average difference between decentralized and centralized solutions is an important measure since it incorporates the average difference of network coverage with all possible k^A and k^K configuration with respect to *p*. The average difference increases from 2.6% to 9.9% while *p* increases from 0.1 to 0.9. For $p = 0.1$, number of road-links covered is more important than number of vehicles detected in a day. On the average, centralized optimal locations can detect 2,417 less vehicles in a day than the decentralized optimal solution. However, 1.7 more road-links can be covered with centralized optimal. On the other end, when $p = 0.9$, on the average 27,544 more vehicles in a day can be detected without giving up any road coverage.

In total, 310 different cases are examined for decentralized and centralized comparison. Out of those, only in 7 cases decentralized network coverage is better than the centralized one. All these 7 cases are observed at $p = 0.1$, where the importance of VC is low. See the following table for those cases:

Table 21. *Cases where decentralized coverage is higher than centralized*

k^A	k^K	ΣVC (%)	ΣRC (%)	NC^D (%)	k^C	ΣVC^C (%)	ΣRC^C (%)	NC^C (%)	ΔVC (%)	ΔRC (%)	ΔNC (%)
7	4	61.6	66.7	66.2	11	60.3	66.7	66.0	-1.2	0.0	-0.1
8	4	66.9	70.2	69.8	12	65.6	70.2	69.7	-1.3	0.0	-0.1
7	5	66.8	70.2	69.8	12	65.6	70.2	69.7	-1.2	0.0	-0.1
9	4	71.3	73.7	73.4	13	69.9	73.7	73.3	-1.3	0.0	-0.1
8	5	72.1	73.7	73.5	13	69.9	73.7	73.3	-2.2	0.0	-0.2
10	4	71.3	77.2	76.6	14	83.2	75.4	76.2	12.0	-1.8	-0.4
9	5	76.5	77.2	77.1	14	83.2	75.4	76.2	6.8	-1.8	-0.9

In all cases above, decentralized solutions include close neighbor locations. Recall that, in case the close neighbors are implemented in neighbor cities, maximum VC of those locations is considered while calculating network coverage. On road coverage calculation, nothing is omitted, and road-links covered by the two close neighbor locations are added up.

Since there are very few alternative locations to switch for $k^C \geq 11$, centralized solution had to give up a location that has a higher weighted score than remaining alternatives due to close neighbor constraint. For the first five cases, the negative impact of VC lost in decentralized solution is smaller than the negative impact of switching to a worse-scored location in centralized solution. Specifically, while decentralized solution uses location 9 (Ankara) and location 14 (Kırıkkale) that are close neighbors, centralized solution had to switch location 9 to a location with lower VC. In last two cases, decentralized solutions incorporating inter-city close neighbors lost VC. However, those close neighbor locations have high RC that compensate the lost in VC. Considering p = 0.1, the impact of lower RC results in lower network coverage in centralized case.

It can be inferred that, for remaining 303 out of 310 cases, network coverage achieved by centralized solution is equal or higher than the network coverage achieved by decentralized solutions. Decentralized solutions implement inter-city close neighbor locations and sub-optimal configuration of k^A and k^K. The cases that decentralized network coverage is better than the centralized are very rare and only observed for high k^C values and low p. In the next section, current state comparisons are provided.

6.3. Current State Scenarios

6.3.1. Current State and Suggested Solutions Comparison

In current state comparison section, location selection of existing ALPR systems in Ankara and Kırıkkale will be examined. ALPR systems are actively used in each city and location selection of those system have been made in a decentralized manner. Authorities in both Ankara and Kırıkkale made their decisions on how many ALPR systems to be installed and where to locate them. Furthermore, while determining the ALPR locations, decision makers of the time neglect the need to avoid vehicle duplication in short distances. In short, close neighbor condition had not been considered while determining ALPR locations in both cities.

The current state will be analyzed in accordance with previous sections and network coverage values and optimal solutions of decentralized, centralized and current states will be compared. Expert opinion obtained on VC weight coefficient, p for both cities. As a centralized decision maker, the expert states that total number of vehicles detected in a day is more important than the number of road-links covered for the Ankara-Kırıkkale region. Consequently, the VC coefficient, p, should be larger than 0.5.

Current state ALPR locations in Ankara and Kırıkkale are given in the table below:

Table 22. *Current state ALPR installations in Ankara and Kırıkkale*

Ankara													*Kırıkkale*					
x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_1	x_2	x_3	x_4	x_5	x_6
		1		1						1			1	1		1		

From Table 22, it can be seen that both Ankara and Kırıkkale have three ALPR systems installed. Decentralized (D) and centralized (C) optimal solutions with the same *k* where *p* is larger than 0.5 are provided in the table below for comparison:

Table 23. *Decentralized and centralized optimal solutions, p>0.5*

D	*Ankara*													*Kırıkkale*					
p	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_1	x_2	x_3	x_4	x_5	x_6
0.7					1				1		1			1		1		1	
0.9					1				1		1			1		1		1	
C	*Ankara*													*Kırıkkale*					
p	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	x_{19}
0.7	1		1		1				1		1				1				
0.9	1		1		1				1		1				1				

Notice that in decentralized part, the optimal location of ALPR systems is determined with respect to $k^A = 3$ and $k^K = 3$ as they are in the current state for both cities. For centralized case, the total number of ALPR systems available is 6 and the optimal locations are determined under total number of ALPR systems in a network rather than using corresponding city limits.

For p=0.7 and p=0.9, decentralized and centralized optimal solutions do not change for both cities. When compared to current state, decentralized optimal solution show similarities. For Ankara, locations 5 and 11 in current state are also observed in decentralized optimal solution. In current state, location 3 is utilized rather than location 9 that is suggested by decentralized optimal solution. For Kırıkkale, location 1 of Kırıkkale is observed in both current state and decentralized optimal. Other 2 current locations are not consistent with the decentralized optimal solution.

In current state, locations 1 and 2 in Kırıkkale are in use. However, they are close neighbor locations within the city. The minimum distance between those locations are

28 km and they are on the same road-link. Due to use of close neighbor locations, VC of Kırıkkale would diminish while calculating network coverage value.

When compared with centralized optimal solution, first thing to consider in current state is that cities do not share the k^C evenly. Centralized optimal solution suggests that for the given *p* values, 5 of 6 ALPR systems should be located on the locations that lie within Ankara and only 1 ALPR system should be located in Kırıkkale.

Current state locations 3, 5 and 11 of Ankara and location 2 of Kırıkkale are also suggested by centralized optimal solution. However, other two current state locations in Kırıkkale should be located in Ankara as the centralized optimal solution suggests. Even though location 1 of Kırıkkale has the best score, it is not included in the centralized optimal since it is a close neighbor of location 9 of Ankara. If they were not close neighbors, it is expected that both location 9 of Ankara and location 1 of Kırıkkale would appear in centralized optimal solution.

This proposition can be supported by the decentralized optimal solutions given in the Table 23. The decentralized case ignores the inter-city close neighbors and both location 9 in Ankara and location 1 in Kırıkkale are observed in their respective decentralized optimal solutions.

The network coverage values for current state, decentralized and centralized cases are provided in the table below:

Table 24. *Current, decentralized and centralized case coverage comparison*

Scenario	*ΣV*	*ΣR*	*ΣVC*	*ΣRC*	*NC* *p=0.7*	*NC* *p=0.9*
Current (T)	102,685	20	41.4%	35.1%	39.5%	40.7%
Decentralized (D)	113,853	19	45.9%	33.3%	42.1%	44.6%
D-T	**11,168**	**-1**	**4.5%**	**-1.8%**	**2.6%**	**3.9%**
Centralized (C)	141,764	20	57.1%	35.1%	50.5%	54.9%
C-T	**39,079**	**0**	**15.7%**	**0.0%**	**11.0%**	**14.2%**

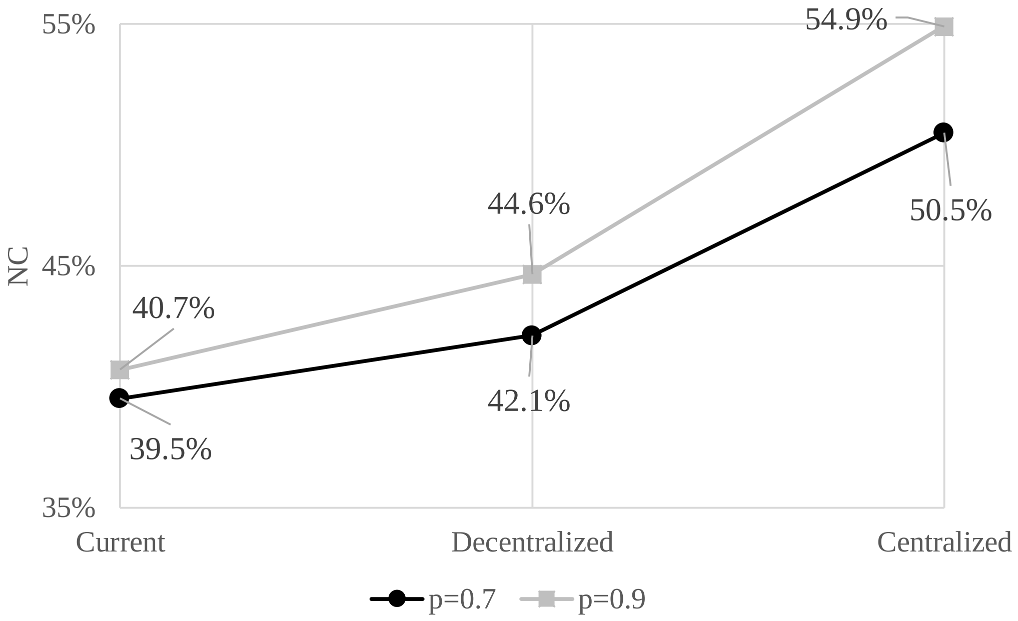


Figure 17. *Network coverage comparison with respect to p*

From Figure 17, it can be inferred that for both p values, centralized optimal network coverage is higher than the decentralized one. Respectively, decentralized optimal network coverage is higher than the current state. From Table 24, the network coverage differences between current state, decentralized and centralized cases can be explained in detail. In current state, neither allocation of ALPR systems among cities, nor close neighbor constraint is concerned. The decentralized optimal solution does not change the allocation of ALPR systems among cities. However, it suggests the optimal locations of ALPR systems considering close neighbors in each city. The decentralized optimal solution would have improved network coverage by 2.6% - 3.9% with respect to p by just selecting the optimal locations for the given k^A and k^K.

The centralized optimal solution takes a step further and incorporates allocation of ALPR system among network. Additional to city-wide close neighbor condition used in decentralized case, centralized case addresses the inter-city close neighbor locations. By determining allocation of ALPR systems over network under close neighbor constraint, the current state network coverage would have been improved by 11% -

14.2% with respect to *p*. It can be stated that the impact of optimal allocation of ALPR systems among cities is larger than the impact of addressing close neighbor locations.

In Table 24, it is shown that the centralized optimal has an absolute advantage over decentralized optimal and current state in terms of VC and RC that are independent from *p* value. Decentralized optimal has a better VC and a worse RC with respect to current state. This situation implies that for larger *p* where VC is more important, decentralized case may give up RC for higher VC to maximize network coverage as expected.

If the optimal locations were set according to decentralized solution with $p = 0.7$, the network coverage would be better than current state. After installation, assuming VC_i and RC_i do not change for any location, if *p* decreases to a value less than 0.28, which is the breakeven point between network coverage of current state and decentralized optimal solution, then the current state would yield better NC than the decentralized optimal solution. On the other side, there is no such concern in centralized case since both VC and RC of centralized optimal is equal or higher than the current state. After setting locations of ALPR systems and installation process, it is very costly to relocate an ALPR system. Therefore, the optimal locations suggested by the centralized case should have been utilized for maximizing NC on the long run.

6.3.2. Improving Network Coverage of the Current State

Another case that should be examined under current state scenarios is improving coverage percentage. Coverage level of existing network is 39.5% where $p = 0.7$ and $k = 6$. How many more ALPR systems are needed to achieve 60% or 70% coverage? Where to locate those additional ALPR systems? Assuming there were no current ALPR systems in the network, would it change the total number of installations for achieving specified coverage levels? To answer those questions, the Model MaxCover is modified as a set covering problem variant. The new model called Model MinInstall is given below:

Model MinInstall

Minimize number of ALPR systems $Z^* = \sum_{i=1}^{I} x_i$ (5)

Subject to:

$$p^* \sum_{i=1}^{I}(x_i * VC_i) + (1\text{-}p) * \sum_{i=1}^{I}(x_i * RC_i) \geq c \qquad (6)$$

$$x_i + x_j \leq d_{ij} + 1 \qquad \forall \text{ i, j} \in \text{I and i} \neq \text{j} \qquad (3)$$

$$x_i \in \{0, 1\} \qquad \forall \text{ i} \in \text{I} \qquad (4)$$

In MinInstall, only (1) and (2) of MaxCover are interchanged. The objective of the MinInstall model is minimizing number of ALPR systems (5) which is the total number of ALPR systems available constraint (2) of the MaxCover. The minimum required network coverage constraint (6) of MinInstall is the objective of MaxCover that is maximizing network coverage (1). A new parameter c is introduced in MinInstall denoting the required network coverage level. In (6), it can be observed that network coverage must be at least c.

The aim of the model is to find the minimum number of ALPR systems needed to achieve specified coverage levels. The problem is solved under centralized approach for different *c* and *p* values. First, it is assumed that the network does not have preexisting ALPR systems installed and problem is solved accordingly. Then, the active ALPR systems located in Ankara and Kırıkkale are taken into consideration and problem is solved again. In this second case, additional location constraints are used to define preexisting ALPR systems. Specifically, $x_3=x_5=x_{11}=x_{14}=x_{15}=x_{17}=1$ constraints are used while solving model MinInstall to minimize the total number of ALPR systems including the existing ones.

The two set of solutions obtained will be used to compare impact of active ALPR systems located in the network. In other words, the difference between building from empty network and cost of upgrading the existing sub-optimal network will be examined. The results are given in the table below:

Table 25. *Minimum number of ALPRs needed to ensure coverage level c*

c	*Build From Empty Network*					*Upgrade Existing Network*				
	p=0.1	*p=0.3*	*p=0.5*	*p=0.7*	*p=0.9*	*p=0.1*	*p=0.3*	*p=0.5*	*p=0.7*	*p=0.9*
20.0%	3	3	3	2	2					
25.0%	4	4	3	3	3					
30.0%	4	4	4	3	3					
35.0%	5	5	5	4	4					
40.0%	6	6	5	5	4	7	7	7	7	6
45.0%	7	7	6	6	5	8	8	7	7	7
50.0%	8	8	7	6	6	8	8	8	8	8
55.0%	9	9	8	7	7	9	9	9	9	9
60.0%	10	10	9	8	7	10	10	11	10	10
65.0%	11	11	11	10	8	11	12	12	12	11
70.0%	13	12	12	11	10	12	13	13	13	14
75.0%	14	14	13	12	11	14	14	INF	INF	INF
80.0%	INF	INF	INF	14	13	INF	INF	INF	INF	INF

It can be observed that for some cases, it is infeasible to have achieve 75 - 80% coverage levels. As expected, the minimum number of ALPR installations needed increases as the required network coverage, *c* increases. For both building from empty and upgrading existing network cases, as *p* increases, same coverages can be achieved with less number of ALPR systems. This proposition is consistent with the centralized problem objective function values given in Figure 15 and originated from the fact that there are more locations with higher VC than RC in the network.

One of the important implication of the results is that there is a gap between two set of solutions. It requires more ALPR systems to upgrade existing network to a specific coverage level than building from empty network with the same coverage levels.

Recall that for Ankara – Kırıkkale network, *p* is larger than 0.5 and there are 6 active ALPR systems already installed. Network coverage of centralized solutions are 39.5% and 40.8% for p=0.7 and p=0.9 respectively. In order to upgrade existing network to 50% coverage, 2 more ALPR systems must be utilized making total of 8 ALPR systems for both *p* values. If the network were empty and location decision were made from start, it would be possible to achieve 50% coverage with total 6 ALPR systems.

In another example, the current state network coverage values of 39.5% and 40.8% that are achieved by 6 ALPR systems, can be achieved by 4 and 5 ALPR systems under $p = 0.7$ and $p = 0.9$ respectively. Installing or relocating an ALPR system is very costly and experts state that an active ALPR system should not be closed down or relocated as possible. From this statement, it can be inferred that if coverage level of a network consisting sub-optimal active ALPR locations is upgraded, then cost of network as a whole is higher compared to building from an empty network with the same coverage level required.

CHAPTER 7

CONCLUSIONS

Automatic License Plate Recognition (ALPR) systems have a wide application area in both public and private sectors. As an Intelligent Traffic System (ITS) application, ALPR system networks provide required traffic information for policy makers to monitor, analyze and manage traffic behavior at both individual and collective levels. In public safety practices, it is important to design an efficient ALPR system network deployment ensuring certain coverage of the concerned network to obtain required level of traffic information. Our study focuses on location optimization of a public safety ALPR systems over a network.

In our study, we suggest an optimization model to maximize network coverage by determining the optimal location of ALPR systems over the network. Network coverage is comprised of weighted sum of vehicle and road coverages of selected ALPR locations. Vehicle and road coverages are used in our study due to practical reasons. The daily average number of vehicles and total number of road-links to be detected are in line with the requirements of the ALPR sensor network examined. Besides, available data enables us to provide a method for calculating vehicle and road coverages for the network. We address the close neighbor locations that are on the same road-link and the minimum distance between them are less than a predefined value. Close neighbor locations cannot be selected together in the optimal solutionsince it would create duplication of vehicle data in a short distance.

In the Experiments section, we introduce Turkish Gendarmerie ALPR systems location selection problem exemplifying two cities from Turkey that are Ankara and Kırıkkale. The number and location of ALPR systems on a city can be determined in two ways: First, local authorities decide on how many systems to be deployed at which locations in their cities. Second, central office decides on allocation of ALPR systems on cities and their locations. We design experiments to find out whether there is any difference between centralized and decentralized decision-making settings in terms of optimal solutions and network coverage. Besides, the current state of the two cities are compared with decentralized and centralized solutions for further analysis.

It turns out that centralized optimal solution generates higher network coverage than decentralized optimal since centralized setting considers inter-city close neighbors and best allocation of ALPR systems over cities. The current state of the two cities yields worst network coverage with respect to decentralized and centralized solutions. The major source of the difference in network coverage between current state and centralized optimal solution is due to the number of ALPR systems allocated to each city.

Our study contributes to literature in several practical aspects. We provide a methodological approach to locate ALPR systems optimally in a road network under different decision-making settings that are centralized and decentralized. We use traffic volume maps issued by General Directorate of Highways to obtain number of vehicles and road-links and suggest a calculation method for vehicle and road coverage parameters of available locations. We introduce a weight coefficient for vehicle and road coverage parameters to distinguish the impact of vehicle and road coverages for different cities. Finally, we suggest a close neighbor constraint that has an effect on distribution and dispersion of ALPR sensors over the network.

In our experiments, we consider two cities from Turkey as a pilot study. However, our method can be extended for a nation-wide network and can be used not only for Turkey, but also for other countries. In Turkey, Ankara and Kırıkkale road networks represent average cases and hence, our method can be implemented directly for most of the cities in Turkey. For the cities requiring special treatment, on the other hand, to address such requirements some adjustments/modifications may be necessary before the implication of the method. For example, Istanbul is one of the most crowded cities and the land trade hub of Turkey. Several adjustments should be made considering the high-volume trade routes and new parameters may be introduced as a crowdedness measure. Anotherexample can be the case of Diyarbakır. Diyarbakır is one of the biggest cities in Turkey that is located east of the country and law enforcement units are struggling with trafficking, terrorism and human smuggling. For such a road network, additional parameters concerning these mass crimes should be incorporated for available ALPR locations.

Our study suggests a methodologic approach for selecting optimal ALPR system locations for a sample network but have certain assumptions and limitations to be addressed in further studies. Our study assumes stationary daily average traffic volume and road network. Since it is costly to relocate an ALPR system after deployment, the new roads, cancellation of existing roads or changes in drivers' choices on which road to follow may affect ALPR location selection. The decision makers of this problem may not have the authority on designing road network. However, drivers' behavior can be analyzed through a trend analysis over the concerned time period to forecast future traffic volumes of road-links. Long term averages of vehicle volumes can be used while calculating VC.

Once the ALPR system is installed on a location, it cannot be relocated unless facing huge costs. There are mobile ALPR (MALPR) systems that are mounted on vehicles that can be located on any road at any time. The MALPR systems use the same databases and follow the same process flow as traditional ALPR systems. However, MALPR can monitor only one direction and certain portion of a road lane and also it uses wireless technology that leads reliability issues on data transfer. MALPR is not included in our study due to its capability/reliability issues. Besides, mobility would require dynamic location determination. In further studies, mobile and fixed ALPR systems may be combined to determine fixed locations for traditional ALPR and dynamic locations for MALPR through network coverage maximization in a progressive manner.

Beyond ALPR and MALPR systems, plate recognition cameras to be located on gas stations can be considered as an alternative data source for the road network. Recall that for a traditional ALPR system, technical and administrative constrains as availability of a nearby Gendarmerie office, a formal permission from General Directorate of Highways while identifying possible ALPR locations limit the number of data collection points. There are vast number of gas stations that are readily available on rural roads that falls in the region of concern for Turkish Gendarmerie. Keeping in mind that gas stations can capture only a certain portion of the traffic volume on the road, they may be added to possible data collection location set if there are no available ALPR location nearby.

As a final remark, reorganization of our study in a such way that it considers human crowdedness rather than traffic volume and number of road-links is a subject of future research. ALPR locations can be set according to closeness to highly populated residential areas and public places as hospitals, schools and industrial regions.

In line with the suggestions above, we aim to work on developing a nation-wide decision support system application maximizing network coverage by centralized, static/dynamic ALPR location selection.

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APPENDICES

A. Optimal Solutions for Decentralized Ankara Case

$p = 0.1$	k^A												
i	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}
1	0	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	1	1	1	1	1	1	1	1	1	1	1
4	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	1	1	1	1	1	1	1
6	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	1	1	1	1	1
8	0	0	0	0	0	0	0	1	1	1	1	1	1
9	0	0	0	0	0	1	1	1	1	1	1	1	1
10	0	0	0	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1
12	0	0	0	0	0	0	0	0	0	1	1	1	1
13	0	0	0	0	1	1	1	1	1	1	1	1	1
z (%)	13.7	26.6	35.1	42.6	50.0	57.0	63.4	69.0	74.5	79.5	79.5	79.5	79.5

p = 0.3	k^A												
i	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}
1	0	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	1	1	1	1	1	1	1	1	1	1
4	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	1	1	1	1	1	1	1	1	1
6	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	1	1	1	1	1
8	0	0	0	0	0	0	0	1	1	1	1	1	1
9	0	0	1	1	1	1	1	1	1	1	1	1	1
10	0	0	0	0	0	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1
12	0	0	0	0	0	0	0	0	0	1	1	1	1
13	0	0	0	0	0	0	1	1	1	1	1	1	1
z (%)	14.0	25.9	35.9	45.0	53.5	59.8	65.8	71.9	77.5	81.8	81.8	81.8	81.8

p = 0.5	k^A												
i	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}
1	0	0	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	1	1	1	1	1	1	1	1	1
4	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	1	1	1	1	1	1	1	1	1	1
6	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	1	1	1	1	1	1	1
8	0	0	0	0	0	1	1	1	1	1	1	1	1
9	0	1	1	1	1	1	1	1	1	1	1	1	1
10	0	0	0	0	0	0	0	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1
12	0	0	0	0	0	0	0	0	0	1	1	1	1
13	0	0	0	0	0	0	0	0	1	1	1	1	1
z (%)	14.3	27.5	38.3	48.8	58.5	64.9	70.7	75.8	80.5	84.1	84.1	84.1	84.1

p = 0.7	k^A												
i	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}
1	0	0	0	0	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	1	1	1	1	1	1	1	1	1	1
4	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	1	1	1	1	1	1	1	1	1	1	1
6	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	1	1	1	1	1	1	1
8	0	0	0	0	0	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1	1	1	1
10	0	0	0	0	0	0	0	1	1	1	1	1	1
11	0	1	1	1	1	1	1	1	1	1	1	1	1
12	0	0	0	0	0	0	0	0	0	1	1	1	1
13	0	0	0	0	0	0	0	0	1	1	1	1	1
z (%)	16.3	30.9	43.5	53.8	63.5	70.3	76.3	80.1	83.6	86.4	86.4	86.4	86.4

p = 0.9	k^A												
i	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}
1	0	0	0	0	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	1	1	1	1	1	1	1	1	1	1
4	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	1	1	1	1	1	1	1	1	1	1	1
6	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	1	1	1	1	1	1	1
8	0	0	0	0	0	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1	1	1	1
10	0	0	0	0	0	0	0	1	1	1	1	1	1
11	0	1	1	1	1	1	1	1	1	1	1	1	1
12	0	0	0	0	0	0	0	0	1	1	1	1	1
13	0	0	0	0	0	0	0	0	0	1	1	1	1
z (%)	19.4	34.4	49.0	59.9	68.5	75.7	81.8	84.5	86.7	88.8	88.8	88.8	88.8

B. Close Neighbor Matrix for Ankara

The minimum acceptable road distance between any two locations is set to 50 kilometers for Ankara.

d_{ij}	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
1	-	0	1	0	1	1	1	1	1	1	1	1	1
2	0	-	1	0	1	1	1	1	1	1	1	1	1
3	1	1	-	1	1	1	1	1	1	1	1	1	1
4	0	0	1	-	1	1	1	1	1	1	1	1	1
5	1	1	1	1	-	0	1	1	1	1	1	1	1
6	1	1	1	1	0	-	1	1	1	1	1	1	1
7	1	1	1	1	1	1	-	1	1	1	1	1	1
8	1	1	1	1	1	1	1	-	1	1	1	1	1
9	1	1	1	1	1	1	1	1	-	1	1	1	1
10	1	1	1	1	1	1	1	1	1	-	1	1	1
11	1	1	1	1	1	1	1	1	1	1	-	1	1
12	1	1	1	1	1	1	1	1	1	1	1	-	1
13	1	1	1	1	1	1	1	1	1	1	1	1	-

C. Optimal Solutions for Decentralized Kırıkkale Case

$p = 0.1$	k^K					
i	x_1	x_2	x_3	x_4	x_5	x_6
1	1	1	1	1	1	1
2	0	0	0	0	0	0
3	0	0	0	0	1	1
4	0	0	0	1	1	1
5	0	1	1	1	1	1
6	0	0	1	1	1	1
z (%)	20.9	40.2	58.8	73.4	84.2	84.2

$p = 0.3$	k^K					
i	x_1	x_2	x_3	x_4	x_5	x_6
1	1	1	1	1	1	1
2	0	0	0	0	0	0
3	0	0	0	0	1	1
4	0	0	0	1	1	1
5	0	1	1	1	1	1
6	0	0	1	1	1	1
z (%)	22.6	40.7	56.3	70.1	82.5	82.5

$p = 0.5$	k^K					
i	x_1	x_2	x_3	x_4	x_5	x_6
1	1	1	1	1	1	1
2	0	0	0	0	0	0
3	0	0	1	1	1	1
4	0	0	0	1	1	1
5	0	1	1	1	1	1
6	0	0	0	0	1	1
z (%)	24.3	41.1	55.1	68.2	80.9	80.9

$p = 0.7$	k^K					
i	x_1	x_2	x_3	x_4	x_5	x_6
1	1	1	1	1	1	1
2	0	0	0	0	0	0
3	0	1	1	1	1	1
4	0	0	0	1	1	1
5	0	0	1	1	1	1
6	0	0	0	0	1	1
z (%)	26.0	41.6	57.1	69.4	79.2	79.2

$p = 0.9$	k^K					
i	x_1	x_2	x_3	x_4	x_5	x_6
1	1	1	1	1	1	1
2	0	0	0	0	0	0
3	0	1	1	1	1	1
4	0	0	0	1	1	1
5	0	0	1	1	1	1
6	0	0	0	0	1	1
z (%)	27.8	44.9	59.1	70.7	77.6	77.6

D. Close Neighbor Matrix for Kırıkkale

The minimum acceptable road distance between any two locations is set to 30 kilometers for Kırıkkale.

d_{ij}	*1*	*2*	*3*	*4*	*5*	*6*
1	-	0	1	1	1	1
2	0	-	1	1	1	1
3	1	1	-	1	1	1
4	1	1	1	-	1	1
5	1	1	1	1	-	1
6	1	1	1	1	1	-

E. Optimal Solutions for Centralized Case

$p = 0.1$	k^C																		
i	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	x_{19}
1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
8	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
10	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
14	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
16	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
17	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
18	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
19	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
z (%)	9.0	17.4	24.6	31.3	37.8	43.3	48.4	53.2	58.1	62.3	66.0	69.7	73.3	76.2	76.2	76.2	76.2	76.2	76.2
k^A	1	2	2	2	2	3	3	4	5	6	7	7	8	9	9	9	9	9	9
k^K	0	0	1	2	3	3	4	4	4	4	4	5	5	5	5	5	5	5	5

$p = 0.3$	k^C																		
i	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	x_{19}
1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
8	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
9	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
10	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
14	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
16	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
17	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
18	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
19	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
z (%)	9.4	17.2	24.6	30.7	36.8	42.6	48.0	53.2	57.8	62.0	66.0	70.0	74.0	77.8	77.8	77.8	77.8	77.8	77.8
k'^{A}	1	2	2	2	3	4	4	5	5	6	7	7	8	9	9	9	9	9	9
k'^{K}	0	0	1	2	2	2	3	3	4	4	4	5	5	5	5	5	5	5	5

$p = 0.5$	k^C																		
i	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	x_{19}
1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
8	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
9	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
16	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
17	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
18	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
19	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
z (%)	9.8	18.9	26.3	33.5	40.1	46.1	51.6	56.0	60.3	64.6	68.9	72.8	76.2	79.3	79.3	79.3	79.3	79.3	79.3
k'^A	1	2	3	4	5	5	5	6	6	6	6	7	8	9	9	9	9	9	9
k'^K	0	0	0	0	0	1	2	2	3	4	5	5	5	5	5	5	5	5	5

$p = 0.7$	k^{C}																		
i	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	x_{19}
1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
8	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
11	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
16	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
17	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
18	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
19	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
z (%)	11.5	21.6	30.4	37.6	44.2	50.5	55.4	60.1	64.8	68.9	72.8	76.0	78.6	80.9	80.9	80.9	80.9	80.9	80.9
k'^{A}	1	2	3	4	5	5	5	6	6	7	7	7	8	9	9	9	9	9	9
k'^{K}	0	0	0	0	0	1	2	2	3	3	4	5	5	5	5	5	5	5	5

$p = 0.9$	k^C																		
i	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	x_{19}
1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
8	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
11	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
16	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
17	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
18	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
19	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
z (%)	13.7	24.3	34.6	42.3	48.9	54.9	60.0	65.1	69.4	73.6	77.1	79.2	81.0	82.5	82.5	82.5	82.5	82.5	82.5
k'^A	1	2	3	4	4	5	6	6	7	7	7	7	8	9	9	9	9	9	9
k'^K	0	0	0	0	1	1	1	2	2	3	4	5	5	5	5	5	5	5	5

F. Close Neighbor Matrix for Centralized Case

The minimum acceptable road distance between any two locations is set to 50 kilometers for Ankara-Kırıkkale network.

d_{ij}	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	-	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	-	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	1	1	-	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	0	0	1	-	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	-	0	1	1	1	1	1	1	1	1	1	1	1	1	1
6	1	1	1	1	0	-	1	1	1	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	-	1	1	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	-	1	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	-	1	1	1	1	0	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	-	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	-	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1	1	-	1	1	1	1	1	1	0
13	1	1	1	1	1	1	1	1	1	1	1	1	-	1	1	1	1	1	1
14	1	1	1	1	1	1	1	1	0	1	1	1	1	-	0	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1	1	1	1	0	-	0	1	1	1
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	-	1	1	1
17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	-	1	1
18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	-	1
19	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	-

G. Network Coverage Comparison of Decentralized and Centralized Optimal Solutions

p = 0.1

k^A	k^K	ΣVC (%)	ΣRC (%)	NC (%)	k^C	k'^A	k'^K	ΣVC^C (%)	ΣRC^C (%)	NC^C (%)	ΔVC (%)	ΔRC (%)	ΔNC (%)
2	0	16.5	17.5	17.4	2	2	0	16.5	17.5	17.4	0.0	0.0	0.0
1	1	19.1	15.8	16.1	2	2	0	16.5	17.5	17.4	-2.6	1.8	1.3
0	2	12.2	14.0	13.9	2	2	0	16.5	17.5	17.4	4.2	3.5	3.6
3	0	24.4	22.8	23.0	3	2	1	24.8	24.6	24.6	0.4	1.8	1.6
2	1	24.8	24.6	24.6	3	2	1	24.8	24.6	24.6	0.0	0.0	0.0
1	2	23.0	22.8	22.8	3	2	1	24.8	24.6	24.6	1.8	1.8	1.8
0	3	13.8	21.1	20.3	3	2	1	24.8	24.6	24.6	11.0	3.5	4.3
4	0	25.9	28.1	27.8	4	2	2	28.7	31.6	31.3	2.8	3.5	3.4
3	1	32.7	29.8	30.1	4	2	2	28.7	31.6	31.3	-4.0	1.8	1.2
2	2	28.7	31.6	31.3	4	2	2	28.7	31.6	31.3	0.0	0.0	0.0
1	3	24.6	29.8	29.3	4	2	2	28.7	31.6	31.3	4.1	1.8	2.0
0	4	17.1	26.3	25.4	4	2	2	28.7	31.6	31.3	11.6	5.3	5.9
5	0	26.9	33.3	32.7	5	2	3	30.3	38.6	37.8	3.4	5.3	5.1
4	1	34.2	35.1	35.0	5	2	3	30.3	38.6	37.8	-3.9	3.5	2.8
3	2	36.6	36.8	36.8	5	2	3	30.3	38.6	37.8	-6.4	1.8	0.9
2	3	30.3	38.6	37.8	5	2	3	30.3	38.6	37.8	0.0	0.0	0.0
1	4	27.8	35.1	34.4	5	2	3	30.3	38.6	37.8	2.4	3.5	3.4
0	5	22.3	29.8	29.1	5	2	3	30.3	38.6	37.8	8.0	8.8	8.7
6	0	41.7	36.8	37.3	6	3	3	38.2	43.9	43.3	-3.5	7.0	6.0
5	1	35.2	40.4	39.8	6	3	3	38.2	43.9	43.3	3.0	3.5	3.5
4	2	38.1	42.1	41.7	6	3	3	38.2	43.9	43.3	0.1	1.8	1.6
3	3	38.2	43.9	43.3	6	3	3	38.2	43.9	43.3	0.0	0.0	0.0
2	4	33.5	43.9	42.8	6	3	3	38.2	43.9	43.3	4.7	0.0	0.5
1	5	33.0	38.6	38.0	6	3	3	38.2	43.9	43.3	5.2	5.3	5.3
7	0	52.8	40.4	41.6	7	3	4	41.5	49.1	48.4	-11.4	8.8	6.8
6	1	41.7	43.9	43.6	7	3	4	41.5	49.1	48.4	-0.3	5.3	4.7
5	2	39.1	47.4	46.5	7	3	4	41.5	49.1	48.4	2.4	1.8	1.8

p = 0.1 (cont’d)

4	3	39.7	49.1	48.2	7	3	4	41.5	49.1	48.4	1.8	0.0	0.2
3	4	41.5	49.1	48.4	7	3	4	41.5	49.1	48.4	0.0	0.0	0.0
2	5	38.7	47.4	46.5	7	3	4	41.5	49.1	48.4	2.7	1.8	1.9
8	0	58.1	43.9	45.3	8	4	4	42.9	54.4	53.2	-15.2	10.5	8.0
7	1	52.8	47.4	47.9	8	4	4	42.9	54.4	53.2	-9.9	7.0	5.3
6	2	45.6	50.9	50.4	8	4	4	42.9	54.4	53.2	-2.7	3.5	2.9
5	3	40.7	54.4	53.0	8	4	4	42.9	54.4	53.2	2.3	0.0	0.2
4	4	42.9	54.4	53.2	8	4	4	42.9	54.4	53.2	0.0	0.0	0.0
3	5	46.7	52.6	52.0	8	4	4	42.9	54.4	53.2	-3.7	1.8	1.2
9	0	62.5	47.4	48.9	9	5	4	43.9	59.6	58.1	-18.6	12.3	9.2
8	1	58.1	50.9	51.6	9	5	4	43.9	59.6	58.1	-14.2	8.8	6.5
7	2	56.8	54.4	54.6	9	5	4	43.9	59.6	58.1	-12.8	5.3	3.5
6	3	47.2	57.9	56.8	9	5	4	43.9	59.6	58.1	-3.3	1.8	1.3
5	4	43.9	59.6	58.1	9	5	4	43.9	59.6	58.1	0.0	0.0	0.0
4	5	48.1	57.9	56.9	9	5	4	43.9	59.6	58.1	-4.2	1.8	1.2
10	0	63.8	50.9	52.2	10	6	4	55.0	63.2	62.3	-8.8	12.3	10.2
9	1	62.5	54.4	55.2	10	6	4	55.0	63.2	62.3	-7.5	8.8	7.1
8	2	62.1	57.9	58.3	10	6	4	55.0	63.2	62.3	-7.0	5.3	4.0
7	3	58.3	61.4	61.1	10	6	4	55.0	63.2	62.3	-3.3	1.8	1.3
6	4	50.5	63.2	61.9	10	6	4	55.0	63.2	62.3	4.6	0.0	0.5
5	5	49.1	63.2	61.8	10	6	4	55.0	63.2	62.3	5.9	0.0	0.6
10	1	63.8	57.9	58.5	11	7	4	60.3	66.7	66.0	-3.5	8.8	7.5
9	2	66.4	61.4	61.9	11	7	4	60.3	66.7	66.0	-6.1	5.3	4.1
8	3	63.6	64.9	64.8	11	7	4	60.3	66.7	66.0	-3.3	1.8	1.3
7	4	61.6	66.7	66.2	11	7	4	60.3	66.7	66.0	-1.2	0.0	-0.1
6	5	55.7	66.7	65.6	11	7	4	60.3	66.7	66.0	4.7	0.0	0.5
10	2	67.7	64.9	65.2	12	7	5	65.6	70.2	69.7	-2.2	5.3	4.5
9	3	68.0	68.4	68.4	12	7	5	65.6	70.2	69.7	-2.4	1.8	1.3
8	4	66.9	70.2	69.8	12	7	5	65.6	70.2	69.7	-1.3	0.0	-0.1
7	5	66.8	70.2	69.8	12	7	5	65.6	70.2	69.7	-1.2	0.0	-0.1
10	3	68.0	71.9	71.5	13	8	5	69.9	73.7	73.3	1.9	1.8	1.8
9	4	71.3	73.7	73.4	13	8	5	69.9	73.7	73.3	-1.3	0.0	-0.1
8	5	72.1	73.7	73.5	13	8	5	69.9	73.7	73.3	-2.2	0.0	-0.2
10	4	71.3	77.2	76.6	14	9	5	83.2	75.4	76.2	12.0	-1.8	-0.4
9	5	76.5	77.2	77.1	14	9	5	83.2	75.4	76.2	6.8	-1.8	-0.9

p = 0.3

k^A	k^K	ΣVC (%)	ΣRC (%)	NC (%)	k^C	k'^A	k'^K	ΣVC^C (%)	ΣRC^C (%)	NC^C (%)	ΔVC (%)	ΔRC (%)	ΔNC (%)
0	2	12.2	14.0	13.5	2	2	0	16.5	17.5	17.2	4.2	3.5	3.7
1	1	19.1	15.8	16.8	2	2	0	16.5	17.5	17.2	-2.6	1.8	0.4
2	0	16.5	17.5	17.2	2	2	0	16.5	17.5	17.2	0.0	0.0	0.0
0	3	13.8	21.1	18.9	3	2	1	24.8	24.6	24.6	11.0	3.5	5.7
1	2	23.0	22.8	22.9	3	2	1	24.8	24.6	24.6	1.8	1.8	1.8
2	1	24.8	24.6	24.6	3	2	1	24.8	24.6	24.6	0.0	0.0	0.0
3	0	31.3	21.1	24.1	3	2	1	24.8	24.6	24.6	-6.5	3.5	0.5
0	4	17.1	26.3	23.5	4	2	2	28.7	31.6	30.7	11.6	5.3	7.2
1	3	24.6	29.8	28.2	4	2	2	28.7	31.6	30.7	4.1	1.8	2.5
2	2	28.7	31.6	30.7	4	2	2	28.7	31.6	30.7	0.0	0.0	0.0
3	1	31.3	28.1	29.0	4	2	2	28.7	31.6	30.7	-2.6	3.5	1.7
4	0	39.2	26.3	30.2	4	2	2	28.7	31.6	30.7	-10.5	5.3	0.5
0	5	22.3	29.8	27.6	5	3	2	36.6	36.8	36.8	14.4	7.0	9.2
1	4	27.8	35.1	32.9	5	3	2	36.6	36.8	36.8	8.8	1.8	3.9
2	3	30.3	38.6	36.1	5	3	2	36.6	36.8	36.8	6.4	-1.8	0.7
3	2	35.2	35.1	35.1	5	3	2	36.6	36.8	36.8	1.4	1.8	1.6
4	1	39.2	33.3	35.1	5	3	2	36.6	36.8	36.8	-2.6	3.5	1.7
5	0	50.4	29.8	36.0	5	3	2	36.6	36.8	36.8	-13.7	7.0	0.8
1	5	33.0	38.6	36.9	6	4	2	47.8	40.4	42.6	14.7	1.8	5.6
2	4	33.5	43.9	40.8	6	4	2	47.8	40.4	42.6	14.2	-3.5	1.8
3	3	36.8	42.1	40.5	6	4	2	47.8	40.4	42.6	11.0	-1.8	2.1
4	2	43.2	40.4	41.2	6	4	2	47.8	40.4	42.6	4.6	0.0	1.4
5	1	50.4	36.8	40.9	6	4	2	47.8	40.4	42.6	-2.6	3.5	1.7
6	0	51.8	35.1	40.1	6	4	2	47.8	40.4	42.6	-4.1	5.3	2.5
2	5	38.7	47.4	44.8	7	4	3	49.3	47.4	48.0	10.6	0.0	3.2
3	4	40.1	47.4	45.2	7	4	3	49.3	47.4	48.0	9.3	0.0	2.8
4	3	44.7	47.4	46.6	7	4	3	49.3	47.4	48.0	4.6	0.0	1.4
5	2	54.3	43.9	47.0	7	4	3	49.3	47.4	48.0	-5.0	3.5	1.0
6	1	51.8	42.1	45.0	7	4	3	49.3	47.4	48.0	-2.5	5.3	2.9
7	0	52.8	40.4	44.1	7	4	3	49.3	47.4	48.0	-3.5	7.0	3.9

p = 0.3 (cont’d)

3	5	45.3	50.9	49.2	8	5	3	62.6	49.1	53.2	17.3	-1.8	4.0
4	4	48.0	52.6	51.2	8	5	3	62.6	49.1	53.2	14.6	-3.5	1.9
5	3	55.9	50.9	52.4	8	5	3	62.6	49.1	53.2	6.8	-1.8	0.8
6	2	55.8	49.1	51.1	8	5	3	62.6	49.1	53.2	6.8	0.0	2.1
7	1	52.8	47.4	49.0	8	5	3	62.6	49.1	53.2	9.8	1.8	4.2
8	0	58.1	43.9	48.1	8	5	3	62.6	49.1	53.2	4.5	5.3	5.0
4	5	53.2	56.1	55.3	9	5	4	65.9	54.4	57.8	12.7	-1.8	2.6
5	4	59.1	56.1	57.0	9	5	4	65.9	54.4	57.8	6.8	-1.8	0.8
6	3	57.3	56.1	56.5	9	5	4	65.9	54.4	57.8	8.5	-1.8	1.3
7	2	56.8	54.4	55.1	9	5	4	65.9	54.4	57.8	9.1	0.0	2.7
8	1	58.1	50.9	53.1	9	5	4	65.9	54.4	57.8	7.7	3.5	4.8
9	0	62.5	47.4	51.9	9	5	4	65.9	54.4	57.8	3.4	7.0	5.9
5	5	64.3	59.6	61.1	10	6	4	67.3	59.6	62.0	3.0	0.0	0.9
6	4	60.6	61.4	61.2	10	6	4	67.3	59.6	62.0	6.8	-1.8	0.8
7	3	58.3	61.4	60.5	10	6	4	67.3	59.6	62.0	9.0	-1.8	1.5
8	2	62.1	57.9	59.1	10	6	4	67.3	59.6	62.0	5.3	1.8	2.8
9	1	62.5	54.4	56.8	10	6	4	67.3	59.6	62.0	4.8	5.3	5.1
10	0	63.8	50.9	54.8	10	6	4	67.3	59.6	62.0	3.5	8.8	7.2
6	5	65.8	64.9	65.2	11	7	4	72.7	63.2	66.0	6.8	-1.8	0.8
7	4	61.6	66.7	65.1	11	7	4	72.7	63.2	66.0	11.1	-3.5	0.9
8	3	63.6	64.9	64.5	11	7	4	72.7	63.2	66.0	9.0	-1.8	1.5
9	2	66.4	61.4	62.9	11	7	4	72.7	63.2	66.0	6.2	1.8	3.1
10	1	63.8	57.9	59.7	11	7	4	72.7	63.2	66.0	8.8	5.3	6.3
7	5	66.8	70.2	69.2	12	7	5	77.9	66.7	70.0	11.1	-3.5	0.9
8	4	66.9	70.2	69.2	12	7	5	77.9	66.7	70.0	11.0	-3.5	0.8
9	3	68.0	68.4	68.3	12	7	5	77.9	66.7	70.0	9.9	-1.8	1.7
10	2	67.7	64.9	65.8	12	7	5	77.9	66.7	70.0	10.1	1.8	4.3
8	5	72.1	73.7	73.2	13	8	5	78.9	71.9	74.0	6.8	-1.8	0.8
9	4	71.3	73.7	73.0	13	8	5	78.9	71.9	74.0	7.6	-1.8	1.0
10	3	68.0	71.9	70.8	13	8	5	78.9	71.9	74.0	10.8	0.0	3.3
9	5	76.5	77.2	77.0	14	9	5	83.2	75.4	77.8	6.8	-1.8	0.8
10	4	71.3	77.2	75.4	14	9	5	83.2	75.4	77.8	12.0	-1.8	2.4

$p = 0.5$

k^A	k^K	ΣVC (%)	ΣRC (%)	NC (%)	k^C	k'^A	k'^K	ΣVC^C (%)	ΣRC^C (%)	NC^C (%)	ΔVC (%)	ΔRC (%)	ΔNC (%)
0	2	12.2	14.0	13.1	2	2	0	25.6	12.3	18.9	13.4	-1.8	5.8
1	1	19.1	15.8	17.4	2	2	0	25.6	12.3	18.9	6.5	-3.5	1.5
2	0	25.6	12.3	18.9	2	2	0	25.6	12.3	18.9	0.0	0.0	0.0
0	3	17.5	17.5	17.5	3	3	0	36.7	15.8	26.3	19.3	-1.8	8.8
1	2	23.0	22.8	22.9	3	3	0	36.7	15.8	26.3	13.7	-7.0	3.4
2	1	25.6	19.3	22.4	3	3	0	36.7	15.8	26.3	11.1	-3.5	3.8
3	0	31.3	21.1	26.2	3	3	0	36.7	15.8	26.3	5.4	-5.3	0.1
0	4	20.7	22.8	21.8	4	4	0	42.4	24.6	33.5	21.7	1.8	11.7
1	3	28.2	26.3	27.3	4	4	0	42.4	24.6	33.5	14.2	-1.8	6.2
2	2	29.5	26.3	27.9	4	4	0	42.4	24.6	33.5	12.9	-1.8	5.6
3	1	31.3	28.1	29.7	4	4	0	42.4	24.6	33.5	11.1	-3.5	3.8
4	0	42.4	24.6	33.5	4	4	0	42.4	24.6	33.5	0.0	0.0	0.0
0	5	22.3	29.8	26.1	5	5	0	50.4	29.8	40.1	28.1	0.0	14.0
1	4	31.5	31.6	31.5	5	5	0	50.4	29.8	40.1	18.9	-1.8	8.6
2	3	34.7	29.8	32.3	5	5	0	50.4	29.8	40.1	15.6	0.0	7.8
3	2	35.2	35.1	35.2	5	5	0	50.4	29.8	40.1	15.1	-5.3	4.9
4	1	42.4	31.6	37.0	5	5	0	50.4	29.8	40.1	7.9	-1.8	3.1
5	0	50.4	29.8	40.1	5	5	0	50.4	29.8	40.1	0.0	0.0	0.0
1	5	33.0	38.6	35.8	6	5	1	57.1	35.1	46.1	24.1	-3.5	10.3
2	4	38.0	35.1	36.5	6	5	1	57.1	35.1	46.1	19.1	0.0	9.6
3	3	40.5	38.6	39.5	6	5	1	57.1	35.1	46.1	16.7	-3.5	6.6
4	2	46.4	38.6	42.5	6	5	1	57.1	35.1	46.1	10.7	-3.5	3.6
5	1	50.4	36.8	43.6	6	5	1	57.1	35.1	46.1	6.8	-1.8	2.5
6	0	55.7	33.3	44.5	6	5	1	57.1	35.1	46.1	1.5	1.8	1.6
2	5	39.6	42.1	40.8	7	5	2	61.1	42.1	51.6	21.5	0.0	10.7
3	4	43.7	43.9	43.8	7	5	2	61.1	42.1	51.6	17.3	-1.8	7.8
4	3	51.6	42.1	46.8	7	5	2	61.1	42.1	51.6	9.5	0.0	4.7
5	2	54.3	43.9	49.1	7	5	2	61.1	42.1	51.6	6.8	-1.8	2.5
6	1	55.7	40.4	48.0	7	5	2	61.1	42.1	51.6	5.4	1.8	3.6
7	0	60.0	36.8	48.4	7	5	2	61.1	42.1	51.6	1.0	5.3	3.1

p = 0.5 (cont’d)

3	5	45.3	50.9	48.1	8	6	2	66.4	45.6	56.0	21.1	-5.3	7.9
4	4	54.8	47.4	51.1	8	6	2	66.4	45.6	56.0	11.5	-1.8	4.9
5	3	59.5	47.4	53.4	8	6	2	66.4	45.6	56.0	6.8	-1.8	2.5
6	2	59.6	47.4	53.5	8	6	2	66.4	45.6	56.0	6.8	-1.8	2.5
7	1	60.0	43.9	52.0	8	6	2	66.4	45.6	56.0	6.3	1.8	4.0
8	0	61.5	42.1	51.8	8	6	2	66.4	45.6	56.0	4.8	3.5	4.2
4	5	56.4	54.4	55.4	9	6	3	71.6	49.1	60.3	15.2	-5.3	5.0
5	4	62.8	52.6	57.7	9	6	3	71.6	49.1	60.3	8.8	-3.5	2.6
6	3	64.8	50.9	57.8	9	6	3	71.6	49.1	60.3	6.8	-1.8	2.5
7	2	64.0	50.9	57.4	9	6	3	71.6	49.1	60.3	7.6	-1.8	2.9
8	1	61.5	49.1	55.3	9	6	3	71.6	49.1	60.3	10.1	0.0	5.0
9	0	62.5	47.4	54.9	9	6	3	71.6	49.1	60.3	9.1	1.8	5.4
5	5	64.3	59.6	62.0	10	6	4	73.1	56.1	64.6	8.8	-3.5	2.6
6	4	68.1	56.1	62.1	10	6	4	73.1	56.1	64.6	5.1	0.0	2.5
7	3	69.2	54.4	61.8	10	6	4	73.1	56.1	64.6	3.9	1.8	2.8
8	2	65.5	56.1	60.8	10	6	4	73.1	56.1	64.6	7.7	0.0	3.8
9	1	62.5	54.4	58.4	10	6	4	73.1	56.1	64.6	10.6	1.8	6.2
10	0	63.8	50.9	57.3	10	6	4	73.1	56.1	64.6	9.3	5.3	7.3
6	5	69.6	63.2	66.4	11	6	5	76.4	61.4	68.9	6.8	-1.8	2.5
7	4	72.4	59.6	66.0	11	6	5	76.4	61.4	68.9	3.9	1.8	2.8
8	3	70.7	59.6	65.2	11	6	5	76.4	61.4	68.9	5.7	1.8	3.7
9	2	66.4	61.4	63.9	11	6	5	76.4	61.4	68.9	9.9	0.0	5.0
10	1	63.8	57.9	60.8	11	6	5	76.4	61.4	68.9	12.6	3.5	8.0
7	5	74.0	66.7	70.3	12	7	5	80.8	64.9	72.8	6.8	-1.8	2.5
8	4	73.9	64.9	69.4	12	7	5	80.8	64.9	72.8	6.8	0.0	3.4
9	3	71.7	64.9	68.3	12	7	5	80.8	64.9	72.8	9.1	0.0	4.6
10	2	67.7	64.9	66.3	12	7	5	80.8	64.9	72.8	13.0	0.0	6.5
8	5	75.5	71.9	73.7	13	8	5	82.2	70.2	76.2	6.8	-1.8	2.5
9	4	74.9	70.2	72.5	13	8	5	82.2	70.2	76.2	7.3	0.0	3.7
10	3	73.0	68.4	70.7	13	8	5	82.2	70.2	76.2	9.3	1.8	5.5
9	5	76.5	77.2	76.8	14	9	5	83.2	75.4	79.3	6.8	-1.8	2.5
10	4	76.2	73.7	74.9	14	9	5	83.2	75.4	79.3	7.0	1.8	4.4

$p = 0.7$

k^A	k^K	ΣVC (%)	ΣRC (%)	NC (%)	k^C	k'^A	k'^K	ΣVC^C (%)	ΣRC^C (%)	NC^C (%)	ΔVC (%)	ΔRC (%)	ΔNC (%)
0	2	5.2	10.5	6.8	2	2	0	25.6	12.3	21.6	20.4	1.8	14.8
1	1	14.9	10.5	13.6	2	2	0	25.6	12.3	21.6	10.7	1.8	8.0
2	0	25.6	12.3	21.6	2	2	0	25.6	12.3	21.6	0.0	0.0	0.0
0	3	9.1	17.5	11.7	3	3	0	36.7	15.8	30.4	27.6	-1.8	18.8
1	2	20.1	14.0	18.3	3	3	0	36.7	15.8	30.4	16.7	1.8	12.2
2	1	25.6	19.3	23.7	3	3	0	36.7	15.8	30.4	11.1	-3.5	6.7
3	0	36.7	15.8	30.4	3	3	0	36.7	15.8	30.4	0.0	0.0	0.0
0	4	12.4	22.8	15.5	4	4	0	44.7	21.1	37.6	32.3	-1.8	22.1
1	3	24.0	21.1	23.1	4	4	0	44.7	21.1	37.6	20.7	0.0	14.5
2	2	30.8	22.8	28.4	4	4	0	44.7	21.1	37.6	13.8	-1.8	9.2
3	1	36.7	22.8	32.6	4	4	0	44.7	21.1	37.6	7.9	-1.8	5.0
4	0	44.7	21.1	37.6	4	4	0	44.7	21.1	37.6	0.0	0.0	0.0
0	5	14.0	29.8	18.7	5	5	0	50.4	29.8	44.2	36.4	0.0	25.5
1	4	27.3	26.3	27.0	5	5	0	50.4	29.8	44.2	23.1	3.5	17.2
2	3	34.7	29.8	33.3	5	5	0	50.4	29.8	44.2	15.6	0.0	10.9
3	2	41.9	26.3	37.3	5	5	0	50.4	29.8	44.2	8.4	3.5	7.0
4	1	44.7	28.1	39.7	5	5	0	50.4	29.8	44.2	5.7	1.8	4.5
5	0	50.4	29.8	44.2	5	5	0	50.4	29.8	44.2	0.0	0.0	0.0
1	5	28.8	33.3	30.2	6	5	1	57.1	35.1	50.5	28.3	1.8	20.3
2	4	38.0	35.1	37.1	6	5	1	57.1	35.1	50.5	19.1	0.0	13.4
3	3	45.9	33.3	42.1	6	5	1	57.1	35.1	50.5	11.2	1.8	8.4
4	2	49.9	31.6	44.4	6	5	1	57.1	35.1	50.5	7.3	3.5	6.1
5	1	50.4	36.8	46.3	6	5	1	57.1	35.1	50.5	6.8	-1.8	4.2
6	0	55.7	33.3	49.0	6	5	1	57.1	35.1	50.5	1.5	1.8	1.5
2	5	39.6	42.1	40.3	7	5	2	61.1	42.1	55.4	21.5	0.0	15.0
3	4	49.1	38.6	46.0	7	5	2	61.1	42.1	55.4	11.9	3.5	9.4
4	3	53.8	38.6	49.2	7	5	2	61.1	42.1	55.4	7.3	3.5	6.1
5	2	55.6	40.4	51.0	7	5	2	61.1	42.1	55.4	5.5	1.8	4.4
6	1	55.7	40.4	51.1	7	5	2	61.1	42.1	55.4	5.4	1.8	4.3
7	0	60.0	36.8	53.1	7	5	2	61.1	42.1	55.4	1.0	5.3	2.3

p = 0.7 (cont’d)

3	5	50.7	45.6	49.2	8	6	2	66.4	45.6	60.1	15.7	0.0	11.0
4	4	57.1	43.9	53.1	8	6	2	66.4	45.6	60.1	9.3	1.8	7.0
5	3	59.5	47.4	55.9	8	6	2	66.4	45.6	60.1	6.8	-1.8	4.3
6	2	60.9	43.9	55.8	8	6	2	66.4	45.6	60.1	5.5	1.8	4.4
7	1	60.0	43.9	55.2	8	6	2	66.4	45.6	60.1	6.3	1.8	4.9
8	0	61.5	42.1	55.7	8	6	2	66.4	45.6	60.1	4.8	3.5	4.4
4	5	58.6	50.9	56.3	9	6	3	71.6	49.1	64.8	12.9	-1.8	8.5
5	4	62.8	52.6	59.7	9	6	3	71.6	49.1	64.8	8.8	-3.5	5.1
6	3	64.8	50.9	60.6	9	6	3	71.6	49.1	64.8	6.8	-1.8	4.2
7	2	65.3	47.4	59.9	9	6	3	71.6	49.1	64.8	6.3	1.8	4.9
8	1	61.5	49.1	57.8	9	6	3	71.6	49.1	64.8	10.1	0.0	7.0
9	0	62.5	47.4	58.0	9	6	3	71.6	49.1	64.8	9.1	1.8	6.9
5	5	64.3	59.6	62.9	10	7	3	75.9	52.6	68.9	11.6	-7.0	6.0
6	4	68.1	56.1	64.5	10	7	3	75.9	52.6	68.9	7.9	-3.5	4.5
7	3	69.2	54.4	64.7	10	7	3	75.9	52.6	68.9	6.8	-1.8	4.2
8	2	66.7	52.6	62.5	10	7	3	75.9	52.6	68.9	9.2	0.0	6.4
9	1	62.5	54.4	60.1	10	7	3	75.9	52.6	68.9	13.4	-1.8	8.9
10	0	63.8	50.9	59.9	10	7	3	75.9	52.6	68.9	12.1	1.8	9.0
6	5	69.6	63.2	67.7	11	7	4	79.2	57.9	72.8	9.6	-5.3	5.1
7	4	72.4	59.6	68.6	11	7	4	79.2	57.9	72.8	6.8	-1.8	4.2
8	3	70.7	59.6	67.4	11	7	4	79.2	57.9	72.8	8.5	-1.8	5.4
9	2	67.7	57.9	64.8	11	7	4	79.2	57.9	72.8	11.5	0.0	8.0
10	1	63.8	57.9	62.0	11	7	4	79.2	57.9	72.8	15.4	0.0	10.8
7	5	74.0	66.7	71.8	12	7	5	80.8	64.9	76.0	6.8	-1.8	4.2
8	4	73.9	64.9	71.2	12	7	5	80.8	64.9	76.0	6.8	0.0	4.8
9	3	71.7	64.9	69.6	12	7	5	80.8	64.9	76.0	9.1	0.0	6.4
10	2	69.0	61.4	66.7	12	7	5	80.8	64.9	76.0	11.7	3.5	9.3
8	5	75.5	71.9	74.4	13	8	5	82.2	70.2	78.6	6.8	-1.8	4.2
9	4	74.9	70.2	73.5	13	8	5	82.2	70.2	78.6	7.3	0.0	5.1
10	3	73.0	68.4	71.6	13	8	5	82.2	70.2	78.6	9.3	1.8	7.0
9	5	76.5	77.2	76.7	14	9	5	83.2	75.4	80.9	6.8	-1.8	4.2
10	4	76.2	73.7	75.5	14	9	5	83.2	75.4	80.9	7.0	1.8	5.4

p = 0.9

k^A	k^K	ΣVC (%)	ΣRC (%)	NC (%)	k^C	k'^A	k'^K	ΣVC^C (%)	ΣRC^C (%)	NC^C (%)	ΔVC (%)	ΔRC (%)	ΔNC (%)
0	2	5.2	10.5	5.7	2	2	0	25.6	12.3	24.3	20.4	1.8	18.5
1	1	14.9	10.5	14.4	2	2	0	25.6	12.3	24.3	10.7	1.8	9.8
2	0	25.6	12.3	24.3	2	2	0	25.6	12.3	24.3	0.0	0.0	0.0
0	3	9.1	17.5	10.0	3	3	0	36.7	15.8	34.6	27.6	-1.8	24.6
1	2	20.1	14.0	19.5	3	3	0	36.7	15.8	34.6	16.7	1.8	15.2
2	1	25.6	19.3	25.0	3	3	0	36.7	15.8	34.6	11.1	-3.5	9.7
3	0	36.7	15.8	34.6	3	3	0	36.7	15.8	34.6	0.0	0.0	0.0
0	4	12.4	22.8	13.4	4	4	0	44.7	21.1	42.3	32.3	-1.8	28.9
1	3	24.0	21.1	23.7	4	4	0	44.7	21.1	42.3	20.7	0.0	18.6
2	2	30.8	22.8	30.0	4	4	0	44.7	21.1	42.3	13.8	-1.8	12.3
3	1	36.7	22.8	35.3	4	4	0	44.7	21.1	42.3	7.9	-1.8	7.0
4	0	44.7	21.1	42.3	4	4	0	44.7	21.1	42.3	0.0	0.0	0.0
0	5	14.0	29.8	15.6	5	4	1	51.4	26.3	48.9	37.4	-3.5	33.4
1	4	27.3	26.3	27.2	5	4	1	51.4	26.3	48.9	24.2	0.0	21.7
2	3	34.7	29.8	34.3	5	4	1	51.4	26.3	48.9	16.7	-3.5	14.6
3	2	41.9	26.3	40.4	5	4	1	51.4	26.3	48.9	9.5	0.0	8.5
4	1	44.7	28.1	43.0	5	4	1	51.4	26.3	48.9	6.8	-1.8	5.9
5	0	50.4	29.8	48.3	5	4	1	51.4	26.3	48.9	1.0	-3.5	0.6
1	5	28.8	33.3	29.3	6	5	1	57.1	35.1	54.9	28.3	1.8	25.6
2	4	38.0	35.1	37.7	6	5	1	57.1	35.1	54.9	19.1	0.0	17.2
3	3	45.9	33.3	44.6	6	5	1	57.1	35.1	54.9	11.2	1.8	10.3
4	2	49.9	31.6	48.0	6	5	1	57.1	35.1	54.9	7.3	3.5	6.9
5	1	50.4	36.8	49.0	6	5	1	57.1	35.1	54.9	6.8	-1.8	5.9
6	0	55.7	33.3	53.4	6	5	1	57.1	35.1	54.9	1.5	1.8	1.5
2	5	39.6	42.1	39.8	7	6	1	62.4	38.6	60.0	22.9	-3.5	20.2
3	4	49.1	38.6	48.1	7	6	1	62.4	38.6	60.0	13.3	0.0	12.0
4	3	53.8	38.6	52.3	7	6	1	62.4	38.6	60.0	8.6	0.0	7.8
5	2	55.6	40.4	54.1	7	6	1	62.4	38.6	60.0	6.8	-1.8	6.0
6	1	55.7	40.4	54.1	7	6	1	62.4	38.6	60.0	6.8	-1.8	5.9
7	0	60.0	36.8	57.7	7	6	1	62.4	38.6	60.0	2.4	1.8	2.3

p = 0.9 (cont’d)

3	5	50.7	45.6	50.2	8	6	2	67.6	42.1	65.1	16.9	-3.5	14.9
4	4	57.1	43.9	55.7	8	6	2	67.6	42.1	65.1	10.6	-1.8	9.3
5	3	59.5	47.4	58.3	8	6	2	67.6	42.1	65.1	8.1	-5.3	6.8
6	2	60.9	43.9	59.2	8	6	2	67.6	42.1	65.1	6.8	-1.8	5.9
7	1	60.0	43.9	58.4	8	6	2	67.6	42.1	65.1	7.6	-1.8	6.7
8	0	61.5	42.1	59.6	8	6	2	67.6	42.1	65.1	6.1	0.0	5.5
4	5	58.6	50.9	57.8	9	7	2	72.0	45.6	69.4	13.4	-5.3	11.5
5	4	62.8	52.6	61.8	9	7	2	72.0	45.6	69.4	9.2	-7.0	7.6
6	3	64.8	50.9	63.4	9	7	2	72.0	45.6	69.4	7.2	-5.3	5.9
7	2	65.3	47.4	63.5	9	7	2	72.0	45.6	69.4	6.8	-1.8	5.9
8	1	61.5	49.1	60.3	9	7	2	72.0	45.6	69.4	10.5	-3.5	9.1
9	0	62.8	45.6	61.1	9	7	2	72.0	45.6	69.4	9.2	0.0	8.3
5	5	64.3	59.6	63.9	10	7	3	75.9	52.6	73.6	11.6	-7.0	9.7
6	4	68.1	56.1	66.9	10	7	3	75.9	52.6	73.6	7.9	-3.5	6.7
7	3	69.2	54.4	67.7	10	7	3	75.9	52.6	73.6	6.8	-1.8	5.9
8	2	66.7	52.6	65.3	10	7	3	75.9	52.6	73.6	9.2	0.0	8.3
9	1	62.8	52.6	61.8	10	7	3	75.9	52.6	73.6	13.1	0.0	11.8
10	0	63.8	50.9	62.5	10	7	3	75.9	52.6	73.6	12.1	1.8	11.1
6	5	69.6	63.2	69.0	11	7	4	79.2	57.9	77.1	9.6	-5.3	8.1
7	4	72.4	59.6	71.2	11	7	4	79.2	57.9	77.1	6.8	-1.8	5.9
8	3	70.7	59.6	69.6	11	7	4	79.2	57.9	77.1	8.5	-1.8	7.5
9	2	68.0	56.1	66.8	11	7	4	79.2	57.9	77.1	11.2	1.8	10.2
10	1	63.8	57.9	63.2	11	7	4	79.2	57.9	77.1	15.4	0.0	13.9
7	5	74.0	66.7	73.3	12	7	5	80.8	64.9	79.2	6.8	-1.8	5.9
8	4	73.9	64.9	73.0	12	7	5	80.8	64.9	79.2	6.8	0.0	6.2
9	3	72.0	63.2	71.1	12	7	5	80.8	64.9	79.2	8.8	1.8	8.1
10	2	69.0	61.4	68.3	12	7	5	80.8	64.9	79.2	11.7	3.5	10.9
8	5	75.5	71.9	75.1	13	8	5	82.2	70.2	81.0	6.8	-1.8	5.9
9	4	75.2	68.4	74.5	13	8	5	82.2	70.2	81.0	7.0	1.8	6.5
10	3	73.0	68.4	72.5	13	8	5	82.2	70.2	81.0	9.3	1.8	8.5
9	5	75.5	75.4	75.5	14	9	5	83.2	75.4	82.5	7.7	0.0	7.0
10	4	76.2	73.7	76.0	14	9	5	83.2	75.4	82.5	7.0	1.8	6.5

H. Turkish Summary / Türkçe Özet

GİRİŞ

Wards Auto'nun dünyadaki araç sayısının 1 milyarı geçtiğini bildiren 2010 yılına ait raporunun üzerinden 4 yıl geçmeden, bu sayı 2014 yılında 1.2 milyara ulaşmış ve 2035 yılına kadar 2 milyara ulaşması beklenmektedir. Artan araç sayısı sebebiyle, trafiği planlamak ve yönetmek için etkin Akıllı Trafik Sistem (ATS) çözümlerine gereksinim duyulmaktadır. Avrupa Parlamentosu direktifinde tanımlandığı üzere ATS, ulaştırma sistemlerini planlamak, tasarlamak, işletmek, sürekliliğini sağlamak ve yönetmek amacıyla; telekominikasyon, elektronik, bilgi teknolojileri ve ulaştırma mühendisliği uygulamalarının birleşmesinden oluşmaktadır. Bilgisayar teknolojisindeki gelişmeler sayesinde, trafik gözetleme ATS'nin temel uygulama alanlarından biri haline gelmiş olup, gerçek zamanlı trafik bilgisinin sensör ağları sayesinde toplanması ulaşım sistemlerinin yönetimi ve analizi için bir gereklilik haline gelmiştir.

Trafik yoğunluğu, başlangıç son matrisleri, araç/plaka tanıma ve takip gibi trafik analizlerine; gözetleme kameraları, hız tespit kameraları, görsel ve manyetik algılayıcılar gibi farklı sensörler tarafından toplanabilen bilgiler sayesinde ulaşılabilmekte, ve bu bilgiler hem kamu hem de özel sektöre geniş uygulama sahası sunmaktadır. Trafiği izlemek ve yönetmek için etkin bir sensör ağı sistemi oluşturulması gerekmektedir. Bu bağlamda, oluşturulacak bu sistem, belirli düzeyde doğruluk ve kapsama sağlamalıdır. Doğruluk, bu sistemlerde kullanılacak sensörlerin kalitesiyle ilişkili olup, yüksek doğru tespit yüzdesi sistemin etkinliğine olumlu etki edecektir. Öte yandan kapsama, bu sistemde kullanılacak sensörlerin trafik ağı üzerinde olabildiğince çok aracı tespit etmeye olanak verecek şekilde doğru sayıda, doğru yerlere konuşlanması ve yayılması ile ilişkilendirilebilir. Ağ üzerinde kullanılacak sensör sayısı, gerek duyulan trafik bilgisi seviyesine göre belirlenmelidir. Çünkü bir ağ üzerindeki tüm yollara sensör kurulumu yapmak pratikten uzak ve yüksek maliyetli bir uygulama olacaktır.

Kısıtlı bütçe altında sensör sayısı ve yerleşimi problemi, trafik yöneticilerin olduğu kadar araştırmacıların da ilgisini çekmiştir. Buradan yola çıkarak bu çalışmamızda, ağ kapsamasını eniyilemek amacıyla Otomatik Plaka Tanıma Sistemi (OPTS) yer seçimi probleminin çözümü için bir yöntem önermeyi amaçlıyoruz. Bu yöntemin, aktif olarak OPTS kullanılan Ankara ve Kırıkkale illeri için ortaya koyduğu sonuçlar farklı karar verme süreçleri altında değerlendirilecektir.

LİTERATÜR TARAMASI

Literatürde tesis yer seçimi problemlerinin çözümüne yönelik bir çok yöntem ve model geliştirilmiştir. Bu yöntemler arasından kapsama problemleri, tesis yer seçimi problemleri içinde en popüler olanlardandır. Kapsama problemleri okul, polis merkezi, kütüphane, park ve atık toplama merkezi gibi tesislerin yerlerinin belirlenmesinde kullanılabilmektedir. Kapsama problemleri literatürde iki başlık altında gruplanabilir: Küme Örtüleme Problemi (KÖP) ve Maksimum Kapsama Problemi (MKP). KÖP'nin amacı en az sayıda tesis ile belirlenen kümedeki talep noktalarının taleplerini karşılamaktır. MKP'de amaç ise eldeki belirli sayıda tesis veya bütçe ile karşılanan talebi eniyilemeye dayanır. Current ve Schilling, hem KÖP hem de MKP problemlerinin NP-zor olduğunu göstermiş ve çözümleri için kullanılan çeşitli sezgisel yöntemleri sunmuştur (1990).

Sensör teknolojisindeki gelişmeler, yollar üzerinde gelişmiş sensörlerden oluşan sensör ağlarının oluşturulmasına olanak sağlamıştır. Gerçek zamanlı trafik bilgisine ulaşmayı mümkün kılan bu ağların optimizasyonuna yönelik olarak Sensör Yerleştirme Problemi (SYP) ortaya çıkmıştır. Ağ kapsamasında kullanılacak sensör adetleri ve yerlerinin belirlenmesi problemi, bu ağların maliyeti ve etkinliği arasındaki ödünleşmeyi yanıstması bakımından araştırmacıların dikkatini çekmiştir.

SYP’de trafik akışının tahmin edilmesi için sık kullanılan yöntemlerden biri başlangıç son (BS) matrislerinin tahmin edilmesidir. Gerçek BS matrislerini oluşturmak çok maliyetli ve uzun süren bir uygulama olacaktır. Bunun yanında BS matrisleri için, yollar üzerine yerleştirilen trafik sayım noktaları sayesinde iyi tahminler elde edilebilmektedir. Yang ve Zhou (1998), sensör yerleşimlerini belirlemek için, BS kapsama, maksimum akış yüzdesi, maksimum akış kesme gibi farklı kurallar belirlemiş ve bu kurallar üzerinden oluşturdukları modeller ile sensör yer ve adetleri için önermelerde bulunmuşlardır.

Bianco ve diğerleri (2001) ilk olarak, maliyeti enazlayan SYP çözerek sensörlerin yerlerini belirlemişler, ardından bu sensörlerden elde edilen akış bilgisini kullanarak BS matrislerini tahmin etmeye çalışmışlardır. Ehlert ve diğerleri (2006) geliştirdikleri yazılım üzerinde belirli BS akışlarına ağırlık verilebilmekte ve bu sayede daha çok bilgi taşıdığına inanılan BS noktaları için önem katsayısı belirlenebilmektedir.

Castillo ve diğerleri (2008b) ağ üzerindeki iki nokta arasındaki rotalar üzerindeki araç akış miktarını belirlemek amacıyla plaka tanıma sensörlerinin yer ve adetlerini belirleyen bir model önermişlerdir. Plaka tanıma sensörlerinin, trafik sayımı yapan sensörlere göre daha fazla bilgi taşıdığını ve bu sebeple BS matrislerini tahmin etmede ve trafik akış diyagramı oluşturma konusunda daha iyi performans gösterdiklerini ifade etmişlerdir. Mitsakis ve diğerleri (2017) Bluethooth sensörlerinden geçen akışı ençoklayan, ikinci dereceden bir model önermişlerdir. Bu modelde, birbirlerine belirli bir mesafeden daha yakın olan yerlerin, çözümde beraber yer almaması için komşu sensör kısıtı tanımlanmıştır.

Bahsi geçen bir çok çalışmada, önceden elde edilmiş veriler ile BS, rota veya yollar üzerindeki trafik akış bilgisinin tahmin edilmesinin amaçlandığı göze çarpmaktadır. Bizim çalışmamızda da benzer şekilde önceden elde edilmiş yol akış bilgileri kullanılarak, OPTS için eniyi yer seçimini belirleyen bir yöntem ortaya koyulmuştur. Ancak literatürün genelinden farklı olarak çalışmamızda, bir trafik bilgisini tahmin etmek yerine araç akış miktarı ve yön sayısı kapsamalarından oluşan ağ kapsamasını ençoklamak amaçlanmıştır. Uzmanlara göre, bir sensör yerleşiminin etkinliği, yüksek trafik hacmi olan yolları ve sürücülerin rotalarını değiştirebileceği yol kesişimlerindeki yönleri kapsaması ile ilişkilendirilebilir. Bu bağlamda, çalışmamızda yer alan araç akış miktarı, bir noktadaki OPTS tarafından tespit edilen günlük ortalama araç sayısı olarak tanımlanmıştır. Benzer şekilde, yön sayısı kapsaması, bir noktadaki OPTS tarafından gözlemlenebilen yön veya yol sayısı olarak tanımlanmıştır.

OTOMATİK PLAKA TANIMA SİSTEMİ

Bir ATS çözümü olarak OPT, araç plakalarının fotograflarının çekilmesi ve bu fotograflardan araç plakalarındaki alfa numerik ifadelerin çeşitli algoritmalarla tespit edilmesidir. İlk olarak 1976'da İngilterede geliştirilen OPTS, laboratuvar ortamında kullanılmıştır. O dönemde dijital kameraların olmaması, bilgisayarların hesaplama kabiliyeti ve bilgi transfer teknolojilerindeki kısıtlar sebebiyle, ilk uygulamalar düşük doğru tespit oranı ve az fonksiyonellik sunabilmekteydi. İlgili alanlardaki teknolojik gelişmeler sayesinde, günümüzde OPTS'lerin kabiliyetleri ve kullanım alanları oldukça genişlemiştir. Otoparklarda, benzin istasyonlarında, ücretli geçiş sistemlerinde, gümrük ve trafik kontrollerinde ve kamu güvenliği alanlarında, farklı ihtiyaçlara cevap verebilen OPTS'ler faaliyet göstermektedir.

Roberts ve Casanova'nın 2012 tarihli raporuna göre, 1993 yılında Londra'da yaşanan terör saldırılarının ardından *çelik koridor* adı verilen kapalı devre kameralar ve plaka tanıma kameralarının kullandıldığı gözetleme ve güvenlik koridoru oluşturulmuştur. LEMAS'ın 2007 ve 2013 raporları incelendiğinde, ABD'deki polis birimleri tarafından OPTS kullanılma oranının 2007-2013 yılları arasında %19'dan %34'e yükseldiği gözlenmiştir.

Bizim çalışmamızda, ülke genelinde kamu güvenliği birimleri tarafından kullanılan OPTS incelenmiştir. Bu kapsamda, kullanılan OPTS'nin kamu güvenliği uygulamalarına ve trafik araştırmalarına destek olması beklenmektedir. Kaçak, kayıp, veya çalıntı plakalı araçların, suça karışmış veya terör aktiviteleri ile ilişkilendirien plakaların tespit ve takip edilmesi; bireysel ve kolektif anlamda trafiğin kontrol edilebilmesi için birden çok OPTS'nin ağ üzerinde doğru noktalarda konuşlandırılması büyük önem teşkil etmektedir.

Türkiye'de kamu güvenliği alanında, Polis teşkilatı ve Jandarma birimleri faal olarak OPTS kullanmaktadırlar. Hem Polis hem de Jandarma birimlerinin bu sistemleri kullanma amacı trafik güvenliği ve kontrolünü sağlamak olsa da, bu birimlerin sorumluluk sahası, teknik ve yönetimsel açıdan OPTS ihtiyaçları farklılık göstermektedir.

Çalışmamızda, Jandarma birimleri tarafından şehir merkezleri dışında, devlet ve il yolları üzerinde kullanılan OPTS ağı incelenecektir. Bu sistemde araç fotografları OPTS noktalarında, başüstü direkler üzerine yerleştirilen kameralar tarafından toplanmaktadır. Toplanan araç fotografları anlık olarak fiber hat üzerinden ilişkili Jandarma ofisine gönderilir ve buradaki OPTS yazılımı sayesinde araç plakası, geçiş zamanı, yönü, araç marka ve rengi gibi bilgiler tespit edilir. Tüm OPTS noktaları, tespit edilen araç bilgilerini merkezi veri tabanına gönderir. Merkezi veri tabanında veriler kaydedilir ve sorgulama veri tabanına iletilir. Sorgulama veri tabanında araç ile ilişkilendirilmiş herhangi bir suç/ihbar tespit edilmişse, ilgili OPTS noktasına alarm iletilir. Alarm oluşturan herhangi bir tespit yapılmamışsa, yine ilgili noktaya plakaya ilişkin olarak suç kaydı olmadığına dair bilgi verilir. Normal şartlarda bütün bu işlemler, aracın OPTS noktasındaki kameraların önünden geçmesinden itibaren birkaç saniye içinde gerçekleşir. Jandarma birimleri, sorgulama veri tabanından gelen bilgilere göre kamu güvenliği faaliyetlerini planlar.

Jandarma birimleri OPTS'yi sorumluluk sahasında trafiği izlemek ve kontrol etmek amacıyla kullanmaktadır. İzleme ve kontrol faaliyetlerinin etkin şekilde yapılabilmesi, olabildiğince çok araç plakasının tespit edilmesiyle başlamaktadır. Trafik hacmi yüksek olan yolları izlemek, adli vakaların tespit edilmesinin yanı sıra veritabanının geliştirerek büyük veri uygulamalarına imkan yaratacaktır. İzleme ve kontrol faaliyetlerinin diğer bir gereksinimi de araçların iz bilgilerinin takip edilmesidir. İleriye veya geriye dönük olarak hangi plakalı araçların hangi yolları kullanarak en son hangi OPTS noktasından geçtiği gibi bilgiler Jandarma ekiplerine araç hırsızlığı, kaçakçılık ve terörle mücadelede hukuki bir temel oluşturmaktadır. Uzmanlara göre, trafik ağına yayılmış OPTS noktaları tarafından günlük toplam tespit edilen plaka sayısı ve izlenen yön sayısı sistemin etkinliği için en önemli kriterler olarak öne çıkmaktadır. Buradan yola çıkarak, kullanılan OPTS sayısı ve yerlerinin doğru belirlenmesi uygulamanın etkinliğine etki eden önemli faktörlerdir çıkarımı yapılabilir.

OPTS sayısı ve yerleri belirlenirken teknik ve idari boyutta kısıtlamalar söz konusudur. Teknik boyutta, OPTS'nin bir noktada kurulabilmesi için; yakın mesafede Jandarma ofisi bulunması, internet bağlantısı, veri transfer altyapısının uygun olması ve karayolları veya belediyelerden teknik onay alınması gerekmektedir. İdari boyutta ise teknik olarak uygun bulunan noktalar içerisinden kaç tanesine ve hangilerine OPTS kurulacağı kararı verilmesi gerekmektedir. OPTS sayısı ve yerleri kararı, merkezi olarak veya il idaresindeki otoriteler tarafından verilebilmektedir. Çalışmamızda bu karar eğer merkezi idare tarafından veriliyorsa *merkezileştirilmiş durum*; ildeki yöneticiler tarafından veriliyorsa *dağıtılmış durum* olarak adlandırılmıştır.

Merkezileştirilmiş ve dağıtılmış durumlar OPTS ağının etkinliğini etkileyen faktörlerdir. Dağıtılmış durumda, ildeki yöneticiler OPTS kararlarını sadece kendi illerindeki yol ağını dikkate alarak vermektedirler. Diğer bir deyişle her şehir kendi sorumluluk sahasındaki OPTS ağını planlar. Merkezileştirilmiş durumda ise tüm Türkiye bir OPTS ağı olarak değerlendirilir ve bu sistemlerin illere kaç adet atanacağı ve hangi yerlere planlanacağı kararı tek bir noktadan verilir. Dağıtılmış durumda, ildeki otoriteler kendi bölgelerine ilişkin trafik konusundaki tecrübe ve bilgi birikimlerini OPTS kararlarında kullanabilirler. Merkezileştirilmiş durumda, coğrafi olarak tüm ülkeye dağılan sistem ağı merkezi otoriteler tarafından analiz edilebilir ve OPTS kararları bu analizlere göre verilebilir.

YAKLAŞIM

Çalışmamızda, OPTS yerlerini belirlemek suretiyle ağ kapsamasını optimize eden matematiksel modeller önermek amaçlanmaktadır. Merkezileştirilmiş ve dağıtılmış karar verme süreçleri için, farklı parametreler altında bu modellerden elde edilen sonuçlar arasındaki farklar incelenerek önermeler yapılacaktır. Çalışmamızda kullanılan modeller, kapsama problemleri altında değerlendirilen KÖP ve MKP olarak ifade edilmiştir. KÖP, kısıtlı OPTS sayısı ile ağ kapsamasını eniyilemek için kullanılmıştır. MKP ise istenen ağ kapsaması seviyesini sağlayacak OPTS sayısını enazlamak için kullanılmıştır.

Ağ kapsamasını oluşturacak parametreler için uzmanlardan OPTS kapsama ihtiyaçları konusunda bilgi alınmıştır. Günlük ortalama araç geçiş sayısı ve izlenen yön sayısının etkin bir OPTS yerleştirme yöntemi için uygun olacağı değerlendirilmiştir. Muhtemel OPTS noktalarına; günlük ortalama araç geçiş sayısı için *araç kapsama* (AK), izlenen yön sayısı için *yol kapsama* (YK) parametreleri atanmıştır. Uzmanlara göre, ağ kapsamasını oluşturan AK ve YK parametrelerinin birbirlerine göre önemi her bölge ve her zaman periyodu için aynı olmayabilir. Kaçakçılık, araç hırsızlığı gibi olayların yoğun olarak yaşandığı bölgelerde izlenen yol sayısı, toplam araç geçiş sayısına göre daha önemli olabilir. Bu tarz suçlara karışmış araçların yoğun olan yollar yerine daha düşük hacimli, ara yolları kullanmaları göz önüne alınırsa, YK daha önemlidir önermesi yapılabilir. Büyük şehirlerin kırsal alanlarında bulunan geniş ve büyük trafik akış hacmine sahip yollarda ise AK daha önemli olarak değerlendirilebilir. Bu yollar üzerinde, kayıtsız plakalı, hacizli veya üzerinde trafik cezası bulunan araçları takip etmek daha kolay olacaktır.

YK ve AK arasındaki önem farklılığını ortaya koymak amacıyla, her il bazında muhtemel OPTS noktalarındaki AK için *p*, YK için *(1-p)* önem katsayısı çalışmamızdaki modellere dahil edilmiştir. Sonuç olarak ağ kapsaması; seçilen OPTS noktalarına ait AK ve YK'lerin p ve 1-p ile ağırlıklandırılmış toplamı olarak ifade edilmiştir. Örnek bir ağ üzerinde AK, YK ve p değerlerinin OPTS yer seçimindeki etkisi incelenmiştir. Muhtemel bir OPTS noktasının YK ve AK'si sabit olmasına rağmen, yüksek p değerlerinde, AK'ye daha çok önem verildiği için AK'si yüksek olan noktalar; düşük p değerlerinde, YK'ye daha çok önem verildiği için YK'si yüksek olan noktaların seçilmesi bu örnek ağ üzerinden gösterilmiştir.

OPTS noktalarının belirlenmesinde göz önüne alınması gereken bir diğer durum ise seçilen noktaların ağ üzerindeki dağılımıdır. Bu dağılım yapılırken, uzmanlardan alınan bilgiler dahilinde birbirlerine yakın komşu olan noktaların çözümde beraber bulunmalarının uygun olmayacağı değerlendirilmiştir. Eğer ağ üzerindeki iki muhtemel OPTS noktası arasındaki en kısa yol mesafesi, her il için ayrı olarak belirlenen bir alt limitin altında ise bu iki nokta yakın noktalar olarak tanımlanmıştır. İlaveten, bu iki nokta rotanın değiştirilemeyeceği, aynı yol üzerinde bulunuyorsa bu noktalar *yakın komşu* noktalar olarak tanımlanmıştır.

Yakın komşu noktaların kullanılması, kısa zaman ve mesafe içinde aynı plakaların tekrar tekrar tespit edilmesine yol açacaktır. OPTS'nin yüksek ilk kurulum maliyetleri ve bu noktaların yer değiştirilmesinin teknik zorlukları değerlendirildiğinde, yakın komşu noktaların beraber kullanılması sistemin hem maliyet etkinliğini hem de veri çeşitliliğini yani ağ kapsamasını olumsuz yönde etkileyecektir. Ayrıca, birçok plaka yakın komşu noktalarda tekrarlanacağı için, sonuçlarda AK olduğundan daha yüksek gözükecektir. Ancak YK için aynı şey söz konusu değildir. Yakın komşu noktalar aynı yol üzerinde olsalar bile kendilerini birleştiren yol dışında bir çok farklı yönde plaka tespiti yapabilir.

Çalışmamızda, yakın komşu noktaların beraber kullanılmaması için modelde kısıtlama kullanılmıştır. Bu kısıtlama merkezileştirilmiş ve dağıtılmış durumlar için önemli bir farklılık oluşturmaktadır. Dağıtılmış durumda, her ildeki karar verici, yalnızca il içindeki OPTS noktalarının yerlerini belirlerken il içi yakın komşuları değerlendirecektir. Merkezileştirilmiş durum için birbirine sehirlerarası yollar ile bağlı komşu iki il düşünelim. Bu şehirlerarası yollardan biri üzerinde, farklı şehirlerin sorumluluk sahasında birbirlerine yakın iki muhtemel OPTS noktası bulunsun.

Şehirlerarası yakın komşu noktalar olarak ifade edilebilecek bu vakada merkezileştirilmiş durum bunu tespit edip OPTS noktalarının yerleri bu koşul altında değerlendirebilecekken, dağıtılmış durumda şehirlerarası yakın komşu noktalar gözardı edilecektir. Dağıtılmış durumda bu iki noktanın farklı iller tarafından OPTS yeri olarak seçilmesi sonucunda, ağın tamamı düşünüldüğünde AK olduğundan daha fazla hesaplanacak ve dolayısıyla ağ kapsaması da olduğundan daha yüksek hesaplanacaktır.

Bu bilgiler ve tanımlamalardan sonra kullanılan setler, parametreler, karar değişkenleri açıklanarak matematiksel model, model MaxCover sunulmuştur. Modeldeki hedef fonksiyonu, yani AK ve YK'nin p ile ağırlıklandırılması ile oluşturulmuş ağ kapsaması fonksiyonu açıklanmıştır. Modelde bulunan bütçe kısıtı (eldeki OPTS sayısı) ve yakın komşu kısıtlaması verilmiş ve açıklanmıştır.

Modelin çalışma prensibini daha iyi anlamak için örnek bir ağ görseli verilmiştir. Bu görselin yanında ağ üzerinde bulunan muhtemel noktaların AK ve YK parametreleri sunulmuş ve farklı p değerleri için yakın komşu kısıtlaması altında OPTS için yer seçimi üzerine örnekler tartışılmıştır.

DENEYLER

Bu kısımda Ankara ve Kırıkkale şehirleri için tasarlanan deneyler anlatılmıştır. Türkiye'nin başkenti Ankara, coğrafi olarak ve karayolları anlamında ülkenin merkezinde yer almaktadır. Komşusu Kırıkkale daha küçük bir şehir olmasına rağmen, Ankara'yı Türkiye'nin doğusuna bağlayan köprülerden biri olarak değerlendirilebilir. Deneyler için bu iki ilin seçilmesinin başlıca üç sebebi vardır:

İlk olarak teknik olarak onaylanmış muhtemel OPTS noktaları iki şehir için de belirlenmiştir. Bu bağlamda, bu iki şehir için yapılacak deneyler gerçek hayattaki teknik kısıtlamalara uygun olarak yer seçimi önerisini olanaklı kılmaktadır. İkincisi, iki şehirde de aktif olarak kurulu OPTS noktaları bulunmakta ve bu sistemler faal olarak kullanılmaktadır. Bu sayede merkezileştirilmiş ve dağıtılmış durum için yapılacak analizler güncel durum ile karşılaştırılabilecektir. İlaveten, faal noktaların bulunması, halihazırdaki ağ kapsamasını geliştirmek için yapılacak analizlerde gerçek hayattaki güncel durumun kullanılabilmesi anlamında önem arz etmektedir. Üçüncü ve son olarak, Ankara ve Kırıkkale birbirlerine birden fazla şehirlerarası yol ile bağlanan komşu illerdir. Güncel durumda bulunan OPTS sayı ve yerleri önceden belirlenmiş ancak şehir içi veya şehirlerarası yakın komşu kısıtlaması göz önüne alınmamıştır. Bu iki ilde, merkezileştirilmiş ve dağıtılmış durumlar için ortaya çıkacak sonuçların güncel durum ile karşılaştırılması, yakın komşu noktaların aktif olarak kullanılmasının ağ kapsaması üzerindeki etkilerini inceleme konusunda önemli bilgiler sağlayacaktır.

Ankara ve Kırıkkale yol ağı için yapılacak deneyler üç ana başlık altında toplanmıştır: İlk olarak dağıtılmış durumda her iki il için ayrı ayrı eniyi OPTS yerleri ve farklı parametreler altında ağ kapsamaları sunulacaktır. İkinci kısımda, Ankara ve Kırıkkale ağı bir bütün olarak değerlendirilecek ve problem merkezileştirilmiş durum olarak çözülecektir. Merkezi durumda farklı parametreler altında hangi ile kaç OPTS atandığı ve hangi noktalara kurulması gerektiği bilgileri paylaşılacaktır. Yine bu kısımda, dağıtılmış durumdan çıkan sonuçlarla merkezileştirilmiş durumun önerdiği çözümler karşılaştırılacaktır. Son olarak, güncel durum senaryoları adı altında, güncel OPTS noktalarının ağ kapsaması, dağıtılmış ve merkezileştirilmiş durumlarda önerilen çözümlerdeki ağ kapsamaları ile karşılaştırılacaktır. Bu bölümde ayrıca, güncel durum ağ kapsamasını belirli seviyelere çıkarmak için ek olarak kaç OPTS'ye daha ihtiyaç duyulacağına ve bu sistemlerin hangi noktalara kurulması gerektiğine ilişkin analizler yapılacaktır.

SONUÇLAR ve TARTIŞMA

Dağıtılmış Durum

Dağıtılmış durum altında Ankara ve Kırıkkale illeri için çözümler sunulmuştur. Her iki il için de problem beş farklı p değeri altında (0,1 - 0,3 - 0,5 - 0,7 - 0,9) çözülmüştür. Her ilde AK ve YK setleri arasındaki korelasyon katsayına bakılmıştır. Eğer bir il için

YK ve AK arasında pozitif yüksek korelasyon gözlenirse, p katsayısının çözüm üzerindeki etkisi düşük olmaktadır. İncelendiğinde Ankara için korelasyon katsayısı 0,06, Kırıkkale için -0.11 çıkmıştır. Bu durumda iki il için de AK ve YK parametreleri arasında pozitif yüksek korelasyon olmadığı tespit edilmiştir.

Ankara ilinde 13 adet, Kırıkkale'de ise 6 adet muhtemel OPTS yeri mevcuttur. Şehir içi yakın komşu noktalar sebebiyle Ankara'da en fazla 10, Kırıkkale'de ise en fazla 5 OPTS noktası seçilebilmektedir. Ankara için en fazla %89 ağ kapsaması gözlenebilirken, Kırıkkale için bu değer %84 olarak ortaya konmuştur. İller için ayrı ayrı olmak üzere, eldeki OPTS sistemi (k) ve p değerlerine göre eniyi ağ kapsaması matrisleri sunulmuştur. Farklı p değerleri için elde edilen eniyi ağ kapsama değerleri grafik olarak verilmiştir. Çözümlerdeki eniyi OPTS noktalarından örnekler verilmiş ve farklı p değerleri için optimal OPTS yerlerinin nasıl değiştiği konusunda yorumlar yapılmıştır.

Merkezileştirilmiş Durum

Merkezileştirilmiş durumda Ankara ve Kırıkkale illeri için toplam 19 muhtemel noktadan oluşan bir ağ değerlendirilmiştir. İller için ortak belirlenen p değerleri (0,1 - 0,3 - 0,5 - 0,7 - 0,9) için çözümler sunulmuştur. Şehir içi yakın komşu noktaların yanı sıra, şehirlerarası yakın komşu noktaların da göz önüne alındığı bu durumda, en fazla 14 nokta seçilebilmektedir. Ağ kapsaması en fazla %82,5 olarak gözlenmiştir.

Dağıtılmış durumda AK ve YK il bazındaki toplamlara oranlanarak hesaplanmaktadır. Bu nedenle dağıtılmış ve merkezileştirilmiş durumları karşılaştırabilmek için dağıtılmış durumda kullanılan AK ve YK parametrelerinin, merkezileştirilmiş duruma göre tekrar düzenlenmesi gerekmektedir. Dağıtılmış durumda iller OPTS adetlerini kendileri belirlerdikleri için, Ankara ve Kırıkkale illerine atanabilecek tüm farklı OPTS adet vakaları için ortaya çıkacak ağ kapsama değerleri, bu adetlerin toplamına denk gelen merkezileştirilmiş durum çözümleri ile karşılaştırılmıştır.

Ağ kapsaması karşılaştırma tabloları adı verilen bu tablolarda, her p değeri için 62 farklı dağıtılmış durum vakası olmak üzere toplam 310 vaka dengi olan merkezileştirilmiş durumla karşılaştırılmıştır. Bu 310 vakadan 65'inde dağıtılmış durumun önerdiği optimal çözümdeki Ankara ve Kırıkkale illerine atanan adetler ile merkezileştirilmiş durumun önerdiği il atama adetleri aynı çıkmıştır. 65 vakadan sadece 21 tanesinde merkezileştirilmiş ve dağıtılmış durumlardan elde edilen ağ kapsamaları eşit çıkmıştır. 40'ı için merkezileştirilmiş ağ kapsaması, dağıtılmış duruma göre daha yüksek olduğu gözlenmiştir. Kalan 4 vakada dağıtılmış durum daha yüksek ağ kapsaması sağlamıştır.

Toplam 303 vakada, merkezileştirilmiş durumdan elde edilen ağ kapsaması, dağıtılmış durumun önerdiğine eşit veya ondan daha yüksektir. Bunun sebebi, merkezileştirilmiş durumda OPTS il atamasının daha iyi yapılması ve şehirlerarası yakın komşu noktaların elemesidir. Kalan 7 vakada dağıtılmış durumun daha yüksek ağ kapsaması sağlama sebebi de şaşırtıcı şekilde şehirlerarası yakın komşu noktaları çözümlerde kullanmasıdır.

Merkezileştirilmiş durumda yüksek ağ kapsaması sağlayan yakın komşu noktalardan en fazla bir tanesi kullanılabilmekte ve diğer nokta daha düşük kapsama sağlayan bir noktayla değiştirilmek zorunda kalınmaktadır. Dağıtılmış durumda şehirlerarası yakın komşuların çözümde beraber kullanılması durumunda, AK'si yüksek olan noktanın AK'si kapsamaya dahil edilirken, düşük olan noktanın AK'si tekrarlanan plakalar sebebiyle kapsamaya dahil edilmemiştir. Buna rağmen, yakın komşu noktaların beraber kullanılmasından kaynaklanan AK kaybı, yine bu noktalardan elde edilen yüksek YK ile telafi edilmiş ve merkezileştirilmiş durumdan daha yüksek bir ağ kapsaması sunmuştur.

Her p için yapılan 62 vakanın ortalama sonuçları paylaşılmıştır. Buna göre her p değeri için merkezileştirilmiş durum daha yüksek ağ kapsaması sağlamıştır. Burada dikkate çarpan bir sonuç ise p değeri 0,1'den 0,9'a doğru artarken, merkezileştirilmiş ve dağıtılmış durumun sağladığı ağ kapsamaları arasındaki farkın artmasıdır. P değeri

0,1 iken merkezileştirilmiş durum ortalama olarak %2,6 daha iyi ağ kapsaması sağlarken, p değeri 0,9 olduğunda bu değer %9,9'a çıkmaktadır. Bunun altında yatan neden; p değeri yükseldikçe AK'ye verilen ağırlık artmakta ve dağıtılmış durumda yakın komşu noktaların kullanılması sebebiyle AK kaybı yaşanmasıdır.

Güncel Durum Senaryoları

Bu kısımda Ankara ve Kırıkkale illerinde halihazırda kurulu olan OPTS'lerin analizi yapılmıştır. Her iki şehirde de üçer OPTS noktası faal olarak kullanılmaktadır. Bu noktalar, dağıtılmış ve merkezileştirilmiş durumların aynı adetler için önerdiği çözümlerle karşılaştırılmıştır. Güncel durumda özellikle göze çarpan durum, Kırıkkale ilinde il içi yakın komşu noktaların tesis edilmiş olmasıdır. Çözümler karşılaştırıldığında ortaya çıkan önemli çıkarımlardan biri de Ankara ve Kırıkkale için doğru adet atamasının yapılmamış olmasıdır. Merkezileştirilmiş durum çözümünde toplam 6 sistemin 5 tanesinin Ankara iline kurulması önerilmiştir. Ancak güncel durumda şehirler 6 sistemi eşit paylaşmışlardır.

Güncel durum, dağıtılmış ve merkezileştirilmiş durumlar bir arada değerlendirilerek önemli bulgular elde edilmiştir. Örneğin p değeri 0,7 için güncel durum ağ kapsaması %39,5 iken dağıtılmış durumun önerdiği çözümün ağ kapsaması %42,1 ve merkezileştirilmiş durumun önerdiği çözümün ağ kapsaması %50,5 olarak gözlenmiştir. Benzer şekilde p değeri 0,9 için, güncel durum %40,7, dağıtılmış durum %44,6 ve merkezileştirilmiş durum %54,9 ağ kapsama değerleri sağlamıştır.

Çözümleri genel olarak özetlersek, dağıtılmış durumun, güncel durumdan daha iyi sonuç vermesinin sebebi il içinde optimal OPTS yerleşimini yapabilmesi ve il içi yakın komşuların beraber kullanımını engellemesi olarak özetlenebilir. Merkezileştirilmiş durumun, dağıtılmış duruma göre daha iyi sonuç vermesinin sebebi ise iller arası OPTS adet atamasını optimal olarak yapması ve şehir içi yanında şehirlerarası yakın komşu noktaları da çözümde değerlendirmesidir.

Güncel durum senaryolarının ikinci aşamasında, güncel durum ağ kapsamasını geliştirmek için analizler yapılmıştır. Faal OPTS yerleri hesaba katılarak istenilen ağ kapsama seviyelerini sağlayacak en az sayıda ilave OPTS adedini bulabilmek için model MinInstall sunulmuştur. Model MinInstall farklı p değerleri ve istenilen ağ seviyerleri (c) için merkezileştirilmiş duruma göre çözülmüş ve çözümler matris olarak verilmiştir.

Örneğin, p=0,7 için, güncel durumun ağ kapsaması 6 OPTS ile %39,5 iken bu kapsamayı %60'a çıkarmak için ilaveten en az 4 OPTS noktası daha kulurması gerekmektedir. Bu noktada, faal noktaların bulunduğu ağ kapsamasını geliştirme ile, OPTS kurulu olmayan aynı ağda, istenen ağ kapsaması seviyesine ulaşmak için gereken toplam OPTS adetleri karşılaştırılmıştır. Toplam %60 ağ kapsaması sağlanması için güncel durumda faal OPTS'lerle beraber toplam 10 sisteme gerek duyulurken, faal sistem olmayan bir Ankara-Kırıkkale ağında aynı ağ kapsamasına ulaşmak için 8 OPTS yeterli olacaktı. Farklı p değerleri için yapılan analizde, p değeri arttıkça güncel durumun ağ kapsamasını geliştirmek için ihtiyaç duyulacak toplam OPTS sayısı ile boş ağ üzerinde aynı kapsamaya ulaşmak için gereken OPTS sayısı arasındaki fark artmaktadır. OPTS'lerin yer değiştirilmesinin güçlükleri düşünüldüğünde, ilk kurulumlar yapılırken merkezileştirilmiş duruma göre planlama yapılmasının avantajlı olduğu vurgulanmıştır.

KAPANIŞ

Bir ATS uygulaması olarak OPTS, trafiği analiz etmek, izlemek ve kontrol etmek için gerekli trafik bilgisini sağlamaktadır. Çalışmamızda, kamu güvenliği alanında kullanılan OPTS için değerlendirmeler ve analizler yapılmıştır. OPTS'nin tarihi ve kullanım alanlarına dair bilgiler ve Türkiye'de Jandarma birimlerinin trafik asayiş uygulamalarında kullandığı OPTS tanıtılmıştır.

OPTS yer seçimi probleminin ağ kapsamasını eniyileyecek şekilde çözülmesi için matematiksel modeller sunulmuştur. Türkiye'de, Ankara ve Kırıkkale illeri için tasarlanan deneyler dağıtılmış ve merkezileştirilmiş karar verme durumları altında incelenerek karşılaştırılmıştır. Güncel durum analizlerinde, faal olarak kullanılan OPTS sistemlerinin sağladığı ağ kapsaması ile, önerilen çözümler arasındaki karşılaştırmalar sonuçları verilmiştir. Merkezileştirilmiş çözümün, dağıtılmış çözüm ve güncel duruma göre daha yüksek ağ kapsaması sağladığı görülmüştür.

Çalışmamız, OPTS yer seçimi için bir metodolojik bir yaklaşım sunmakla beraber, ileriki çalışmalarda değerlendirilmesi gereken bazı kısıtlamaları bulunmaktadır. Çalışmamızda araç ve yol kapsamasını hesaplamak için kullanılan günlük ortalama araç sayıları ve yol ağı sabit kabul edilmiştir. OPTS yer seçimi için karar vericilerin yol ağı tasarımı üzerinde yetkisi olmasa da, sürücülerin davranış ve tercihleri uzun vadeli günlük araç ortalamaları alınarak tahmin edilebilir. OPTS yer seçimi yapılırken, gelecek tahminleri üzerinden parametrelerin belirlenmesi değerlendirilebilir.

Çalışmamızda tanıtılan OPTS sabit bir noktada kurulu olan ve kurulumu ve taşınması oldukça maliyetli olan bir sistemdir. Teknik kısıtlamalar da değerlendirildiğinde, daha düşük hacimli ara yolların veya anlık yoğunluk yaşanan bölgeleri izleyebilmek için Mobil Plaka Tanıma Sistemleri (MPTS) kullanılmaktadır. Araçlar üzerine kurulumu yapılabilen ve istenildiği zaman istediği yerde uygulamaya olanak veren MPTS sabit OPTS ile aynı şekilde çalışmaktadır. Ancak, MPTS sadece tek bir yönü izleyebilmesi, ve kablosuz veri transfer teknolojisi kullanması sebebiyle yaşanabilen güvenilirlik sorunu açılarından farklılık arz etmektedir. Ayrıca yer değiştirmeye olanak veren MPTS'nin yer belirleme problemi daha dinamik bir çözüm gerektirmektedir. MPTS bu farklılıklar sebebiyle çalışmamıza dahil edilmemiştir. Gelecek çalışmalarda, bu güvenilirlik ve mobilite boyutları da çalışmaya dahil edilerek, MPTS ve OPTS'ler den oluşan bir ağ için çözümler geliştirilebilir.

Çalışmamızda detaylandırıldığı üzere OPTS kurulumları için teknik ve idari boyutlardan ötürü kısıtlı sayıda muhtemel veri toplama noktası bulunmaktadır. Bunun arttırılabilmesi için farklı veri toplama noktaları de gelecekteki çalışmalara dahil edilebilir. Yollar üzerindeki benzin istasyonları, dinlenme tesisleri gibi tesisler plaka tanıma sistemi için ilave veri toplama noktaları olarak kullanılabilir. Ancak, bu noktaların yol üzerinde yalnızca kendilerine uğrayan araçları tespit edebilecekleri göz önünde bulundurulmalı ve sağlayacakları ağ kapsamaları buna göre değerlendirilmelidir.

I. Tez Fotokopisi İzin Formu

ENSTİTÜ

Fen Bilimleri Enstitüsü ☐

Sosyal Bilimler Enstitüsü ☒

Uygulamalı Matematik Enstitüsü ☐

Enformatik Enstitüsü ☐

Deniz Bilimleri Enstitüsü ☐

YAZARIN

Soyadı : GÖR
Adı : BUĞRA
Bölümü : Business Administration

TEZİN ADI (İngilizce) : Automatic License Plate Recognition System Location Selection

TEZİN TÜRÜ : Yüksek Lisans ☒ Doktora ☐

1. Tezimin tamamından kaynak gösterilmek şartıyla fotokopi alınabilir. ☐
2. Tezimin içindekiler sayfası, özet, indeks sayfalarından ve/veya bir bölümünden kaynak gösterilmek şartıyla fotokopi alınabilir. ☐
3. Tezimden bir bir (1) yıl süreyle fotokopi alınamaz. ☒

TEZİN KÜTÜPHANEYE TESLİM TARİHİ: