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# Introducing the RZ model for definition and optimization of the boundary of low emission zones

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## Abstract

Poor urban air quality is one of the most pressing environmental problems, and the rapid growth in the number of motor vehicles is a major contributor to it. To tackle this problem, low emission zones (LEZs) were introduced and they have been applied in many of the mega cities around the world. Yet, a scientific approach to design the boundaries of LEZs is missing. This study develops an innovative model to address this gap, using total vehicle kilometers traveled (VKT) as the basis. The model allows defining and/or optimizing the LEZ boundaries. It is applied for the Tehran metropolitan area, as a case study, and the results show the optimality of the existing LEZ boundaries; however, they challenge the efficiency of the proposed policies on modifying current boundaries.

*Keywords:* radial zone (RZ) model; low emission zone (LEZ); coverage optimality; transportation management; OD matrix

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## 1 INTRODUCTION

Elsom, in 1996, warned that the world, particularly mega cities, will be 'choking on pollution from traffic and industry'. He considered poor urban air quality as one of the most pressing environmental problems of our times because of the rapid growth in the number of motor vehicles, among some other reasons. The case is no different between Los Angeles, London, Mexico City and other world's mega cities. To improve the air quality in critical parts of a city, policies and measures are already in place to reduce the number, the frequency of use and the distances traveled by vehicles [1]. It was indeed in that year that the first well-known low emission zones (LEZs) were introduced in a number of cities in Sweden. LEZs are areas where access by certain types of vehicles is restricted within a specific boundary, typically in the city center [2].

As predicted by Elsom, currently, one of the main challenges in mega cities is that throughout the year, for a number of days, weeks or months, the air pollutants' concentration exceeds the standard thresholds. Litman suggests that there exist two general categories of approaches to deal with this problem. The first category is introduced as 'Cleaner Vehicle' strategies while the second category is defined as 'Mobility Management' strategies [3]. The focus of the first category lies within how a vehicle would produce less pollutant while the second category discusses the potential of reducing vehicles' movements. Nowadays, LEZs, as one of the approaches in the second category, are used in many mega cities around the world in order to reduce air pollution.

To design and then implement a new LEZ in a city's network, two primary questions have to be answered. The first question is concerned about the location of LEZ boundaries which primarily asks, 'Where should be the boundaries of the new LEZ?' The second question is related to the fleet and asks, 'What type of vehicles should be affected by the new LEZ?' Several researchers, over the years, have widely studied the effects of LEZ from different perspectives by considering the situation prior to and after the implementation of each particular LEZ [2, 4, 5, 6, 7, 8, 9, 10, 11, 12]. Those research studies have assessed the efficiency of the LEZ based on the fleet and its consequences on air pollutants. The results demonstrated satisfactory reductions of air pollution in some places and less efficient results in other places. What is missing in the literature is a scientific approach on the design of the 'boundaries' of LEZs. More specifically, the research lacks an approach that challenges existing LEZs or proposes new boundaries for an optimum outcome. The aim of this study is to introduce an innovative approach that allows design of optimum LEZ boundaries.

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The general approach in defining the LEZ boundary starts by evaluating the air quality index (AQI) or a similar air pollution representative in various stations within the area of concern such as the condensed areas of a mega city [13, 14, 15, 16]. The candidate areas for applying restrictions on vehicles are the ones where pollution measures exceed (or are expected to exceed in the near future) a certain threshold. Once the areas with critical measures are identified, a few number of potential LEZ boundaries are considered and they are evaluated in short and long runs. Using the output of that evaluation, the boundaries of the LEZ are set so that it is most beneficial (compared to any other suggested boundary in terms of improving air quality of the concerned area) and affects the least from other perspectives such as public compliance. This LEZ will then be implemented.

The 'European City Pass for Low Emission Zones' suggests following in defining LEZ boundaries: 'It is strongly recommended to base determination of LEZ boundaries on urban mobility plans and use traffic modeling tools for LEZ impact analyses. Developers of LEZ must be familiar with specific area traffic network, request-demand matrices and should have the clear vision about future traffic trends with and without LEZ' [17]. There are a number of feasibility studies considering this statement. For instance, the feasibility study for Bradford LEZ assesses the baseline road transport emissions and emissions resulting from LEZ interventions by developing a local fleet emission profile using automatic number plate recognition (ANPR) cameras. The target zones in this study are categorized into the Inner Ring Road and Outer Ring Road and across the Bradford Urban District, but there is no preliminary evaluation for such categorization [13]. A similar approach also exists for Leeds [18] and Newcastle [14]. In Sheffield, a detailed traffic model in Aimsun was updated using data from the SRTM3 transport model to assess appropriate tools for modeling transport emissions. It then was used indirectly in the LEZ strategy development [15]. In the city of York, a traffic microsimulation model (Paramics) that was linked with a detailed emission model (PHEM) was used to allow emissions from individual vehicles on the network to be modeled [19]. The latter LEZ description and its feasibility study targeted buses. The model could take account of factors such as the age of the vehicles, the number of stops made along the route and the level of congestion encountered along a typical journey. Different to pre-mentioned LEZs which are applied in an area, the York LEZ plan is applied along 2 km of a particular street in the city center through which all current scheduled bus services pass. Yet, no preliminary scientific study was carried out to define the coverage area as a street. The feasibility study of the Oxford zero emission zone employs the COPERT 5 model to translate traveled distances by vehicles into air pollution; nevertheless, the approach in defining the boundaries is based on the pollutants' concentrations calculated for candidate streets adjacent to the city center. These candidate sites are chosen based on the existing concentrations of pollutants [20].

LEZ in London, as one of the largest LEZs in the world, also suffers from a modeling approach to define the boundaries. The feasibility study carried out for London LEZ considers six different zones to be introduced as the target zones. The decision on defining the appropriate area for London LEZ has been driven from air quality modeling for an early stage to reach the desired effectiveness. The study discusses various options including the vehicles affected by the plan and emission criteria to assess the outputs. Issues such as the complexity of including a large number of additional local authorities have come into play, and finally, the study recommends that the most appropriate option for a London LEZ would be a scheme including all of the Greater London area [16, 21]. There also exist other feasibility studies in other countries of which only a few report summaries are provided in English. However, the approaches seem to be similar as the ones explained for UK cases [22].

Although the literature is rich on evaluating the implemented LEZs and their impact on air quality, there is little evaluation on how the boundaries of LEZs stand and how they may affect the results of applying the LEZ. Typically, and as mentioned here, feasibility studies propose an approach on defining the boundaries of LEZs based on air pollutants' concentrations. Such studies offer to apply LEZ plans in polluted areas where, after applying LEZ, the pollutants' concentrations show a reduction to acceptable thresholds using a trial and error approach. Initially, a committee of city administrators, transport and air pollution specialists is formed. This committee is provided with the information regarding air pollutants' concentrations in the city, vehicular traffic data and existing and predicted challenges in the city. The committee discusses the situation and decides whether to evaluate the results of applying a LEZ. If agreed on, a number of potential areas where the plan is believed to be influential are suggested and discussed. Among the suggested areas, the most promising ones are selected for further evaluation by transport and air pollution specialists. These specialists use simulation software trying to predict the consequences of applying the LEZ restrictions on vehicles' movement and thus air pollution. The results are again discussed in the committee, and the process may be repeated several times trying to reach the best outcome. Such approach on defining LEZ boundaries has two major flaws. First, since the initial step has to be carried out by city administrators, transport and air pollution specialists, a human-based factor in defining the area is included in the process, which is subjected to error. Second, the process of evaluating the results of applying restriction policies is not a straightforward approach and based on the available data and network simulation properties may take weeks to complete. Unfortunately, the research lacks a scientific approach for an optimized design of LEZ boundaries. The current study develops a new approach that, once implemented, increases the effectiveness of LEZs' spatial coverage to its utmost possible extent and reduces the complexity of applying LEZ plans in transportation networks.

## 2 METHODOLOGY

Considering a hypothetical transportation network, a new approach, called the radial zone (RZ) model, is introduced that enables an evaluation of existing and new boundaries of LEZs in that network. It is then discussed, and the general procedure to transfer it to a new network is presented using a flowchart. The RZ model is used in a case study to evaluate existing and proposed LEZ plans (in form of scenarios) which are introduced and discussed.

## 2.1 RZ model development

To simplify the description of the model, its principles are discussed using a hypothetical network with 12 districts (Fig. 1a). The model constitutes two underlying assumptions: the first assumption is that the origin–destination (OD) matrix (a matrix that displays the number of trips going from each origin in the study area to each destination) is available for this network for different trips of any purpose (commuters, educational, shopping, etc.). The second assumption is that an existing LEZ boundary is also applied in this network (Fig. 1b). The methodology is described in four stages as comes in following sections.

### 2.1.1 *Defining RZs*

The first step in developing the RZ model for our hypothetical network is to consider a point as the center of the network. This point could be a geometrical center or, more precisely, the center of trip attraction (in other words, the center of CBD) or (in the presented case) the center of the existing LEZ boundary. Once this hypothetical center is defined (Fig. 1c), the zoning process starts. The goal is to draw a number of lines from the center to the outer boundary of the network in a manner that the characteristics of the travelers in a surrounded area between each two adjacent lines only vary radially (some unavoidable minor errors may exist but are not critical). The characteristics may include trip generation rates, mode choice patterns, being in a LEZ or any other relevant and available data regarding trips made in the network.

Once the hypothetical center of the area is determined, a line may be drawn from the center to the outer boundary of the area as shown in Fig. 2a. The second line is drawn as shown in Fig. 2b. To explain why this position has been selected, note that if you move on the line from the center towards the outer boundary of the network, four distinct regions, here called RZs, could be defined (Fig. 3):

1. $A1$ is a region within the D8 district, and it is located within the LEZ boundaries.
2. $A2$ is a region in D7 and also in the LEZ area.
3. $A3$ is a region in D6 and also in the LEZ area.
4. $A4$ is an area in D6 which is outside the boundary of LEZ.

Repeating the procedure for the whole network creates $n$ RZs (Fig. 4). In doing so, minor errors may exist as shown in this figure, which could be usually eliminated (or minimized) by adding extra lines from the center. However, one has to decide between adding extra lines with the aim of extra precision and keeping the current division, hence reducing the upcoming mathematical formulation.

As it can be seen in Fig. 4, RZs have random shapes. In order to use them in the following calculations, they are converted to concentric circular sections. Considering the four RZs defined in Fig. 3, the procedure to convert RZs to concentric circular sections is defined as follows:

1. In the first stage, the central angle of all the sectors should be determined. By such definition, the sector in which our four RZs are located may be referred to as $\alpha_1$ here as it is shown in Fig. 3.
2. The first RZ's radius, representing the area $A1$ in Fig. 3, is calculated using Equation (1):

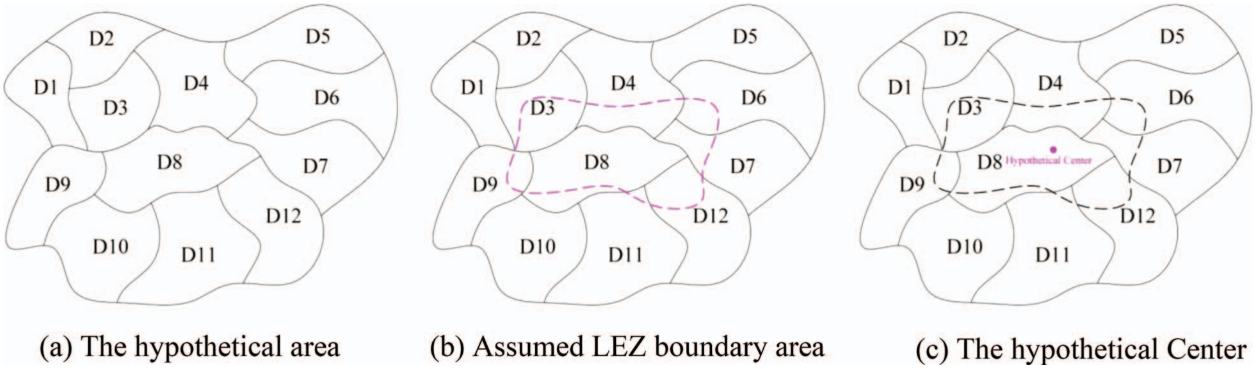
$$R_1 = \sqrt{\frac{A_1 \times 360}{\pi \times \alpha_1}} \tag{1}$$

where

$R_1$ is the radius of the first concentric circular section representing the zone with the area of $A_1$ shown in Fig. 3. (Note that $\alpha_1$ is in degrees)

For all the first RZs adjacent to the hypothetic center, the following general equation could be used:

$$R_1^j = \sqrt{\frac{A_1^j \times 360}{\pi \times \alpha_j}} \tag{2}$$



(a) The hypothetical area (b) Assumed LEZ boundary area (c) The hypothetical Center

**Figure 1.** *The hypothetical considered area (a), considered LEZ boundary (b) and the hypothetical center (c).*

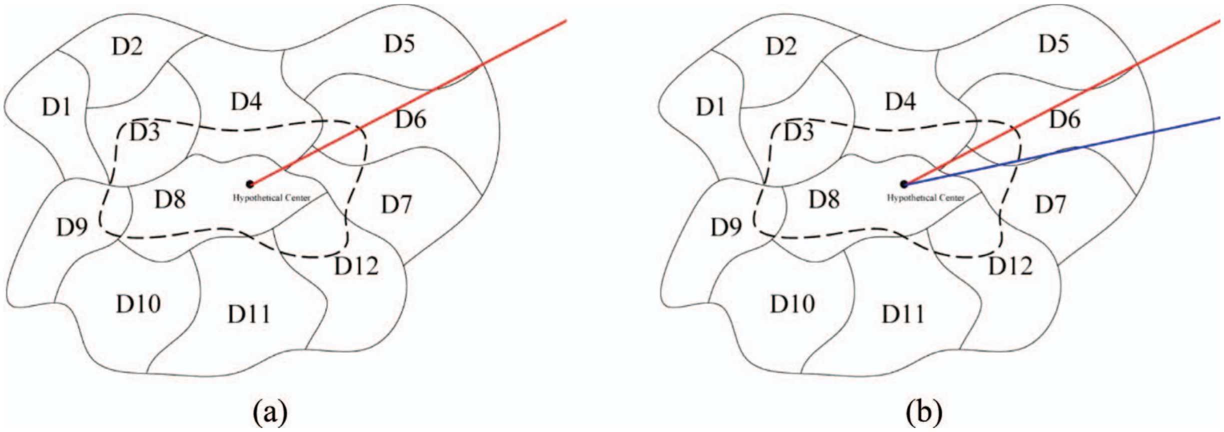


**Figure 2.** *Drawing the first line (a) and the second line (b) in the hypothetical network.*

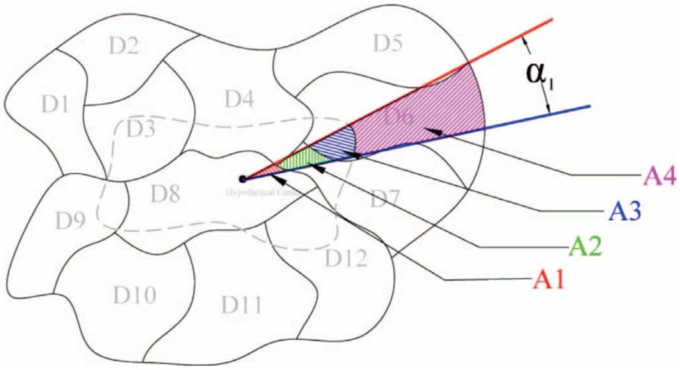


**Figure 3.** *Four RZs bounded by the two drawn lines in the hypothetical network.*

where

$j$: number of sectors defined in the area

$R_1^j$: radius of the first RZ in the $j$th sector (among which $\alpha_1$ represents the first sector's angle)

$A_1^j$: first bounded area in the $j$th sector for which the radius is being calculated

$\alpha_j$: central angle of the $j$th sector in degrees

3. For all the other RZs in Fig. 4, Equation (3) could be used:

$$R_m^j = \sqrt{\frac{A_m^j \times 360}{\pi \times \alpha_j} + \left(R_{m-1}^j\right)^2} \tag{3}$$

where

$R_m^j$: radius of the $m$th RZ in the $j$th sector

$A_m^j$: $m$th area bounded in the $j$th sector

$R_{m-1}^j$: radius of the $(m-1)$th RZ in the $j$th sector

Other terms are defined previously.

Each of the RZs has a general shape either shown in Fig. 5a for the zones adjacent to the center or Fig. 5b for those away from the center. In this figure, arcs (inner or outer) in both shapes may represent the boundary of a municipal district, LEZ boundary or any other boundary representing a parameter which may affect trip patterns (trip generation, attraction, mode choice behavior, etc.). Using Equations (2) and (3), all the RZs' radii could be calculated for our hypothetical network as shown in Fig. 6. Note that in this figure, there are $n$ bijective (one-to-one) relations between the bounded areas on the left (distinguished by different hatch colors) and RZs on the right (which have the either shapes shown in Fig. 5).

### 2.1.2 *Calculating new OD trip matrix*

For all the RZs shown in Fig. 6, a new OD trip matrix could be defined. Assuming that the existing data is available based on the 12 districts in our hypothetical area, trip generation and attraction could be calculated in each RZ using the following equations:

$$P_r^R = \frac{S_r^R}{S_R} \times P_R \tag{4}$$

where

$P_r^R$: the total number of trips generated in the $r$th RZ in municipal district $R$

$S_r^R$: the area of the $r$th RZ in municipal district $R$

$S_R$: the area of municipal district $R$

$P_R$: the total trips generated in municipal district $R$

Similar equations are applicable for calculating the number of trip attractions, by substituting $P$ with $A$, which represents trip attraction:

$$A_r^R = \frac{S_r^R}{S_R} \times A_R \tag{5}$$

where

$A_r^R$: the total number of trips attracted in the $r$th RZ in municipal district $R$

$A_R$: the total trips attracted to municipal district $R$

Other terms are defined previously.

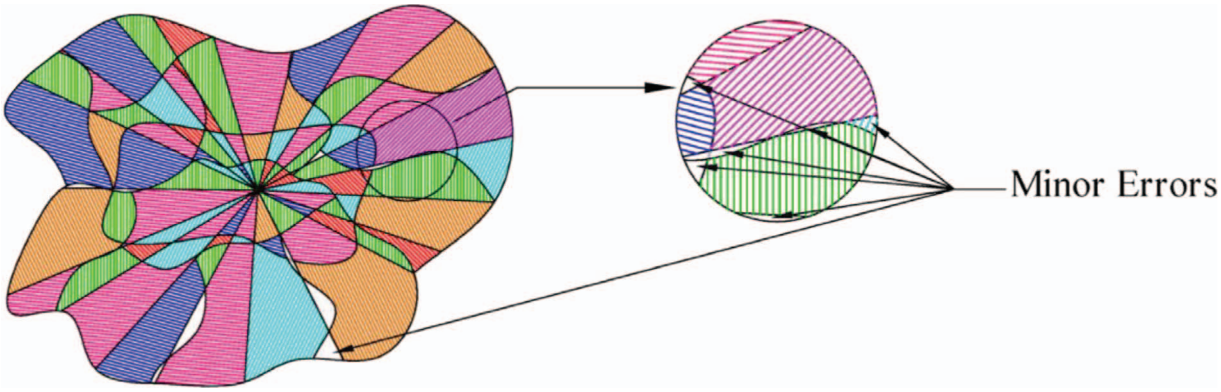


**Figure 4.** *Defining all RZs in the hypothetical network with a magnified area containing minor errors.*

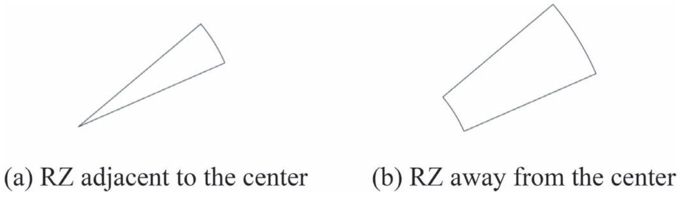

(a) RZ adjacent to the center (b) RZ away from the center

**Figure 5.** *General shapes of RZs.*

The following expressions are evident:

$$P_{\text{Hypothetical Area}} = \sum_{R=1}^{12} P_R$$

$$A_{\text{Hypothetical Area}} = \sum_{R=1}^{12} A_R$$

where

$P_{\text{Hypothetical Area}}$: the total number of trips generated in the area
$A_{\text{Hypothetical Area}}$: the total number of trips attracted to the area

The upper bound of summations, 12, represents the number of districts in our hypothetical area (Fig. 1).

After applying Equations (4) and (5), there are $n$ RZs, for which the number of trips generated in and attracted to is defined. Distributing the trips generated in each RZ among the other zones results in an $n \times n$ OD matrix in the hypothetical area. Equation (6) is used to calculate the OD matrix elements:

$$T_{ij} = P_r^R \times \frac{A_r^R}{A_{\text{Hypothetical Area}}} \quad \text{for} \quad i,j = \{1,2,3,\ldots,n\} \tag{6}$$

where

$T_{ij}$: the total number of trips from RZ $i$ to RZ $j$.

It should also be noted that the expression

$$\sum_{i=1}^{R} r_i = n \quad \text{for } R = 12$$

applies, in which $r_i$ is the number of RZs in municipal district $R$ and again the upper bound of summations, 12, represents the number of districts.

Once the number of trips between each two RZs is defined, by using the distance that travelers traverse between each two zones, the total passenger kilometers traveled (PKT) could be calculated. The next section describes the procedure for calculating distances between RZs defined in the radial zoning system.

### 2.1.3 *Calculating travel distances*

Generally, the distance between each two points in a transportation network is the distance traversed in street canyons; however, here, the aerial distance between the centers of two RZs is assumed as the average distance that all the travelers from RZ $i$ traverse to reach RZ $j$ as a simplified substitution. This distance would result in a matrix called *OD–Distance* matrix here.

In order to calculate *OD–Distance* matrix elements, by defining the centroid of each RZ, as shown in Fig. 7, Equation (7) can be used to calculate the latitude and longitude of each zone using Equations (8) and (9).

$$D_r^R = \frac{2 \times \sin\left(\frac{\alpha_j}{2}\right)}{3 \times \frac{\alpha_j}{2}} \times \frac{R_1^2 + R_2^2 + R_1 R_2}{R_1 + R_2} \tag{7}$$

$$X_r^R = D_r^R \times \cos\beta_j \tag{8}$$

$$Y_r^R = D_r^R \times \sin\beta_j \tag{9}$$

All terms in Equations (7–9) are shown in Fig. 7 (Note that $\alpha_j$ is in radians in Equation (7)). Knowing the coordinates of the centroid of two RZs allows the distance between centroids to be readily calculated as

$$\begin{aligned} D_{ij} &= \sqrt{\left(\left(X_r^R\right)_i - \left(X_r^R\right)_j\right)^2 + \left(\left(Y_r^R\right)_i - \left(Y_r^R\right)_j\right)^2} \quad \text{for} \\ i,j &= \{1,2,3,\ldots,n\} \end{aligned} \tag{10}$$

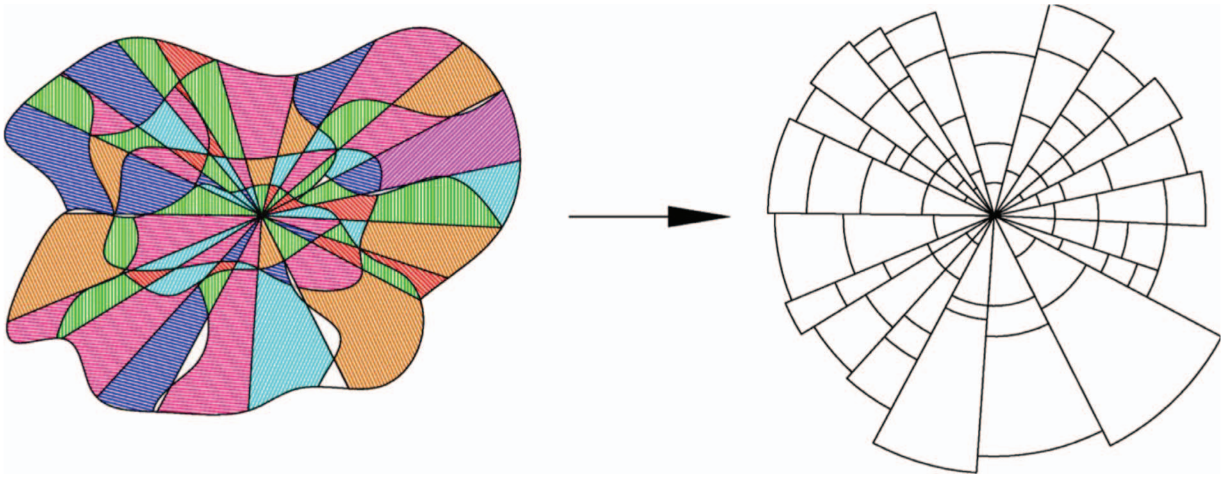


**Figure 6.** *The initial RZs in the hypothetical network (left) and the concentric circular sections representing the same network (right).*

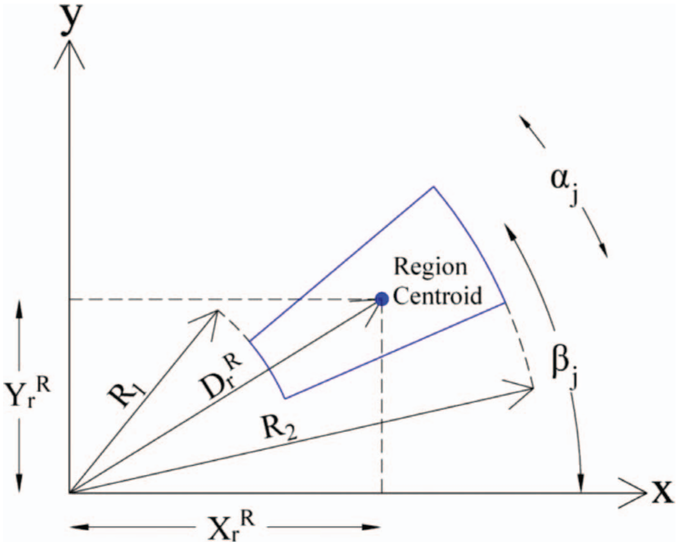


**Figure 7.** *Calculation of RZ's centroid coordinates in the RZ model.*

in which $D_{ij}$ is the distance between RZ $i$ and RZ $j$ and represents the elements of the *OD–Distance* matrix. Now that the distances are defined, total PKT could be calculated for the hypothetical area considered in Fig. 1 using the following equation:

$$\mathrm{PKT}_{ij} = T_{ij} \times D_{ij} \tag{11}$$

where

$\mathrm{PKT}_{ij}$: total passenger kilometers traveled between RZ $i$ and RZ $j$

$T_{ij}$: the total number of trips from RZ $i$ to RZ $j$ as calculated in Equation (6)

$D_{ij}$: the distance between RZ $i$ and RZ $j$ as calculated in Equation (10)

It is believed that the most affecting parameter in a transportation network which leads to traffic congestion and air pollution is that portion of PKT by personal vehicles, known as vehicle kilometers traveled (VKT). The value of VKT and its fluctuations is a promising representative of how a transport policy has been successful in terms of reducing congestion and air pollution. Thus, in the next phase, converting the PKT value to VKT is discussed.

### 2.1.4 *Calculating total VKT*

In order to calculate VKT, the portion of the trips made by personal vehicles should be defined. Typically, mode choice probabilities (the probability of how a traveler chooses a mode of transport which may include personal vehicle, bus, taxi, metro, etc.) are defined by carrying out a comprehensive transport study in the considered area in which, as an outcome, mode choice equations and vehicular shares are formulated. These equations are generally based on the characteristics of the travelers and may include average income, household properties, vehicle ownership and access to public transit or any other relevant parameters which have the potential of affecting a mode choice significantly. The comprehensive transport study divides a study area to regions in which it is believed that the characteristics of all the residents within each region could be assumed to be similar. As a result, it is believed that the travelers within each region choose a mode of transport, say personal vehicle for example and of concern here, with the same probability. Remembering that the definition of the initial RZs was based on parameters that could affect trip patterns, among which mode choice patterns are a major concept, RZs would actually behave like regions considered in the comprehensive transport study. It is expected that all residents within each of the RZs choose a mode of transport and, of interest here, personal vehicles, with the same probability. $\mathrm{PVshare}_{ij}$ is used to show the probability of using a personal vehicle (PV) by a set of travelers in their trips made from zone $i$ to zone $j$. Thus, the total VKT from RZ $i$ to RZ $j$, denoted by $\mathrm{VKT}_{ij}$, shall be calculated as

$$\mathrm{VKT}_{ij} = T_{ij} \times D_{ij} \times \mathrm{PVshare}_{ij} \tag{12}$$

All terms are defined previously. Based on Equation (12), the total VKT in our hypothetical area shown in Fig. 1 is calculated as

$$\mathrm{VKT}_{\text{Hypothetical Area}} = \sum_{i}\sum_{j}\mathrm{VKT}_{ij} \quad \text{for} \quad i,j=\{1,2,3,\ldots,n\} \tag{13}$$

where $\mathrm{VKT}_{\text{Hypothetical Area}}$ is the total vehicle kilometers traveled in our hypothetical area by travelers.

## 2.2 RZ model discussion

The procedure described till here is capable of calculating total VKT in a transportation network using existing data and also an existing LEZ as shown in Fig. 1. A question may rise here asking, 'What if a new LEZ is to be defined?' In order to answer this question, consider the hypothetical RZ shown in Fig. 7. If a new LEZ boundary is to be defined, its radius in each sector may either be less than $R_1$, between $R_1$ and $R_2$ or greater than $R_2$. Considering the first situation, nothing is affected and the RZ behaves as before. If the new LEZ boundary is greater than $R_2$, the mode choice behavior for all the trips generated in and attracted to the RZ is changed and it may easily be integrated in calculations. If the radius of the new LEZ lies between $R_1$ and $R_2$, the considered RZ is divided into two separated new RZs in each; mode choice equations differ since they are subjected to different limitations. Nevertheless, the whole procedure described here is still valid and the only thing that changes is the number of RZs. Thus, total VKT could also be defined for the new situation. Having this in mind, one may consider the radius of a new LEZ boundary in each sector of the area (shown in Fig. 6) as an unknown variable, calculate VKT and solve an optimization problem for unknown variables to

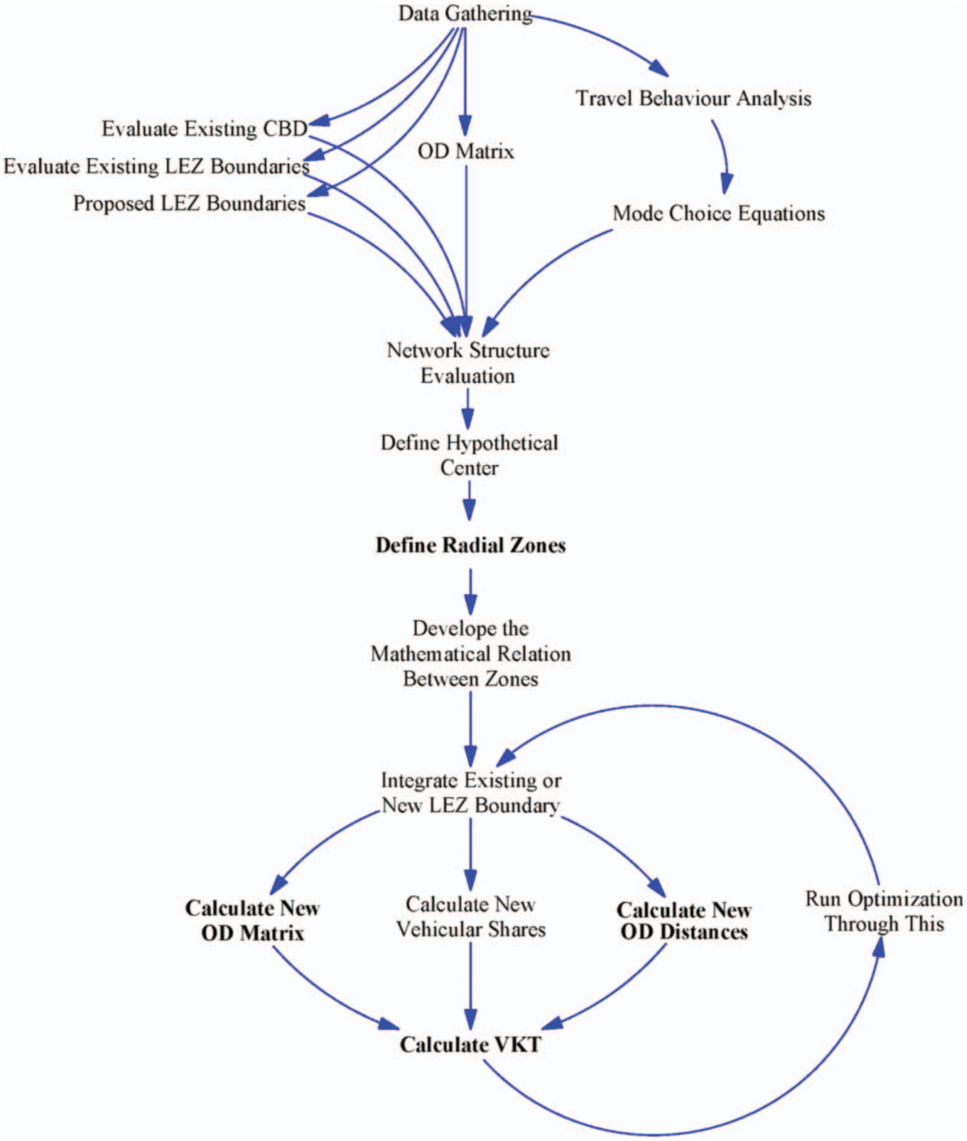


**Figure 8.** *The flowchart for transferring the RZ model to a new network.*

get the most possible effect by having the least possible VKT in the area. The resulting variables (which represent a LEZ boundary) just need to be translated to the most appropriate street Canyons where LEZ should be applied. An example of this process would be discussed later in a case study.

To sum up, the general procedure for the RZ model is illustrated in Fig. 8. As presented in Fig. 8, required data in order to develop the RZ model which include the OD matrix, travel mode choice equations, data regarding CBD and existing LEZ if available should be gathered first. In the next phase, the network structure is evaluated to see where the hypothetical center of the area would be. After defining the hypothetical center, a combination of different concentric circular sections are defined and named 'Radial Zones'. These RZs are defined based on the properties of the area they cover, trying to have the surrounded travelers in each RZ behaving similarly in terms of traveling within the network. Existing or new LEZ boundaries (to be evaluated) are also integrated in defining RZs. OD trips and distances among mode choice probabilities are calculated, and then total VKT is calculated. At this stage, one may consider changing the values for a new LEZ boundary or any other relevant parameters which may affect VKT to evaluate the results. The procedure may be repeated as long as the desired outcome is reached; hence, an optimization problem could be defined to find the most influential parameter in calculating total VKT.

In the next section, the Tehran metropolitan area (TMA) is introduced as a case study. The RZ model is developed for this metropolitan area, and the results of applying a number of proposed scenarios in the area are evaluated using the RZ model. Besides, the model is used to develop new LEZ boundaries for this metropolitan area.

## 2.3 Introducing the case study

Tehran, the capital of Iran, was selected as the case study since it is one of the largest metropolitan areas around the world and it deals with the problem of traffic congestion and air pollution. Tehran initially used restriction plans to deal with the problems of traffic congestion in 1987. The plan has been updated 19 times in terms of affected fleet, time schedule and of the most interest here, the LEZ boundaries, while also taking into account the environmental consequences. The current plans are generally applied in the older part of the city: the CBD which attracts a great number of daily trips. Despite the numerous changes, the problem of air pollution and traffic congestion still exists.

Currently, two major LEZ plans are in use in TMA to reduce the congestion and improve the air quality: the Restricted Area Policy (RAP) and the Odd–Even day Traffic Restriction Policy (OETRP). RAP restricts traffic in the central part of the city as follows: no vehicle is allowed to enter the restricted area except for taxis and public buses. A limited number of daily permits are sold at high prices for those who insist on using personal vehicles within this area. Residents of the area can purchase annual permits at lower prices. The OETRP is based on the vehicle license plate number (odd or even) and the area encompassed by this plan

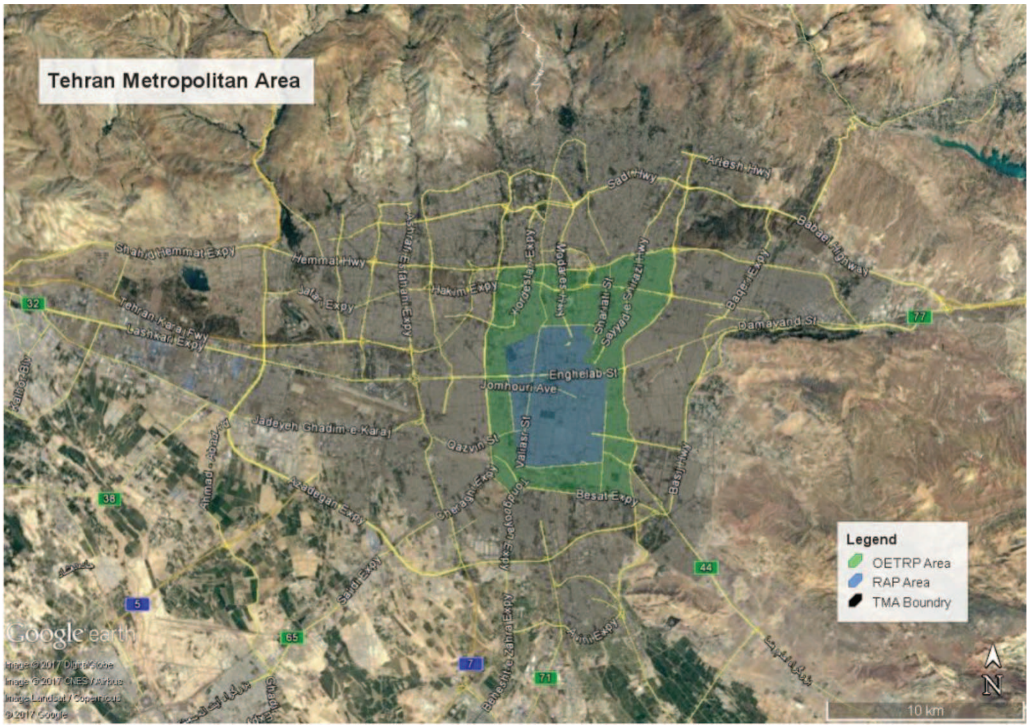


**Figure 9.** *Tehran metropolitan area.*

surrounds, but it is much larger than the area for RAP. Those who purchase daily RAP permits are allowed to enter the OETRP area regardless of plate number. TMA regulations restrict the sale of daily and annual permits to recent model vehicles. Fig. 9 shows a view of the TMA with the OETRP and RAP areas. The Origin–Destination (OD) matrix available in the metropolitan area is a 22 × 22 matrix in its largest form, based on the 22 municipal districts which are shown in Fig. 10. Besides, mode choice equations are also calculable separately for the 22 districts based on their residents' characteristics. Choosing a mode of transport is strongly influenced if the origin or destination of a trip is located within a LEZ boundary.

Due to unequal distribution and overlap of the municipal districts (where mode choice equations are available) and RAP and OETRP areas, introducing new LEZ boundaries or extending existing ones becomes very complicated. The RZ model can overcome this complication. In the following sections, the procedure to apply the RZ model in TMA is presented.

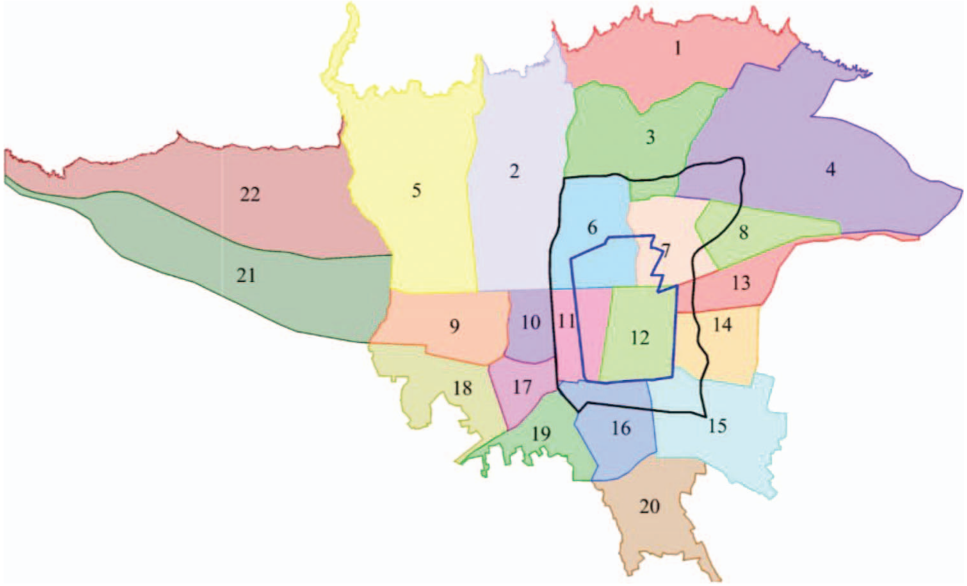


**Figure 10.** *TMA comprising 22 municipal districts along with RAP (blue) and OETRP (black) boundaries (LEZ boundaries).*

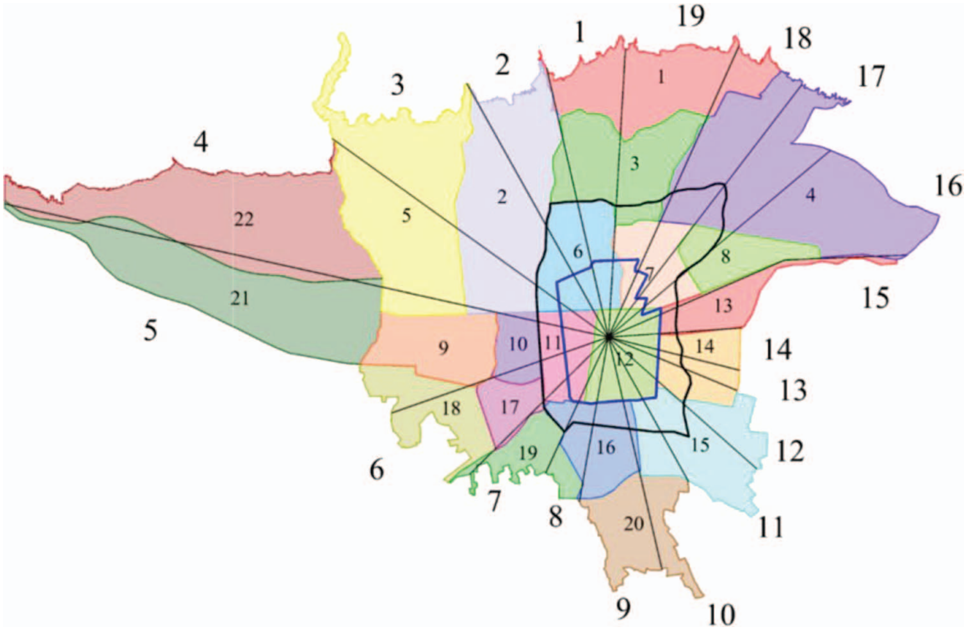


**Figure 11.** *Proposed radial zoning system for TMA.*

### 2.3.1 *Developing RZs in TMA*

Considering the TMA structure, RAP and OETRP area boundaries and municipal districts in TMA, initial lines to form concentric sections were drawn (as in Fig. 11) and RZs were determined for TMA as shown in Fig. 12. In the new zoning system in this figure, there exist 19 sectors and there are 74 RZs, denoted as *RxxPyy*, where *xx* denotes the larger municipal district number in which the RZ is located and *yy* denotes a sequential number starting from 01 for all RZs located in district *xx*.

### 2.3.2 *Personal vehicle share*

In order to determine the personal vehicle share, the study is narrowed to commuter daily trips, which form the highest share in vehicular traffic in TMA. Here, the last updated version of transport studies among metropolitan commuters was used. The latter study, based on data derived from 21761 residents, suggests a nested logit model in order to calculate the mode choice probabilities of travelers. The first level of the model consist of personal vehicles and public transit, while the second level for the public transit covers bus and taxi as shown in Fig. 13 [23].

According to Fig. 13, it is suggested [23] that the following utility function be used for each mode denoting $U^{ij}_{\text{mode}}$ as the utility function for traveling from region $i$ to region $j$ using *mode* as

$$U^{ij}_{\text{PV}} = 7.6503 \times \left(co - \text{pop}\right) - 0.6011 \times \text{Ln}\left(c - \text{car}\right) - 1.006\left(J - \text{CBD}\right) \qquad (14)$$

where

$co - \text{pop}$: average vehicle ownership
$c - \text{car}$: personal vehicle cost usage

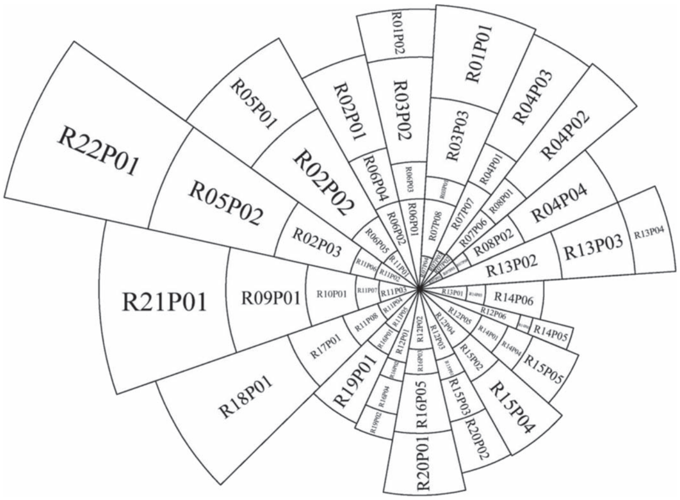


**Figure 12.** *RZs in TMA.*

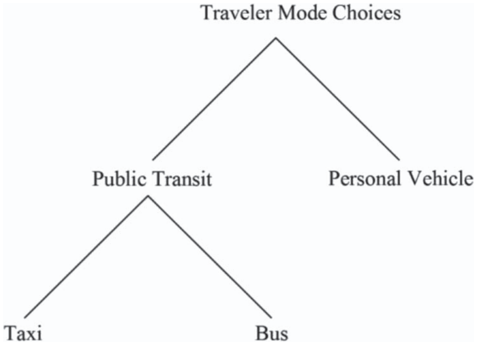


**Figure 13.** *The nested logit model configuration developed for commuter trips [23].*

$J - \text{CBD}$: destination location with regard to restricted areas and

$$\begin{cases} 0; \text{if the trip is made toward theTMA area} \\ 0.5; \text{if the trip is made toward the OETRP area} \\ 1; \text{Ii the trip is made toward the RAP area} \end{cases}$$

The utility function of the public transit users would be calculated as

$$U^{ij}_{\text{Public Transit}} = 0.8072 \times \text{Ln}\left[\exp\left(U^{ij}_{\text{Bus}}\right) + \exp\left(U^{ij}_{\text{Taxi}}\right)\right] \qquad (15)$$

The utility functions for taxi and bus are calculated as

$$U^{ij}_{\text{Taxi}} = 5.1185 \times \left(co - \text{pop}\right) - 0.6206 \times \text{Ln}\left(c - \text{Taxi}\right) - 0.7173\left(J - \text{CBD}\right) \qquad (16)$$

$$U^{ij}_{\text{Bus}} = -2.1854 - 0.0183 \times \left(\text{Bus} - \text{in} + \text{Bus} - \text{out}\right) + 0.0455 \times \frac{\text{Dist}-z}{\text{Bus}-n} \qquad (17)$$

where

$c - \text{Taxi}$: cost of using taxi
$\text{Bus} - \text{in}$ and $\text{Bus} - \text{out}$: travel time in the bus and travel time outside the bus, respectively
$\text{Dist} - z$: distance between the origin and destination
$\text{Bus} - n$: number of ride changes through a trip made by bus

Using Equations (14–17), the probability of using a personal vehicle could be defined using Equation (18):

$$\text{PVshare}_{ij} = \frac{\exp\left(U^{ij}_{\text{PV}}\right)}{\exp\left(U^{ij}_{\text{PV}}\right) + \exp\left(U^{ij}_{\text{Public Transit}}\right)} \qquad (18)$$

It should be noted that in calculating mode choices, the average values for each district have been used where available.

### 2.3.3 *LEZ boundary movement in TMA*

As mentioned before, moving the boundaries of LEZ areas in the TMA has always been a challenging task. The suggested zoning system helps to overcome this challenge and, subsequently, assesses the results of applying the policy more clearly. As mentioned before, being the trip origin or destination in a region in TMA where a LEZ plan applies influences mode choice options strongly. By assuming that the focus in this study is on moving existing LEZ boundaries, Table 1 lists different trip types based on existing LEZ boundaries in TMA. In this table, 'R', 'O' and 'T' letters denote being in the RAP OETRP or Outer-TMA (where no plan is applied), respectively. These areas are shown in Fig. 9. Based on the trip's origin or destination point, taking into account that each of these points would be located in one of these three areas, nine different trip types are introduced, as shown in Table 1. Thus, in each trip type, the first letter indicates where the origin of the trip is while the second letter represents the trip destination.

RAP and OETRP plans exert different restrictions on travelers while the Outer-TMA area is left with no restrictions. Thus, choosing the personal vehicle as the mode of transport by a traveler is strongly affected by how these plans affect the origin or destination of the traveler's trip. More specifically, the mode of transport is influenced enormously by the type of the trip presented in Table 1. If the target here is to move the existing LEZ boundaries (RAP and OETRP), the trip's origin or destination may differ, and thus the trip type differs; thus, choosing the mode of transport is re-considered by the traveler. For example, using the personal vehicle in an old *TT* trip may not be justifiable anymore if it becomes *TO* trip due to the changes in the OETRP boundaries. Generally, this may increase or decrease the total number of trips done by personal vehicles which directly affects total VKT. This has a direct relationship with air pollution and congestion. Having this in mind and aiming at moving the RAP and OETRP boundaries, the following assumptions are also made prior to LEZ boundaries' movement:

- The RAP area does not become smaller.
- The OETRP area may become smaller, but it always covers a larger area than the RAP area.
- Boundary movements in adjacent sectors are independent from each other.

**Table 1.** *Trip categories for the TMA.*

| Trip origin area | Trip destination area | Abbreviation* |
|---|---|---|
| RAP | RAP | RR trips |
| RAP | OETRP | RO trips |
| RAP | Outer TMA | RT trips |
| OETRP | RAP | OR trips |
| OETRP | OETRP | OO trips |
| OETRP | Outer TMA | OT trips |
| Outer TMA | RAP | TR trips |
| Outer TMA | OETRP | TO trips |
| Outer TMA | Outer TMA | TT trips |

Based on these assumptions and freezing the 19 first RZs (based on the first assumption above), moving the LEZ boundaries may affect the remaining 55 RZs. Fig. 14 shows one of the 55 RZs outside the current RAP area which may change by moving LEZ boundaries. As it is shown in Fig. 14, either of these situations may happen:

- (a) A zone may not be affected by new boundaries at all (being in the Outer-TMA region thoroughly).
- (b), (c) A zone may be subjected to just one LEZ boundary which may be either RAP or OETRP.
- (d) A zone may be subjected to both LEZ boundaries (RAP and OETRP).

It is obvious that what is shown in Fig. 14a–c are special cases of what is shown in Fig. 14d. Thus, the most complicated situation happens when an RZ is subjected to both RAP and OETRP plans (Fig. 14d). In this situation, the brown and red lines divide the RZ into three parts—three new RZs—in each, only ONE plan (RAP, OETRP or none) is applied. If all the RZs which have the potential of being subjected to a LEZ plan (the 55 zones discussed previously) are divided into three parts by two hypothetical LEZ boundaries (RAP and OETRP boundaries as shown in Fig. 14d), 165 potential new RZ are defined. In this total 184 (potential) RZs in TMA after adding the 19 first-level RZs in the RAP area in each, only ONE plan, either RAP, OETRP or none of them, is applied. Thus, it is believed that the travelers in each of these 184 RZs behave similarly in terms of trip characteristics including transport mode selection which is of real concern.

### 2.3.4 *Calculating total VKT*

Now that the total number of trips between all 184 RZs and the distance between them could be calculated, considering the probability of using personal vehicles by travelers in each zone, the total vehicle kilometers traveled from RZ $i$ to RZ $j$, denoted by $VKT_{ij}$ could be calculated as in Equation (12) (and expressed again here):

$$\mathrm{VKT}_{ij} = T_{ij} \times D_{ij} \times \mathrm{PVshare}_{ij}$$

The total VKT in TMA is calculated as

$$\mathrm{VKT}_{\mathrm{TMA}} = \sum_i \sum_j \mathrm{VKT}_{ij} \quad \text{for} \quad i,j = \{1,2,3,\ldots,184\} \tag{19}$$

where $\mathrm{VKT}_{\mathrm{TMA}}$ is the total vehicle kilometers traveled in TMA by commuters (note again that the commuters' trip generation was used as the base along with mode choice probabilities for commuters in TMA).

To evaluate the results of the calculated VKT by the proposed RZ model, this value is compared with the total PKT reported in the TMA. The TCTTS (Tehran Comprehensive Transport and Traffic Studies) organization has the TMA transportation network details modeled in EMME software and publishes reports regarding this model. As reported by TCTTS in 2016, there has

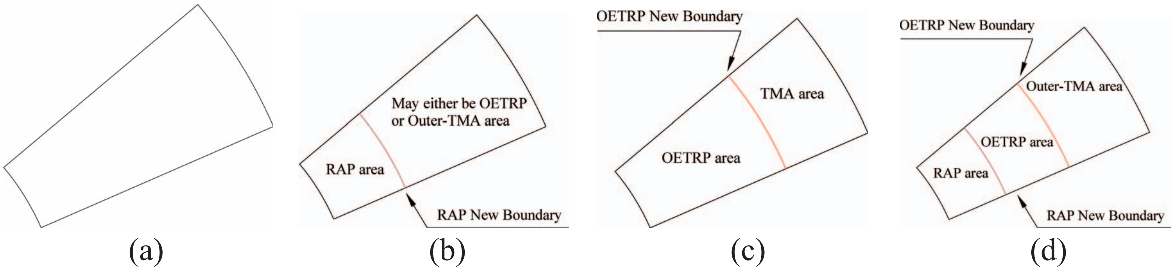


**Figure 14.** *RZs in TMA subjected to LEZ boundary movement.*

been a total number of 7.3 million PKT in TMA in the morning peak hour. As calculated by the RZ model in this study, a total number of 9.0 million vehicle-kilometers are traveled only by commuters each day. Commuting trips form an average of 36% of the total trips in TMA. Thus, the total number of VKT estimated by the model equals 25.3 million for all trip categories including commuters. As calculated by the nested logit mode choice model developed by TCTTS which was also integrated in the RZ model here, an average of 32% of travelers use their personal vehicles in their trips. This results in a total value of 79.0 million PKT for all modes of transport during the day in TMA. Assuming a peak hour traffic distribution factor equal to 0.09 (also as reported by TCTTS), a total number of 7.2 million PKT is estimated for the peak hour in the introduced model which is closely equal to the 7.3 million PKT reported by TCTTS. Surely the detailed model of TMA in EMME/2 software would be useful in many ways; however, the RZ model surely has capabilities of modeling TMA and its traffic restriction plans in such way that no software is capable of yet. The model here is capable of defining and applying various scenarios in major mode choice variations, restricting boundary movements and changing restriction policies, then evaluating the results. To use the RZ model more practically, eight different scenarios have been developed and evaluated out of which one is representing the current situation, four are representing extreme cases in terms of existing transport restrictions in TMA and three are some of the strongest suggestions currently in debates by policymakers in TMA to reduce air pollution and congestion.

# 3. SCENARIO DEVELOPMENT: RESULTS AND DISCUSSION

Now that the procedure to calculate total VKT in TMA is defined, new boundaries (new radii) for RAP and OETRP in each sector could be suggested. These suggested values can be used to define whether each of the 184 RZs is covered by these restriction plans and afterwards, a new total VKT is calculable. This procedure could also be used in a repeated cycle (by means of an optimization algorithm like genetic), as shown in Fig. 8 to gain an optimized combination of RAP and OETRP radii in each sector gaining the least possible VKT.

## 3.1 Current situation and extreme scenarios

A ‘BASE’ scenario is introduced to represent the current situation. Total VKT equals to 9.0 million in the BASE scenario for TMA commuters. As mentioned before, two major plans exist in TMA now, RAP and OETRP policy. A number of extreme conditions which could be defined for these plans are as follows:

- Scenario #1 Expanding the OETRP area boundary reaching the Outer-TMA boundary
- Scenario #2 Expanding RAP boundary reaching the current OETRP boundary
- Scenario #3 Expanding RAP boundary reaching the Outer-TMA boundary
- Scenario #4 Eliminating current OETRP area

Scenario #1 leaves nowhere in the metropolitan area without restriction policies. This is the plan that is put into practice now for times that the air quality index is considerably above standards, usually during winter times. The plan has one major drawback: as there are no traffic cameras all over the city, controlling the vehicles should be done by police officers which demands a great deal of human effort and expenses. Scenario #2 is one of the suggestions by the city transport planners because implementing it takes the least effort in order of time and expenses; the cameras controlling the current OETRP plan could be easily modified to follow the rules of the RAP plan. Scenario #3, though being similar to Scenario #1, is introduced here in order to compare the restrictions of the RAP policy over the OETRP plan. Scenario #4 also describes the situation in which the current OETRP plan is removed, leaving the metropolitan area with the RAP and the outer TMA boundaries. The results of applying these scenarios, as the total VKT in TMA, are compared in Fig. 15.

The results shown in Fig. 15 reveal some interesting points. The first would be the maximum amount of VKT that can be eliminated by applying restriction plans in their current condition (anything except coverage area) on TMA commuters. Total VKT equals to 8.1 million in Scenario #1 and 7.1 million in Scenario #3 which show a reduction of 11.0 and 22.0%, respectively, compared to the BASE scenario. Scenario #2 only reduces the total VKT from 9.0 million to 8.9 million: a reduction of 2.2%. The 7.1 million VKT calculated in Scenario #3 shows that the maximum potential of the restriction policies in TMA in order

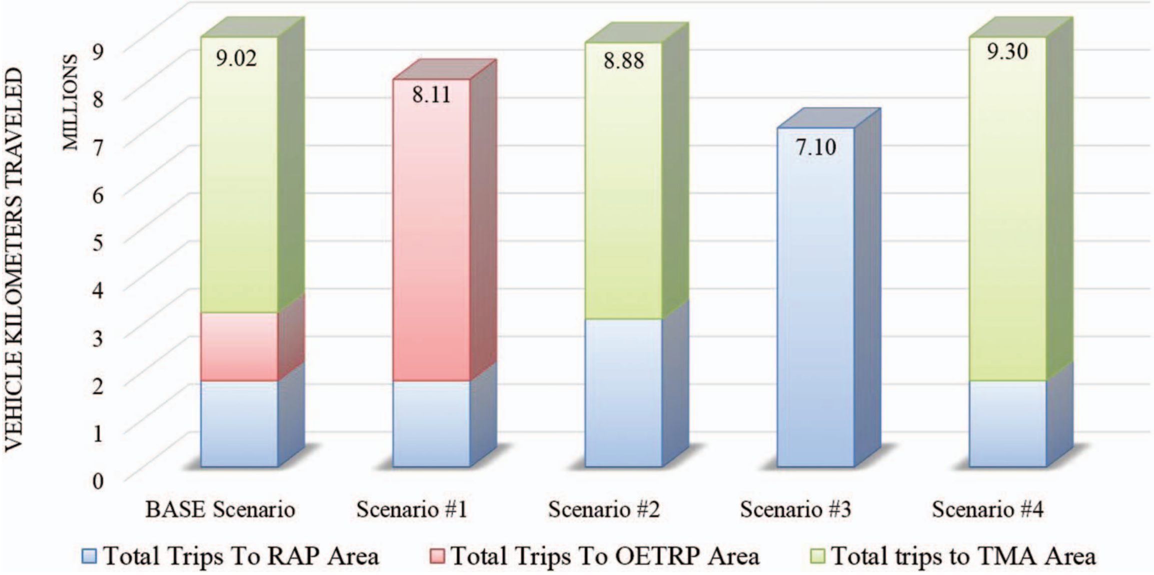


**Figure 15.** *Total number of trips in TMA using personal vehicles.*

to reduce using personal vehicles is about 22%. Thus, the rest of the VKT should be controlled by other means of restriction, or alternatively, improving public transit. Applying stricter rules to the current RAP plan sounds illogical since, as mentioned before, there are only public transit vehicles traveling within the RAP area along with a limited number of licensed vehicles. Scenario #2 is capable of reducing VKT by an amount of 0.2 million. Since the plan does not need major changes in the system and almost all the controlling equipment is already installed, it is a suggestible plan on the administration side as long as improving public transit systems within the area being affected comes to the policymaker priorities. The Base scenario, representing the current plans in TMA, has a total VKT of 9.02 m. This number has the potential of being reduced to a minimum amount of 7.10 m, should Scenario #3 be implemented. More specifically, if the RAP restriction (the strictest restriction) is applied all over the metropolitan area, a reduction of 21.3% in VKT will be achieved. This scenario, however, is not a practical one as the current public transport network in Tehran is not sufficient to accommodate for the extra journeys of those who decide to change their mode of transport. The more practical scenario compared to Scenario #2, but still an extreme one, is Scenario #1. Indeed, the city administrators implemented this scenario occasionally in some of the days of winter when the concentration of air pollutants exceeds the standard thresholds. In this scenario, the OETRP plan is applied all over the metropolitan area, which reduces the total amount of VKT by 10.1% compared to the BASE scenario. Although this number may look small, one has to consider that this reduction covers 47.4% of the total potential reduction in VKT introduced in Scenario #3, and thus, it is believed to be effective. As has been discussed by the city administrators, the authors are aware that Scenario #2 (expanding RAP boundaries to reach the current OETRP boundaries) is being considered currently as one of the 'good' options for the reduction in pollution. Interestingly, as the results of the analysis in this study demonstrate, this scenario reduces the total amount of VKT only by 1.6%. Since the RAP restrictions are so tight, it seems unjustifiable to restrict vehicle movement in the OETRP area in such way, only to get a 1.6% reduction in VKT. Beside all these scenarios, there is Scenario #4 which shows the ability of the current OETRP plan in reducing VKT. As it is shown in Fig. 15, the current OETRP plan reduces the total VKT by 3.0% (a value of 0.28 million). As an example on showing the potentials of the RZ model, in order to evaluate the optimality of the OETRP plan, new scenarios were introduced which are discussed in the next section.

## 3.2 New restriction scenarios in TMA

Despite Scenario #3, Scenario #1 seems doable; however, some points should be addressed. The RZ model developed in this study assumes the current RAP area in the CBD being unchanged while assuming the OETRP area boundary as a variable. This allows for an optimization problem being solved in order to calculate the best choices where the boundary of the OETRP area is being expanded. The base situation for such optimization is shown in Scenario #4 in Fig. 15. Minimizing the total VKT in the metropolitan area would be the goal of such optimization problem; however, restricting the boundaries as small as possible would be the limiting issue. Thus, three different scenarios were introduced as follows and the results are presented in Table 2:

- Scenario #5 Implementing a new OETRP boundary in TMA which equals the current OETRP plan in coverage area
- Scenario #6 Expanding the current OETRP coverage area twice as much assuming the current boundaries not getting smaller in all directions

**Table 2.** *Total calculated VKT*[a] *in various scenarios based on trip type.*

| Total calculated VKT | Base scenario | Scenario #5 | Scenario #6 | Scenario #7 |
|---|---|---|---|---|
| RR trips | 0.06 | 0.06 | 0.06 | 0.06 |
| RO trips | 0.06 | 0.07 | 0.10 | 0.10 |
| RT trips | 0.20 | 0.18 | 0.15 | 0.14 |
| OR trips | 0.16 | 0.21 | 0.45 | 0.51 |
| OO trips | 0.13 | 0.18 | 0.58 | 0.70 |
| OT trips | 0.48 | 0.40 | 0.67 | 0.66 |
| TR trips | 1.58 | 1.53 | 1.29 | 1.23 |
| TO trips | 1.24 | 1.44 | 1.83 | 1.83 |
| TT trips | 5.10 | 4.89 | 3.68 | 3.56 |
| Total VKT to RAP area | 1.80 | 1.80 | 1.80 | 1.80 |
| Total VKT to OETRP area | 1.43 | 1.69 | 2.51 | 2.64 |
| Total VKT to TMA area | 5.79 | 5.48 | 4.51 | 4.36 |
| Total VKT in TMA | 9.02 | 8.97 | 8.82 | 8.80 |

[a] All units are in millions

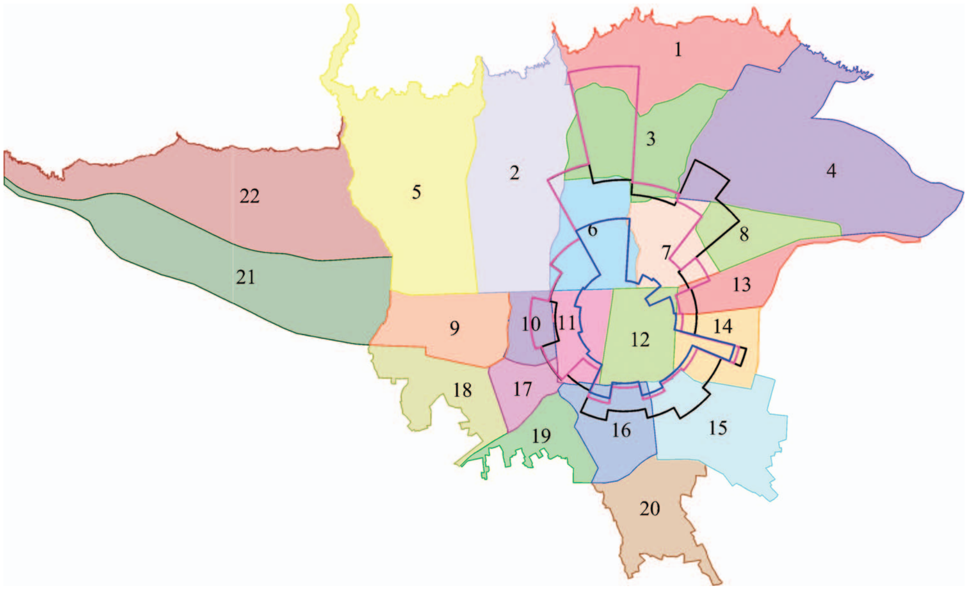


**Figure 16.** *Best possible OETRP plan (Scenario #5) in purple, current OETRP plan (Base scenario) in black and RAP plan in blue.*

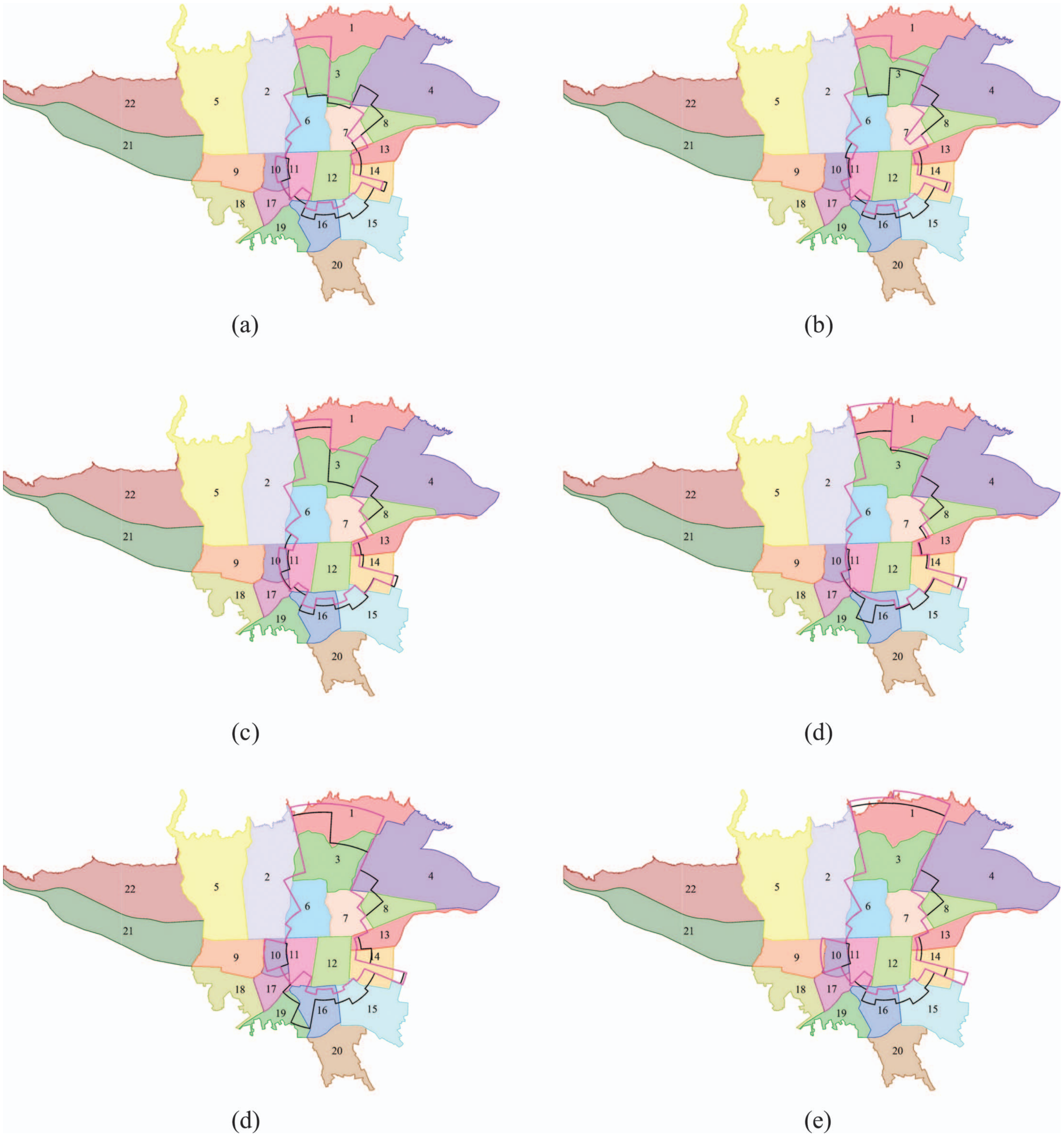
- Scenario #7 Expanding the OETRP boundary in Scenario #5 to cover an area twice as the current plan coverage

Even though there is always the chance of local optimization, Scenario #5 shows that the current OETRP plan works really fine as the optimal boundary in the proposed model reduces the total VKT only by 0.05 million (less than 1%) as it is shown in Fig. 16 and Table 2. However, it should be noticed that as it is shown in Fig. 16, the new OETRP boundary tends to cover the northern part of the city.

Scenarios #6 and #7 show how the current coverage and the new coverage in Scenario #5 would act if they have a chance to be doubled in the coverage area. The procedure for expanding the area was carried out in five steps (in other words, the optimization problem has been run in five steps), increasing the coverage area by 20% in each step. The expansion process is illustrated in Fig. 17. As it is noticeable in Table 2, expanding the current OETRP plan to double its current size does not make significant changes to total VKT (it is 1.6% for Scenario #6 and 1.9% for Scenario #7).

## 3.3 Discussing TMA scenarios

As it is shown in Fig. 16, the optimal OETRP boundary (in purple) lies close to the RAP boundaries in the southern part of the area. This implies that the southern part of the RAP area would not be a good option to expand the boundaries. The west part of the area seems satisfactory on the current OETRP boundary while, in some regions in the east, the current boundary seems over-expanded. Allowing the model to expand the coverage area in the OETRP plan, twice, as expressed in Scenarios #6 and #7, results in northern side boundaries being moved more. As it is shown in Fig. 16, the expanded OETRP area covers mostly Districts 3



(a) (b)

(c) (d)

(d) (e)

**Figure 17.** *Expansion process by 20% steps for OETRP–Base and #5 scenarios.*

and 1. The reason for this lies within two main reasons: the greater vehicle ownership in this areas and the greater number of generated trips from these areas to CBD. Based on this, the TMA administrative is well informed that the expansion of the boundary to the southern part is of no use. Besides, it could be concluded that Districts 1 and 3 have the most potential in increasing VKT; thus, budget allocations to increase the public transport facilities in these areas should be of first priority.

## 4. CONCLUSION

As the research background lacked a scientific approach in defining LEZ's boundaries, in this study, a new approach introduced as the RZ model was developed to fill this gap. The RZ model uses a simplified structure of transportation networks which makes it capable of instantaneous evaluation of existing restriction plans as well as proposed ones. The RZ model uses total VKT in a network as the basis which is believed to be in direct relation with air pollution responses. Due to the mathematical relationship between traveling behaviors and network structure that is developed in the RZ model, the model is also capable of being run by optimization algorithms to find the best possible solution based on desired constraints. The latter feature of the RZ model reduces the human-based parameters in defining LEZ boundaries, thus proposing a boundary with minimum possible errors.

The RZ model was applied in TMA as the case study, where policymakers have been dealing with the problem of traffic congestion and air pollution for decades and have adopted LEZs to overcome the problem. The model was used to evaluate current restriction policies along with some recently proposed ones. The results confirmed the optimal boundaries of the OETRP area (one of the LEZs in TMA) while suggesting further consideration of proposed policies in order to expand it. By assuming a coverage area as twice as the current OETRP area as a constraint for a new LEZ, a genetic algorithm was used to identify the best possible boundaries in TMA in terms of reducing VKT. Results of the latter analysis showed that in contrast to current proposals, the best solution suggests on inequivalent expansion of boundaries in different parts of the city.

The RZ model converts the existing Origin–Destination (OD) trip matrix in a network (which is based on existing study zones) to a new one based on new zones which are called RZs. Regarding this, a number of simplifying assumptions were made to ensure an achievable, but at the same time very reasonable, outcome. It is obvious that considering more RZs would result in more accurate responses. However, since the model works based on available OD trip data, adding extra zones may not increase the model performance as expected. Studies on the performance increment of the model are yet to be done.

It should be noted that the proposed model is aimed at the macro-scale evaluations to help policymakers to develop optimized plans; thus, the streets and traffic details were not included in it. Interestingly yet, the proposed model is capable of integrating any advanced formulation of trip generation and distribution. The reason is that the source data are derived from the base regions for which the OD survey has been carried out. Mode choice patterns could also be integrated in any desired formulation developed for the considered network. Thus, despite the simple description of the model, it can be upgraded using the most recent available data for the considered network. Moreover, although the transportation network facilities are not directly included in the model, the behavior of the model totally is in line with the facilities available in the transportation network since the mode choice probabilities calculated for each mode of transport totally depend on the provided facilities in the network and the level of service they offer.

Considering further research about what was proposed here, it should be noted that in this study, RZs with a fixed center were used to develop the RZ model. However, one may consider using a mesh grid, for example, allowing some movement to the central point of the restricted area or assuming more than one restricted areas. Indeed, it would be appropriate to consider more than one CBD and evaluate separate LEZs in a metropolitan area to minimize air pollution and congestion while keeping the region as accessible as possible by personal vehicles, another area for further research.

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