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Dynamic congestion toll pricing strategies to evaluate the potential of route-demand diversion on toll facilities

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Abstract

Congestion pricing has been proved to be an effective traffic management measure to reduce traffic congestion in metropolitan regions. Its aim is to limit the access of traffic towards heavily congested areas, thus to force road users to shift to other means of transportation by imposing toll fares to the vehicles willing to access these areas. Previous urban congestion pricing schemes have been efficiently discouraging individual vehicles from accessing congested areas by reducing traffic and mitigating environmental emissions. This study presents a new methodology for a dynamic zone-based congestion pricing system in networks with heterogeneous users, where the variable fares are calculated based on traffic congestion and environmental emission indicators. Congestion pricing methodology aims to determine optimal toll fares based on traffic congestion, vehicle type, and emissions produced based on the London Emission Model (LEM) to ensure reduction of emissions in the network-wide level. Further, methodology is developed within Dynamic Traffic Assignment (DTA) framework with a microscopic simulation model, that enables behavioral adaptation of the drivers during the pricing period as well as realistic congestion propagation. The performance of the proposed methodology is evaluated against a potential fixed pricing scheme in a Leicester city network, with 9652 sections, 3757 nodes where pricing policy area covers four zones with radius of 1.5 km from the centre. Simulation outputs have shown decrease in traffic delay time and NO_x emissions within the cordon area where the congestion pricing policy is applied. However, further strategic traffic management improvements are required to control the mode shift phenomena in the boundary area produced by the congestion policy.

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Keywords: dynamic congestion pricing; urban tolls; traffic analysis; traffic modeling.

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1. Introduction

In most major cities in EU, the statutory European guideline of 40µg/m3 for nitrogen dioxide (NO_2) in the urban area is exceeded, with most of this pollution coming from road traffic emissions (Local Air Quality Management (2009)). To improve air quality at the EU target level, it is important to alleviate traffic congestion, through a set of cost-effective measures to tackle the growing tendency of NO_x in the cities.

Congestion pricing is considered an effective management policy to reduce traffic congestion in the network, that aims to limit the access of traffic towards heavily congested areas by imposing toll fares on the vehicles willing to access these areas (Milioti, C., et.al. (2008)). The congestion pricing effects can be analyzed by obtaining recorded traffic flows, while the ex-ante assessment of potential congestion pricing schemes may be estimated via stated preference techniques and traffic simulation tools. For decades, toll pricing has been utilized as a form of congestion pricing, and within the last decade, a new form of toll pricing, one which charges a dynamic toll based on real-time traffic conditions, has attracted researchers and practitioner. According to De Palma and Lindsey (2011), congestion pricing schemes can be categorized into three groups: (1) facility based schemes applied on roads, bridges and tunnels, (2) cordon schemes applied to vehicles crossing a cordon and (3) zonal schemes applied to vehicles entering, exiting or travelling within a zone.

The toll fare can be determined based on the following factors: distance travelled, time of day, traffic volume, vehicle class, emissions produced. In most congestion pricing schemes in operation (e.g., London, Stockholm) the toll fare determination is based on the time of the day and vehicle class. Table 1 shows considerable reduction in traffic congestion, noise and air pollution even for not responsive toll fare pricing scheme. However, the responsive toll fares determined based on traffic volume and emission has been recognized by policy decision makers as a new congestion pricing scheme.

Table 1. Traffic and environmental effects of congestion pricing schemes ((Eliasson, J., et al, 2009), (Chen, X., et al, 2015), (Olszewski, P, et al, 2005), (Transport for London, 2008), (Goh. M., et al, 2002), (Ieromonachou, P., et al, 2006), (Lindsey, R., et al, 2000)).

	Reduction in traffic congestion	Environmental Impacts
London	33%	-15.7% CO_2, -17% NO_x, -24% PM10
Singapore	38%	- in traffic emissions, less radiation from the system
Oslo	10%	- in emissions and noise pollution
Stockholm	22%	- 14% CO_2

In this paper, we focus on the development of a new methodology for a dynamic zone-based congestion pricing system in networks with heterogeneous users, where the variable fares are calculated based on traffic congestion and environmental emission indicators. Integrating a proper traffic model that captures congestion dynamics is critical in designing the optimal toll prices (Zheng et al, 2012). Recent applications of macroscopic simulation models in pricing scheme design (see e.g. De Palma and Lindsey (2006) and (Zheng et al, 2012)) has shed some light on this to overcome limitations of simplified traffic models that do not capture congestion dynamics. While many studies have showed that dynamic congestion pricing can reduce congestion in policy affected areas more efficiently, a network-wide, dynamic zone-based pricing modelled in microscopic representation of the congestion for heterogeneous users deserves further investigation. Thus, we consider a Dynamic Traffic Assignment (DTA) framework with a microscopic simulation model using the simulation software Aimsun Next (Aimsun (2017)), that enables behavioural adaptation of the drivers during the pricing period as well as realistic congestion propagation. Furthermore, developed methodology aims to determine optimal congestion pricing fares based on traffic congestion, vehicle type, and emissions produced based on the London Emission Model (LEM) to ensure reduction of emissions in the network-wide level. The performance of the proposed dynamic congestion pricing methodology is evaluated against a potential fixed pricing scheme in a real large-scale network, with 9652 sections, 3757 nodes where pricing policy area covers four zones with radius of 1.5 km from the centre.

This paper is organized as follows. In the first part of paper, methodology for dynamic congestion pricing policy design that relies on determination of responsive tolls based on traffic conditions and emissions has been presented.

The second part of paper presents experiment design that consists of three scenarios: do nothing, fixed toll pricing, and dynamic toll pricing scheme, in order to access the benefits of the new congestion pricing policy measures. Paper closes with overview of simulation results for each scenario in large-scale real network, Leicester city and further directions for the methodology improvement.

2. Methodology

A zone-based dynamic congestion pricing methodology controlled by DTA is developed and implemented as an Application Programming Interface (API), within a stochastic route choice model using Aimsun Next. The API includes a collection of functions, in Python or C++ that allows the user to apply the congestion pricing methodology inside the simulation software. The idea here, instead of using the traditional demand-supply curve, is to determine a dynamic toll fare so that the traffic in the network operates in non-congested level and reduced emissions. In this direction an API, triggered by real time traffic emission NO_x measurements for the cordon area has been developed, which is implemented in a stochastic route choice model (Florian M., et al, 2001), (Florian M., et al, 2002) using Aimsun Next (TSS-Transport Simulation Systems, (2015)), to evaluate the impacts of the congestion pricing policy through the simulation of the alternative scenarios. In detail, the API uses the London Emissions Model (LEM) model to calculate the NO_x emissions (plus travel time, speed and density) in several links inside Leicester' cordon and boundary network. Table 3 shows the different fares applied in the DT implementation. The proposed design of the dynamic congestion pricing methodology within DTA framework – encompassing three main components, conceptually illustrated in Fig. 1 – is generic and allows comparison of different fare scenarios in a variety of settings and conditions in the network.

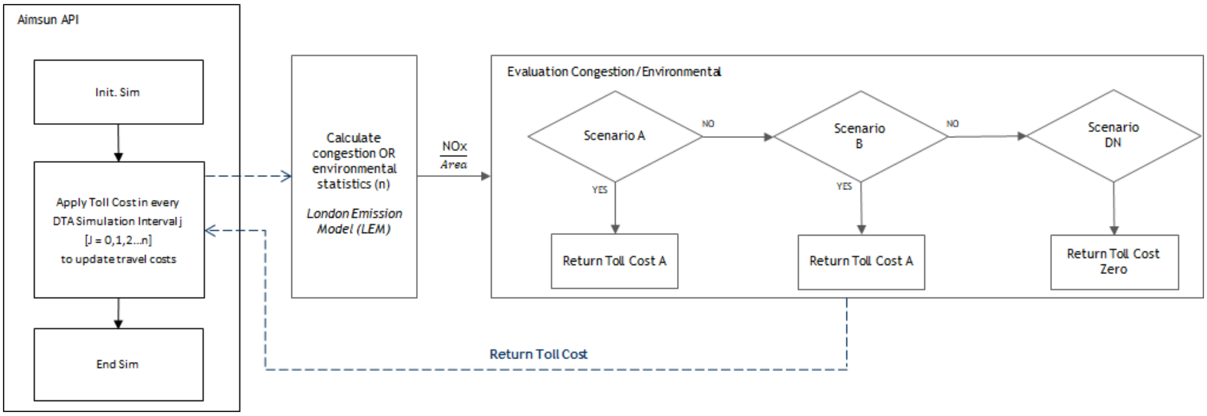

Fig 1: Dynamic congestion pricing methodology

Our goal is to determine a variable congestion pricing scheme for all the vehicles entering areas under pricing policy. Given that the zone boundaries and cordon in the urban area that will be covered by zone-based pricing policy are defined, the following steps are developed within the API:

1. The first step uses the London Emissions Model (LEM) to calculate the NO_x emissions inside the cordon and/or boundary network. The LEM, London Emission Model uses one of two polynomial relationships, derived by regression analysis, to fit an emission factor for CO_2 and NO_x.

$$y = ax^z + b \qquad : x < 10 \text{ km/h} \quad (1)$$

$$y = ax^3 + bx^2 + x + c \qquad : x \geq 10 \text{ km/h} \quad (2)$$

Where in the (1) and (2) y is the emission (grams/km) a, b, c, z, are derived constant and x is the average speed in the micro trip. In this step, for each zone, the level of NO_x is computed based on the traffic conditions in the network in every simulation interval.

2. The second step deals with the fare computation per access zone and per vehicle type affected in every simulation interval, e.g. 15 minutes. Fares are determined based on the aggregated NO_x threshold value generated for each zone in the network without pricing policy implementation. A real supply/demand state from the calibrated microscopic network model leads to the calculation of true NO_x and congestion levels in the network. In this respect, a wide range of possible pricing scenarios for various levels of NO_x and congestion compared to their threshold values can be calculated. Therefore, this approach allows the design of multiple fare scenarios and enables their evaluation within a framework.
3. The third step focuses on translating selected toll fares into costs (i.e., in minutes) based on Value of Time (VoT). Table 2 shows the VoT per vehicle class depending on driver's purpose.

Table 2. VoT, UK Transport Department TAG data book (2017).

Value of Time (2017)	
Vehicle	Perceived Cost (£)
Car - Work	18.08
Car - Commute	12.10
Car - Other	5.52
LGV	12.45
HGV	14.66

Once fares are translated into costs, new path costs are updated and stochastic route choice within the DTA framework is executed. Furthermore, adaptivity of the users to toll system has been modelled within the DTA framework to reflect that drivers with a destination inside the cordon area can change their destination to avoid paying the toll. For each destination zone inside the cordon area, three walking links to the nearest zones outside the cordon area have been created, as illustrated in Fig. 2. Thus, drivers can leave the vehicle outside the toll area and then continue to the original destination using an alternative mode. The walking speed can be set to 2m/s and the distance can be calculated based on the shortest path distance between these destinations. Since route choice algorithms are based on the calculation of the costs per link, each driver will decide whether to pay the toll and enter the cordon area or to park the vehicle outside and then walk to the destination.

In general, the conceptual zone-based dynamic congestion pricing methodology presented in this section should be operationalized in an evaluation analysis, capable of performing comparisons between different congestion pricing schemes (e.g., do nothing, fixed fare scheme) in a wide range of case studies and experimental setups. Therefore, the paper presents a practical instance of implementation of a dynamic congestion pricing over alternative pricing strategies in practice.

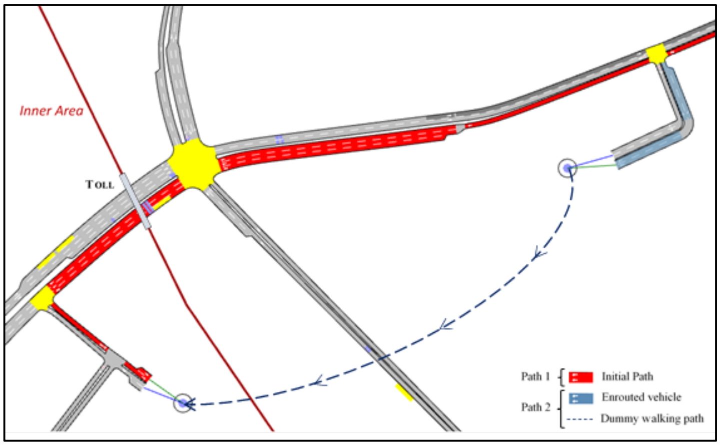

Fig 2: Example of driver's destination change.

3. Experiment setup

This section presents the experiment setup for evaluation of the proposed congestion pricing scheme as follows:

1. Define the study area and define the relevant inputs of the traffic model
2. Scenario development and the congestion pricing policies:
    a. Base scenario with do nothing policy (DN)
    b. Base scenario with fixed toll policy (FT)
    c. Base scenario with the dynamic toll policy based on NO_x emissions (DT)

3.1. Study area and definition of the relevant inputs

To start with, the Leicester model under analysis consists of 9652 sections with a total section length of 1784 km and total lane length of 2189 km and 3757 intersections (controlled by SCOOT: 206 and fixed time controlled: 427), reserved lanes for buses, zones, traffic demand with O-D matrices (per vehicle type and 15min period). The initial O-D matrix used in the analysis originates from year 2008. The O-D matrix was updated using traffic counts for the year 2016, from 423 detection points (SCOOT) and updated through the matrix adjustment procedure of the Aimsun Next, which is based on a bi-level optimization method (Codina E., et al, 2014), (Florian M., et al, 1995). The simulation experiments started at 05:00 am and finished at 10:00 am. The traffic network model has been calibrated and validated to reflect real traffic conditions with respect to the AM peak hour. The cordon area is covered by a radius of 1-1.5km from the city centre. Fig. 3 shows the transition from the strategic network to the Leicester microscopic model and the definition of the cordon area.

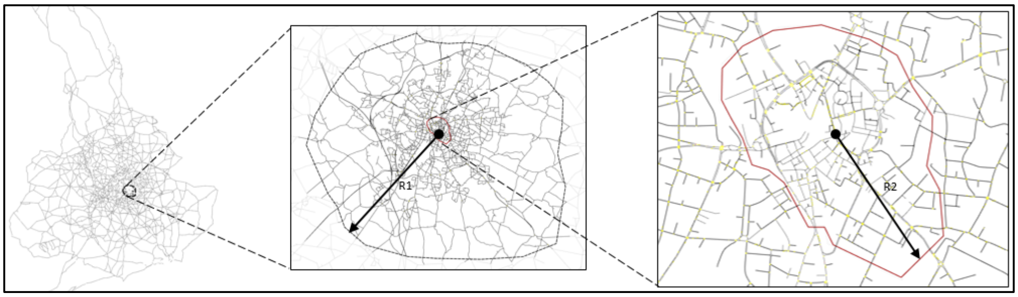

Fig. 3. Transition from the Leicester strategic model to microscopic model of the central area and the cordon area.

Fig. 4 depicts the defined detection points to measure the effectiveness of the proposed pricing scheme and the fare collection points at the entrances of the cordon area.

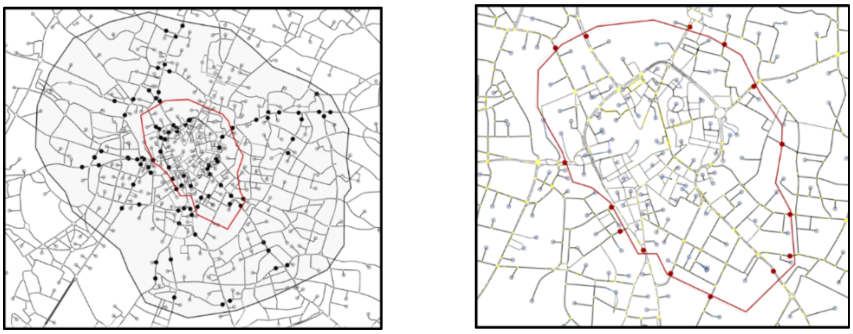

Fig. 4. (a) Detection points within the cordon and its buffer area; (b) Fare collection points at the entrances of the cordon area.

3.2. Scenario development and the Congestion Pricing Policies

3.2.1. Do Nothing scenario (DN)

The DN scenario represents the current calibrated Leicester traffic network model without any toll implementation in the entrances of the cordon area.

3.2.2. Fixed Toll scenario (FT)

FT scenario is designed by applying a distinct fare per vehicle class at each entrance of the cordon area. The toll fare is fixed anytime at any entrance heading towards the cordon area. Table 3 shows the FT pricing scheme per vehicle class.

Table 3. FT pricing scheme per vehicle class

Vehicle Class	**fare (euros)**
Car-Work	3
Car-Commute:	3
Car-Other	3
LGV	5
HGV	7

3.2.3. Dynamic Toll scenario (DT)

The boundary and cordon area were split into four subareas (Red, Green, Yellow, Blue). Based on the aggregated NO_x statistics of each area the variable toll will be calculated and updated every 15-min using the API in Aimsun Next. Fig. 5 depicts with distinct colors the boundary and cordon areas that NO_x data was gathered by LEM model and processed to apply a variable toll cost at the different entrances of each zone in the network.

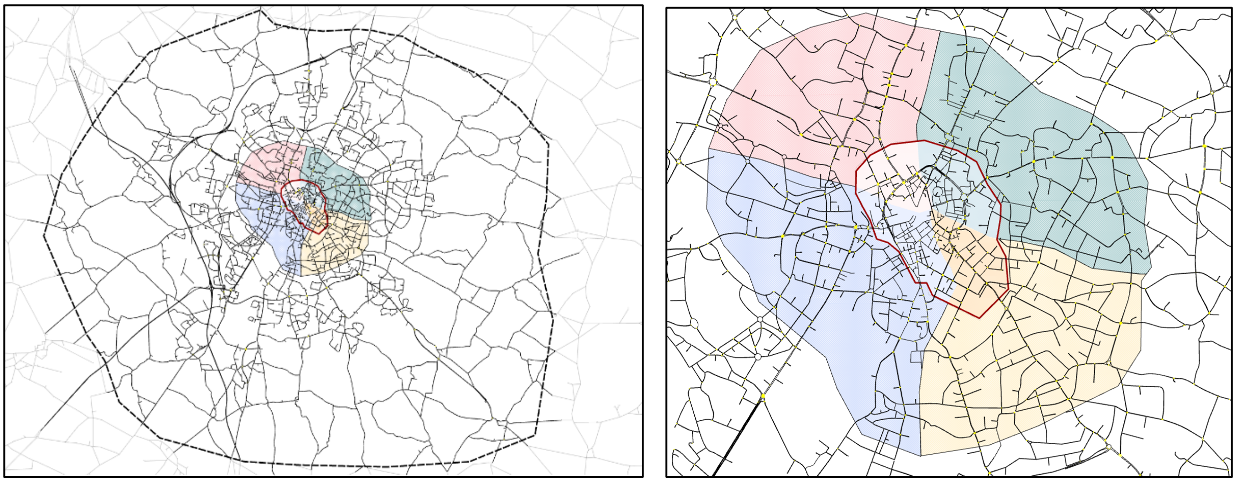

Fig 5: Boundary and cordon areas with red, green, yellow, and blue toll zones.

Table 4 shows the various toll fares of the DT pricing scheme.

Table 4. Dynamic Toll pricing scheme per vehicle class

Vehicle Class	NOx < 25g/km	25g/km < NOx < 35g/km	NOx > 35g/km
Car-Work	3	4	6
Car-Commute:	3	4	6
Car-Other	3	4	6
LGV	5	6	10
HGV	7	10	20

4. Results

In this section, the simulation results for the different fare scenarios are presented. Figures 6 and 7 show the NO_x and delay time simulation results for the AM peak hour for three different scenarios: a) DN, b) FT, c) DT with respect to the cordon area. It can be observed that the FT policy improves the NO_x and delay time compared to the DN scenario in the cordon area by -16.46% and -5.03% and the dynamic-toll policy improves even more these indicators by -25.53% and -5.87% respectively.

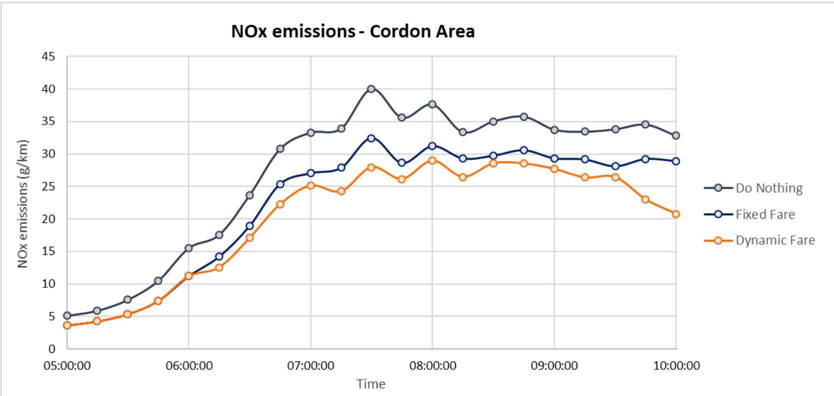

Fig 6: NOx emissions for Cordon Area

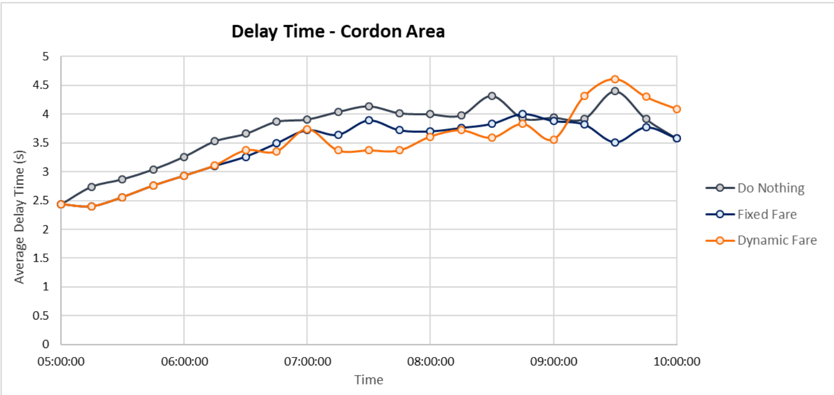

Fig 7: Traffic delay for Cordon Area

Figures 8, 9 and 10 show the delay time in the boundary area and cordon area for all three scenarios. Figure 10 clearly shows that from 9:15am till the end of the simulation, a gridlock on the west part of the boundary area has been formed due to the high traffic demand on the tested dynamic toll scenario.

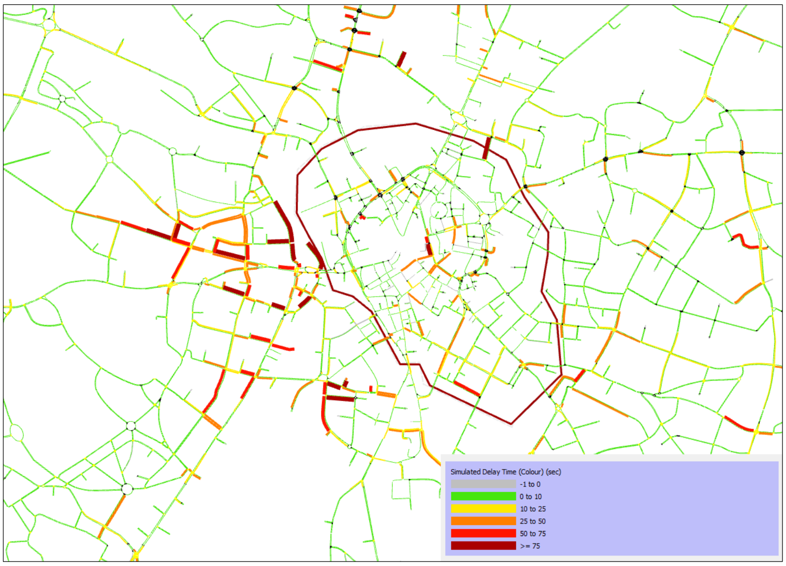

Fig 8: Delay Time for Do Nothing scenario

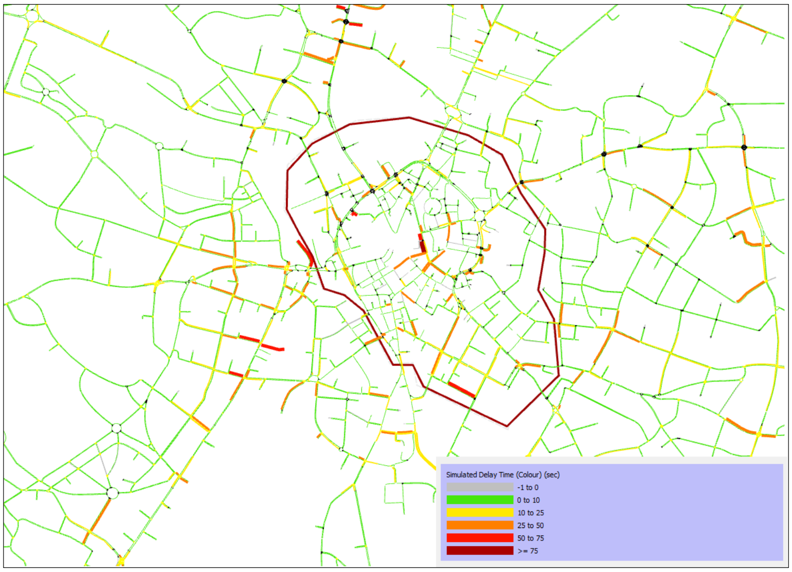

Fig 9: Delay time for FT scenario

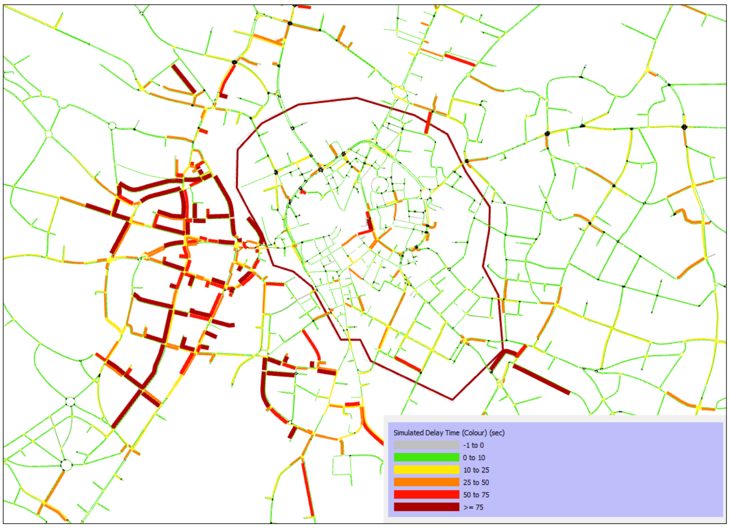

Fig 10: Delay Time for DT scenario (gridlock)

Table 5 shows that the FT scenario significantly increase the delay time and NO_x by 41.69% and 7.47% respectively, in the boundary area. Furthermore, DT scenario causes even further increase of the delay time and NO_x by 166.20% and 10.44% . The reason for that delay time increase can be explained by the fact that the current network loading process does not consider the adequate mode shift from the private vehicles to the public transport or other environmental friendly modes of transport. Mode shift phenomena resulting in demand change has been observed in the past in London, Stockholm and Singapore due to congestion pricing policy implementation. In addition, to enhance intermodality, other traffic measures can be applied such as the implementation of new parking lots outside the cordon area. To better serve the increased bypass traffic, the optimization of the traffic lights and the few infrastructure modifications should be also considered.

Table 5. Summary of the performance indicators per scenario.

Scenarios	Delay time (min) cordon	Delay time (min) boundary	NO_x-cordon (g/km)	NO_x-(boundary) (g/km)
DN	3.58	3.55	26.01	20.21
FT	3.40 (-5.03%)	5.03 (+41.69%)	21.73 (-16.46%)	21.72 (+7.47%)
DT	3.37 (-5.87%)	9.45 (+166.20%)	19.37 (-25.53%)	22.32 (+10.44%)

5. Conclusions

In this paper, the formulation of the new methodology for the dynamic zone-based congestion pricing within microscopic traffic simulation model is presented. It is shown that this new methodology has several advantages over non-existing or other existing fixed pricing schemes. The most important feature is that the calculation process of the fare per vehicle class and zone area is based on the emissions NO_x produced by the vehicles in the boundary and cordon area of a network. The LEM model has been used to calculate the NO_x simulation outputs.

Congestion pricing is widely recognized as an effective traffic management measure. In this paper the impact of a congestion pricing scheme for Leicester, UK is investigated with the use of a microscopic traffic simulation model. However, dynamic zone-based congestion pricing methodology is replicable due to its development in the API format that allows further analysis of dynamic congestion pricing policies in multiple case studies.

The performance of the proposed dynamic zone-based pricing methodology shows an improvement of delay time by -25.53% and NO_x by -5.87% compared to do nothing scenario in the cordon area of Leicester city. Further, results show slight reduction in delay time by 0.88% and NO_x emissions by 10.86% when dynamic over fixed toll pricing strategies are compared. However, significant traffic capacity drop in the boundary network has been observed.

One explanation for observed capacity drop can be the lack of adequate traffic management measures, such as en-route information, that will complement dynamic traffic charging. For example, en-route information would enable drivers to shift to alternative route, select alternative mode or change their trip destination. Thus, in future research, the proposed methodology will be extended by computation of the trip costs based on predicted traffic conditions using historical and real data. Future work will also focus on the application of the real environmental data obtained from environmental stations, instead of estimated values from the LEM model, that will enable assessment of the various emission pricing policies. Furthermore, extension of the API is required to establish full integration of all road users behavioral aspects (e.g., taxi, bicycles, pedestrians, public transportation services).

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