Quantifying road traffic emissions embedded in a multi-objective traffic assignment model

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Abstract

In a road network, drivers typically seek to minimize their own travel time, often affecting system-wide performance. With the increasing environmental awareness, for an efficient traffic assignment (TA), besides concerns with travel times, traffic managers should not neglect the system-wide level of both global and local pollutant emissions. Measuring road traffic emissions can be costly and different models based on vehicle-specific parameters with many input variables have been suggested in the literature. This paper proposes a simple way to quantifying carbon dioxide (CO_2) and nitrogen oxides (NO_X) emissions with only average speed as input variable and presents a multi-objective TA approach that seeks to minimize system-wide travel time, distance travelled (associated with fuel consumption) and global and local pollutant emissions. A real-world case study on an intercity corridor with many alternative routes between two zones is presented. Experiments considering TA based on travel time, and on time, distance travelled, and pollutant emissions are reported. Results highlight that system optimal distribution based on the suggested multi-objective TA based on three components yields savings in terms of distance travelled (2.6%) and emissions (1.3% for CO_2 and 1.1% for NO_X), but penalizes travel time 3%, which is translated in an increase of 20sec per vehicle, when compared to the solution only focused on minimizing travel time. The developed methodology is a suitable tool for traffic analysts to predict vehicle system-wide travel time, distance travelled and pollutant emissions with few vehicle information but with a reasonable detail for a specific traffic flow on a given road network, to support analyses for sustainable transport policies and may be used, for instance, as an environmental impact component of a pricing scheme, traffic signal control strategies based on emissions reduction, or to minimize congestion by giving prior information to drivers on the specific routes to be chosen.

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Keywords: Multi-objective Dynamic Traffic Assignment; Emissions; COPERT

1. Introduction

Transport sector represents almost a quarter of Europe's total greenhouse gas (GHG) emissions, being the road transport its major contributor (EU, 2018). Road transport is also a main source of air pollution, especially of harmful pollutants which include nitrogen oxides (NO_X) (EEA, 2018a). In Portugal, data from 2017 show the fuel consumption of road transport increased, being diesel the main fuel consumed (79%), increasing more than 2%, while gasoline decreased almost 3% (PEA, 2019). Moreover, in numerous European cities, passenger car share is very high (EU, 2018), and this high reliance on the passenger car leads to significant levels of congestion, consequently increasing pollutant emissions. Therefore, air quality and climate change should be tackled jointly using policies and measures that should be developed through an integrated approach (EEA, 2018a), requiring appropriate, easy-to-use and fast tools to analyse current and future scenarios and discuss mitigation measures and strategies.

Traffic assignment is an important step for traffic planning and, typically, studies are based on individual drivers behaviour that seek to minimize their own travel time assuming user equilibrium conditions, i.e., drivers are likely to

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choose the route with the shortest travel time, or a generalized cost, which can combine, for instance, travel time and tolls (Perederieieva, Raith, & Schmidt, 2018). However, when road users are just focusing on minimizing their own travel cost, it may result in increased travel cost for the whole system (van Essen, Thomas, van Berkum, & Chorus, 2016). Nevertheless, TA tends to focus on minimizing travel time, while indirect environmental impacts have been receiving less consideration. In an era where cities need sustainable mobility systems, it is important to study the system-wide environmental consequences of an individual behaviour in a congested network. Moreover, pollutant emissions in urban areas should be estimated to ensure air quality is not compromising environment and human health.

Traffic assignment models have been applied for traffic flow and travel time forecasting in long-term transport planning studies, as well as in short-term traffic operation management and control (Wang et al., 2018). Static TA models (time-invariant variables) have been applied for a long time and for planning purposes, and are considered to be an important tool for strategic policy decisions mainly due to its simplicity and computational efficiency (Saw, Katti, & Joshi, 2015). Dynamic TA (DTA) models seek to provide more detailed spatial and temporal vehicular interactions, considering changes in traffic behavior throughout the journey, which reflect travel choices and traffic flows in a more realistic manner (Wang et al., 2018).

Some studies have been considering emission-based TA and results show travel time-based TA may not minimize pollutant emissions (Ahn & Rakha, 2008; Patil, 2016; Sugawara & Niemeier, 2002). Recent studies show an environmentally conscious behaviour of drivers may generate a negative impact on system-wide emissions (Bandeira et al., 2018). Research on methodologies based on micro-scale simulation to provide information to travellers regarding the level of emissions on certain routes was explored, for instance in (Bandeira et al., 2016) and showed choosing a CO_2 saving route may increase other pollutants. These results suggest a multi-objective approach should be considered based on minimizing both travel time and emissions, which is the main focus of this study.

On-road vehicle emissions can be directly measured using a Portable Emissions Measurement System (PEMS) however, it is considered impractical and expensive to adopt by local authorities, since all vehicles had to have installed a PEMS device. Thus, emission estimation models are important tools to evaluate scenarios and provide support to decision-making with quantitative estimates. There exist various emission models such as the microscopic model VSP – Vehicle Specific Power (US EPA., 2002), the mesoscopic models suggested by (Gori et al., 2013; Jamshidnejad et al., 2017; Rakha, Yue, & Dion, 2011), and the widely used macroscopic model COPERT – COmputer Programme for calculating Emissions for Road Traffic (Emisia SA, 2018), varying in complexity and input data requirements. VSP requires instantaneous speed, acceleration and road grade as input variables and has showed to be an useful explanatory variable for estimating variability in emissions (Frey, Zhang, & Rouphail, 2008). The VT-MESO model predicts vehicle fuel consumption and emission rates based on vehicles average speed, average number of stops per unit distance, and average stop duration, and results show a prediction error of less than 10% for CO_2 and between 10-27% for NO_X emissions when compared to a microscopic model based on vehicles instantaneous speed and acceleration levels (Rakha et al., 2011). On the other hand, in (Gori et al., 2013), a dynamic mesoscopic emission model was developed for specific links signalized intersections, allowing to distinguish between vehicles in/entering or exiting a queue using data derived from a DTA. Emissions are computed using a dynamic mesoscopic model starting from the VSP approach for all the links approaching a signalized intersection, and a macroscopic average speed-based approach for all the remaining links. System-wide results show links approaching signalized intersections are damped by the remaining links of the network. In (Jamshidnejad et al., 2017), a mesoscopic integrated flow-emission traffic model is proposed based on a microscopic emission model. Since it provides instantaneous emission estimates, second-by-second individual speed and acceleration of vehicles are needed, and such information may be difficult to obtain for all vehicles in a link or road. In the macroscopic model COPERT, the inputs are trip-based or road section-based average speed and vehicle kilometres travelled, which are relatively easy to obtain from field measurements (Wang et al., 2018), and it has been shown this type of macroscopic models are useful for estimating average emission rates at a regional level (Coelho et al., 2009). Since it is often difficult to compile detailed vehicle data, here, a COPERT-based approximation approach to estimate emissions is suggested for a representative vehicle of the national fleet, based on average speeds per link.

Bearing in mind the need for an assessment combining the key components of efficiency (determined in terms of the total travel time and distance in the network), climate change (represented by the total CO_2 emissions), and air quality (in terms of system-wide NO_X emissions), the present research intends to provide a methodology that optimizes the performance of a road network by spreading traffic not only with the aim of minimizing travel times and distance travelled, which affects fuel consumption, consequently emissions, but also accounting for the impact of global (CO_2) and local (NO_X) emissions. A simplified way to adopt COPERT in order to estimate network level emissions under different driving modes is embedded in a multi-objective DTA framework through a simulation-based approach using Vissim (PTV AG, 2016) and Vissim COM (Component Object Model) API through Matlab. A DTA model was chosen to account for time varying flow, possibly congestion and specific conditions/events, such as pay tolls, traffic lights or other road singularities.

The objective of this paper is to propose a methodology thought to overcome the lack of enough measurement data availability and local financial issues to monitoring traffic-related environmental impacts, by suggesting a basis for integrated knowledge in terms of quantifying road traffic efficiency, climate and air quality system-wide impacts for adopting policies and plans towards a more sustainable mobility.

The remainder of this paper is structured as follows. In Section 2, the methodology followed in this work, the details behind the simplified way to adopt COPERT used to estimate emissions, as well as the proposed multi-objective DTA approach are described. Section 3 is devoted to evaluation of the suggested emission models and results on the evaluation of the proposed multi-objective DTA applied on a real-world case of an intercity corridor with many alternative routes between two zones are presented and discussed. Conclusions are drawn in Section 4.

2. Methodology

In this section, we describe the developed methodology. Figure 1 depicts the conceptual framework designed for this study, in which the main sections/tasks and interaction between them are illustrated.

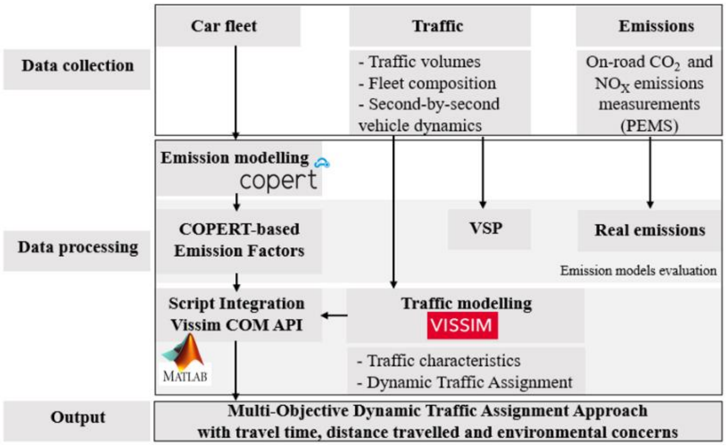

Fig. 1. Methodology overview.

2.1. Traffic Data Collection

In order to build and calibrate a traffic model, enough amounts of data collected in the field should be available so that the variation of traffic and congestion is understood and quantified. A microscopic traffic model is able to describe driving behaviour and offers detailed vehicle operation and vehicles speed, which are key data for microscopic and macroscopic emission estimate models. Thus, over multiple typical days, a collection of link volume (manual counting) and second-by-second vehicle dynamics data were acquired. Three probe vehicles equipped with GNSS (Global Navigation Satellite System) data-logger were driven along with the traffic stream by different persons for different driver behaviours. The link average speed was determined by averaging the instantaneous speed profile.

2.2. Emissions Modelling

Emissions can be estimated using for instance, COPERT (Emisia SA, 2018) or VSP (US EPA., 2002) methodologies. First case, detailed vehicle data on category, fuel type, engine size, and technology/emission standard are input variables. Second case is a regression-based model, where different average emission rates (g/s) are derived as a function of VSP ranges (kW/ton) and it requires instantaneous speed, acceleration and road grade as input variables, returning a VSP mode, which in turn is associated to emission factors. However, when this level of information is not available, such models cannot be used. If link-based travel time is available, it is possible to know link-based average speed. Here, we propose a simplified COPERT-based model to estimate CO_2 and NO_X emissions for a representative vehicle of the Portuguese national fleet that only uses average speed (s) as input variable. In fact, the proposed approach may be regarded as mesoscopic in the sense that it considers an aggregated behaviour for different vehicles, though similar to somewhat extent.

This is based on emissions computed considering a reasonable range of speed values using the software COPERT5.2 and the national vehicle fleet statistics (year 2014). COPERT emission factors can be seen as group-dependent regressions, while our approach can be regarded as an approximation, where specific group structure is not considered explicitly. The advantage of this approach is that an approximate emission factor can be obtained without prior information on vehicle technology and engine capacity classes. This way emission factors based on COPERT results for the national vehicle fleet composition are established for a representative vehicle type. Here, we present the results on CO_2 and NO_X emission factors for diesel passenger cars, but this methodology can be extended to different vehicle types, namely, light duty vehicles (LDV), heavy duty trucks or buses. Studies have been showing a correlation of speed level and emissions describing parabolic-shaped curves, with high emissions for low and high speeds (Yao & Song, 2013). The least squares fitting technique was used to find the best-fitting curve. The CO_2 emission factors (g/km) for diesel passenger cars can be given by

$$ef_{CO_2}(s) = \begin{cases} 0.072s^2 - 7.530s + 360.424 \ (\mathrm{R}^2 = 98\%, Fsig = 1.25\times10^{-6}), \ s \le 50\text{km/h} \\ 0.016s^2 - 2.382s + 232.506 \ (\mathrm{R}^2 = 99\%, Fsig = 2.14\times10^{-8}), \ 50 < s \le 90\text{km/h} \\ -0.013s^2 + 4.063s - 118.640 \ (\mathrm{R}^2 = 98\%, Fsig = 1.25\times10^{-6}), \ \text{otherwise.} \end{cases} \quad (1)$$

while NO_X emission factors (g/km) can be obtained using

$$ef_{NO_X}(s) = \begin{cases} 0.0003s^2 - 0.0281s + 1.3511 \ (\mathrm{R}^2 = 98\%, Fsig = 6.77\times10^{-7}), \ s \le 50\text{km/h} \\ 0.0001s^2 - 0.0142s + 1.0232 \ (\mathrm{R}^2 = 99\%, Fsig = 8.49\times10^{-13}), \ 50 < s \le 90\text{km/h} \\ -0.0001s^2 + 0.0334s - 1.5687 \ (\mathrm{R}^2 = 97\%, Fsig = 8.48\times10^{-10}), \ \text{otherwise.} \end{cases} \quad (2)$$

To compute emission estimates on specific road sections, first we require, qualitative variables (road type – urban, rural, highway) in the pre-step where COPERT is used to developed the suggested emission factor functions, and then, quantitative traffic situation variables (e.g., average speed, traffic volume, and link length). Models (1) and (2) are less data intensive than other approaches and their application integrated with TA is the purpose of this study.

2.3. Multi-objective Dynamic Traffic Assignment with Travel time and Environment concerns

A traffic network can be represented by a set N of nodes and a set A of links (road segments). Demand can be represented by origin-destination pairs, connected by a path, which can include more than one link $a \in A$, describing the pattern of travel in terms of trip movements across the network and between sets of origin and destination points.

Road traffic external effects are of great importance for policy decisions related to the traffic management and planning. A full picture of the network efficiency should be aligned with environmental impacts. The multi-objective DTA approach that we propose seeks to minimize system-wide travel time, distance travelled and pollutant emissions, and involves the following objective functions within each component:

$$\begin{aligned} &\text{Efficiency: } \sum_a \sum_m x_{am} l_a / s_{am} \text{ (travel time)}, \quad \sum_a \sum_m x_{am} l_a \text{ (distance travelled)}, \\ &\text{Climate: } \sum_a \sum_m x_{am} ef_{CO_2}(s_{am}) l_a, \\ &\text{Air quality: } \sum_a \sum_m x_{am} ef_{NO_X}(s_{am}) l_a, \end{aligned} \quad (3)$$

where x_{am} and s_{am} are the vehicle type m inflow to and the average speed on link a, respectively, and l_a(km) represents the length of link $a \in A$.

The presented objectives are used to determine optimal traffic distributions using a DTA model to account for traffic dynamics and time-variant demand. The Vissim microsimulation tool (PTV AG, 2016) is an efficient way of describing time-varying network traffic conditions and finding shortest routes (in terms of travel time, distance travelled, and/or a specific cost per link). Thus, a DTA simulation-based modelling approach using Vissim was used in the performance analysis of an intercity corridor. A Matlab custom procedure able to access Vissim through COM interface was developed to incorporate the multi-objective nature of the proposed model. All computations regarding network equilibrium are done using the Vissim Dynamic Traffic Simulation Model. The controlling process launches Vissim, loads the network, integrates the objective functions at each DTA step, and sends back costs per link to Vissim. This allows controlling Vissim model and simulation in real-time.

The computational efficiency makes it suitable for the evaluation or design of various traffic management strategies with environmental concerns, providing valuable information for the decision-making process.

3. Results and Discussion

3.1. Case Study

The methodology reported was tested on a real intercity corridor comprising many alternative routes between two zones (Fig.2). The network is characterized by 2 origins (O_1, O_2), 3 destinations (D_1, D_2, D_3), 17 segments, 9 major intersections. Large part of Routes 1 and 6 is on trip sections with speed limit of 50km/h, roundabouts and traffic light intersections. Other routes are mostly characterized by higher speed limits, traffic volume levels (A1 section has three times more volume than A29 (IMT, 2019), while volume in N109 varies from 500-1200) and two or more lanes per direction, since significant part is on highway sections. The network was coded in Vissim with 50 links.

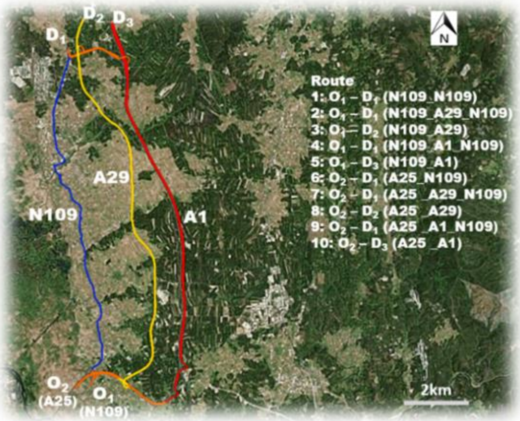

Fig. 2. Case study network.

Vehicle dynamic data was collected for these routes (almost 1300km of road coverage) using probe vehicles equipped with GNSS data-logger and PEMS (for real emission estimation). Three EURO 6 emission standard diesel passenger cars with the following specifications were used in to collect vehicle dynamics data: Car1 (1.2l, 70kW, 89g CO_2/km - NEDC), Car2 (1.4l, 66kW, 82g CO_2/km - NEDC) and Car3 (1.6l, 73kW, 98g CO_2/km - NEDC). For this type of vehicles, the 2015 CO_2 EU target is set to 130g/km, and for 2021 is 95g/km (EEA, 2018b).

3.2. Validation of the COPERT-based Emission Models

Tests were conducted to evaluate accuracy of the COPERT-based models (1) and (2) over VSP and a comparison was made on a test sample using a PEMS for on-board emission measurements on several routes. This sample included more than 135km of on-road emission data. Details on length and average speed, and CO_2 and NO_X emissions per route are shown in Table 1. The reported results focused on three selected routes with more variability in terms of traffic volumes and number of interrupted traffic facilities such as roundabouts, traffic lights or pay tolls.

Table 1. Results on emissions for selected routes using PEMS, and VSP and COPERT-based models.

Route	Length (km)	Speed (km/h)	CO_2 (g/km)			NO_X (g/km)		
			PEMS	VSP	Model (1)	PEMS	VSP	Model (2)
1 - N109_N109	12.122	43.9 ± 3.3	181 ± 63	155 ± 9	162 ± 21	1.3 ± 0.8	0.7 ± 0.1	0.6 ± 0.1

2 - N109_A29_N109	14.758	94.2 ± 2.9	204 ± 26	155 ± 7	163 ± 15	1.9 ± 0.2	1.1 ± 0.1	0.7 ± 0.2
4 - N109_A1_N109	17.401	83.8 ± 2.3	237 ± 35	159 ± 2	164 ± 24	2.2 ± 0.3	1.0 ± 0.1	0.7 ± 0.2

Results show real CO_2 emissions are inflated almost 40% when compared to the regulated level, and that both VSP and COPERT-based models clearly underestimate on-road emission values. Focusing on VSP and COPERT-based results, these suggest Model (1) reflects better variability on data for CO_2 emissions. Regarding NO_X, Model (2) performs less well than expected, which may be due to be unable to account accurately for stop-and-go cycles that have significant impact on NO_X emissions (Fernandes, Coelho, & Rouphail, 2017).

3.3. Multi-objective Dynamic Traffic Assignment Simulation

The traffic data and intercity corridor geometry were coded into Vissim (Fig. 2). Traffic demands were coded in the form of origin-destination matrix. The model was calibrated using the collected data (traffic volumes, travel time) to better approximate the real-world driving conditions and the movements across the network, and driving behaviour parameters were adjusted for each coded link. It was validated by comparing the estimated and observed traffic flows and travel time using Geoffrey E. Havers statistic and Mean Absolute Percent Error (Fernandes et al., 2017). Traffic count in specific sections of the network resulted on average, 90% of passenger vehicles and LDV. Thus, the study focused on these vehicles, considering the local fleet distribution: 39% and 40% petrol and diesel passenger cars, respectively, and 21% LDV (Emisia SA, 2018). The DTA simulation-based model involved a 30min warm-up period, and data extracted only for the remaining 60min. Analysing the traffic model, around 500-600 vehicles (per hour) had their zones of origin and destination within the study area. Two different TA simulation cases were conducted with: C1) travel time concerns, and C2) time, distance travelled and environmental concerns. For both cases, system-wide CO_2 and NO_X emissions were estimated. Results are reported in the following table, while average trade-offs between the efficiency, climate and air quality objectives are presented in Table 3.

Table 2. Multi-objective DTA results for each simulation case and associated pollutant emissions.

Route	Length (km)	Volumes (vph)		CO_2 (Kg)		NO_X (Kg)	
		C1	C2	C1	C2	C1	C2
1 - N109_N109	12.122	26	74	64.91	177.35	0.15	0.42
2 - N109_A29_N109	14.758	35	0	96.80	0.00	0.28	0.00
3 - N109_A29	14.753	18	18	48.56	49.83	0.15	0.16
4 - N109_A1_N109	17.401	13	0	39.98	0.00	0.11	0.00
5 - N109_A1	16.452	17	17	48.02	46.90	0.14	0.14
6 - A25_N109	12.835	4	19	8.58	49.74	0.02	0.12
7 - A25_A29_N109	15.057	15	0	42.79	0.00	0.13	0.00
8 - A25_A29	14.954	244	244	694.31	711.90	2.11	2.20
9 - A25_A1_N109	17.700	0	0	0.00	0.00	0.00	0.00
10 - A25_A1	16.751	175	175	541.47	529.06	1.54	1.55

Considering the results of the modelling and emission estimation, it is important to stress that significant emission reductions can be achieved by assigning traffic with efficiency, climate and air quality concerns, when compared with the scenario just focused on minimizing system-wide travel time. It can be observed that different optimal traffic distributions are obtained for C1 and C2. In particular, in the latter, more volume is assigned to Routes 1 and 6, when compared to C1 and in essence, the routes with destination points on highway sections are preferable.

Table 3. System-wide average trade-offs between both cases.

System level	Efficiency		Climate Change	Air Quality
	Travel Time (min)	Distance Travelled (km)	CO_2 (ton)	NO_X (Kg)
C1	6584.321	8460.543	1.585	4.641
C2	6765.431	8236.663	1.564	4.589
Trade-offs	+2.75%	-2.65%	-1.3%	-1.14%

From the results reported on Table 3, assuming just 1 hour per day along a year for the same travel demand 500-600 vehicles every hour, it is possible to save approximately 7.5ton of CO_2 and 20Kg of NO_X accepting an average increase of 20sec per vehicle, which seems not significant in trips that take 9-17 minutes.

4. Conclusions and Future Research

Traffic models play an important role for application of traffic management measures. The core of this work is to present a multi-objective DTA tool to evaluate network performance, embedding simple traffic emission estimate models in a traffic modelling tool to predict reliable traffic flows for a DTA with environmental concerns. First, a simplified way of adopting COPERT for estimating global (CO_2) and local (NO_X) pollutants for different vehicle types and driving conditions (urban, rural, highway) was compared with VSP model results. Results show none of these models is able to capture CO_2, but specially NO_X values in an effective way when compared to real emissions obtained with PEMS. Then, COPERT-based functions were embedded in a multi-objective DTA simulation-based approach through Vissim COM API using Matlab. In particular, the proposed tool allows to assess network performance over three components: efficiency (total travel time and distance travelled), climate change (total CO_2 emissions) and air quality (total NO_X emissions) impacts. This was applied in a case study for a realistic network to simulate a typical day network conditions at the system-wide level. Results show the objectives of efficiency, climate and air quality are mainly aligned. The solution that optimizes these objectives results in approximately 3% higher travel times, but yields savings in distance travelled around 3%, and 1% for CO_2 and NO_X emissions. For the presented case study, the optimal solution does not make use of all available routes. In particular, those with destination points on highway sections are preferable to assign the most of traffic.

This study shows COPERT-based models yield quite similar results to VSP. The advantage lies in being less data intensive and estimations can be obtained down to the link level. This can be of particular interest if a limited number of road traffic variables is known. The proposed multi-objective DTA framework is a suitable tool to support traffic planning and management analyses for sustainable transport policies and may be used, for instance, as an environmental impact component of a pricing scheme, traffic signal control strategies based on emissions reduction, or to minimize congestion by giving prior information to drivers on the specific routes to be chosen.

It should be mentioned that since it is expected that on-road fleets will become cleaner, the COPERT-based emission estimate models can be easily updated with new car fleet data to better reflect the current situation. Next step is to create a graphical user interface and then, the proposed framework can be incorporated into a practical and computationally efficient model that can be used for intelligent transport system applications.

This study was conducted for specific local traffic situations and can only partially validate the suggested multi-objective DTA. Thus, future research will focus on exploring different traffic conditions and more complex networks for an overall model evaluation. Additionally, the suggested multi-objective approach can be improved by considering a safety component, possibly relying on the number of accidents and/or population exposure per road type and calculated using a risk-based safety model, and also a traffic noise component. Since microscopic simulation can be computationally intensive depending on the level of network detail, a further improvement may be incorporation of mesoscopic simulation models.

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