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Routing Strategy Including Time and Carbon Dioxide Emissions: Effects on Network Performance

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ABSTRACT

Traffic congestion leads to delays and increased carbon dioxide (CO_2) emissions. Traffic management measures such as providing information on environmental route costs have been proposed to mitigate congestion. Multi-criteria routing dynamic traffic assignment (MCR-DTA) models are needed to evaluate the effectiveness of such measures. This paper presents a simulation-based bi-level optimization method to solve the MCR-DTA problem, which works as follows. Route costs include travel times and emissions, but those are updated inside two different loops. In the inner loop, emission costs are considered fixed; the assignment is performed by updating route travel times, using a traditional DTA tool. Then, in the outer loop, emissions are calculated based on link loads and fed back to the DTA tool, which performs a new assignment. The MCR user equilibrium is found when emissions or predefined generalized costs converge to an equilibrium. The bi-level method is first tested on a small network, showing that the proposed method is able to effectively solve the MCR-DTA problem. Next, the method is applied to a medium-size urban network. The results show that if drivers choose routes based on emissions besides travel time, the average travel time and emissions per vehicle decrease. This occurs because congested links have a higher impact on route costs; hence the equilibrium is pushed away from the single-criteria routing (SCR) user optimum towards the SCR system optimum. Results support the conclusion that informing drivers about CO_2 emissions per route can potentially lead to decreased delay and emissions in real networks.

1 INTRODUCTION

With the rapid increase in road transport, big cities are suffering from severe traffic congestion and air pollution. According to the 2007 European Commission Database, road transport is responsible for about 20% of all carbon dioxide (CO_2) emissions within the European Union, with passenger cars contributing about 12%. It is well known that the CO_2 emissions produced by vehicles increase when traffic becomes congested. Results from real driving tests *(1, 2)* show that CO_2 emissions increase rapidly as traffic speeds fall below 30 mph (48 km/h). When traffic speed drops from 30 mph to 12.5 mph, CO_2 emissions double. Therefore, mitigating traffic congestion can significantly reduce CO_2 emissions.

One way to address rising traffic congestion and environmental problems is to use Dynamic Traffic Management (DTM) measures. DTM measures regulate traffic flows on the basis of real-time information with the objective of making better use of the existing road network capacity, improve traffic safety and reduce CO_2 emissions. Within DTM measures, the use of network-wide DTM measures has increased considerably in the last years *(3)*. Examples of DTM measures include incident management, signal control and traveler information.

Various studies show that providing trip-specific information on environmental costs to travelers influences their route choice behavior in such a way that they adopt a more sustainable behavior. To evaluate the potential benefits of traveler information measures on the overall performance of road networks, it is often necessary to use multi-criteria routing dynamic traffic assignment (MCR-DTA) models. However, standard DTA models do not include traffic emission models, and most previous MCR-DTA models with route cost functions including CO_2-emission costs cannot guarantee stability. We propose to solve the multi-criteria routing DTA problem by means of a bi-level optimization method.

This paper investigates the effects that providing information to drivers about the emission costs of route alternatives may have on network performance, extending the analysis carried out in *(4)*. A simulation-based bi-level optimization method is used to solve the MCR-DTA problem. The method requires: i) a standard single-criteria routing dynamic traffic assignment model able to incorporate fixed external link costs; and ii) a CO_2-emission model. First, the proposed bi-level method is tested on a small network in order to verify that the method is able to effectively solve the multi-criteria routing dynamic traffic assignment (MCR-DTA) problem. Next, the method is applied to a realistic medium-size urban network (corresponding to the road network of Helmond, the Netherlands) in order to investigate the effects of a multi-criteria routing strategy on network performance.

This paper is organized as follows. Section 2 contains some background information on route choice behavior and multi-criteria routing traffic assignment models. Section 3 presents the method used in this research to solve the MCR-DTA problem. Section 4 presents the setup and results of the small-network experiment aimed to test the effectiveness of the method. Section 5 presents the setup and results of the medium-size urban network experiment aimed to determine the effects of the proposed multi-criteria routing strategy on network performance. Finally, Section 6 presents the conclusions of this paper.

2 BACKGROUND

Several studies show that providing trip-specific information to travelers (e.g., information on environmental costs) externally influences their perceptions and route choice behavior *(5, 6, 7)*. Bogers *et al. (5)* developed a conceptual framework of route choice behavior and performed a series of interactive travel simulator experiments that showed that travel informantion play a major role in route choice behavior. Gaker *(6)* performed various experiments and surveys and found that access to personalized trip-specific information regarding greenhouse gas emissions induces travelers to adopt a more sustainable behavior. Chen *et al. (7)* carried out numerous surveys and found that if available routes have comparable travel time and out-of-pocket costs, travelers prefer to choose the most environmentally friendly route.

In transportation modeling, traffic assignment concerns the selection of routes between origins and destinations in transportation networks. Traditional traffic assignment models, such as Dynasmart-P, assume that drivers choose routes based mainly on the travel time of each available route. Those models assign flows to the network solely on the basis of that criterion. However, that is not entirely accurate. As mentioned above, in reality drivers do not choose routes only on the basis of route travel times. If information is available and presented in an adequate manner, drivers generally take into account other criteria as well, such as CO_2 emissions *(6, 7)*.

Efforts to include environmental costs in traffic assignment models date back to the 1990's, when static assignment models were modified to accommodate multi-criteria route choice strategies including that type of costs. Generally, multi-criteria routing traffic assignment models calculate a *generalized* cost for each available route. The generalized cost is constructed by adding the individual costs corresponding to each relevant variable, e.g., travel time and CO_2 emissions. In order to construct the generalized cost, it is necessary to convert all relevant variables to the same units (generally, monetary units). The most common conversion factors for travel time and greenhouse gas emissions are value-of-time (VoT) and value-of-green (VoG), respectively. The value-of-time (VoT) indicates the monetary worth of time for travelers. A recent study shows that in the Netherlands the VoT corresponding to trips made for commuting and business purposes are 9.25 €/h and 26.25 €/h, respectively *(8)*. Analogously, the value of green (VoG) was introduced to describe the monetary worth of greenhouse gas emissions for travelers. Gaker *et al. (6)* found that the value of greenhouse gas emissions for drivers is around 0.4 €/kg.

To the best of our knowledge, the first traffic assignment model with multi-criteria routing was introduced by Quandt *(9)*. That model was extended by Schneider *(10)*. Both models assume that travelers select their optimal routes based on several criteria, such as travel time and travel cost. However, those costs are assumed to be fixed, i.e., independent from the traffic flows on the route. A flow-dependent model was later introduced by Dafermos *(11)*, who took into account congestion effects and obtained an infinite-dimensional variational inequality formulation of the multi-class and multi-criteria traffic network equilibrium problem. Adler *et al. (12)* used a simulation method to evaluate the impacts of bi-objective routing strategies on user and system performance. Travel cost is defined as the linear weighted additive sum of travel time and monetary cost. Tzeng *et al. (13)* developed a framework for multi-criteria routing traffic assignment in which route choice behavior is influenced by travel time, travel distance and pollutant emissions. Wismans *et al. (14)* used a bi-level method to solve the multi-criteria routing problem. Nagurney *et al. (15)* developed a multi-class and multi-criteria network equilibrium model in which travelers are assumed to choose routes on the basis of various criteria, including an environmental criterion. Nagurney *et al.* prove that a solution exists and is unique, provided that the cost function is monotone.

The most important limitation of those models is that they update all individual costs that are part of the generalized route costs simultaneously during the assignment process. Adding one extra cost component without consistency may cause too big changes in the network states and destabilize the updating process, which can make it difficult for the model to find an equilibrium solution. Also, it is important to remark that most existing DTA software packages (e.g., Dynasmart) do not contain any traffic emission model, hence it is impossible for them to incorporate CO_2 emissions into the route costs. Finally, it is difficult to use an analytical approach to solve the MCR-DTA problem for large-scale networks.

Because of all that, the most effective way to perform a MCR-DTA in a consistent way when route costs include CO_2 emissions costs is generally to use simulation-based bi-level optimization methods. With a bi-level method, a standard DTA tool is used to perform a traffic assignment keeping the emission costs fixed. Only travel time costs are updated during the assignment process. Emission costs are calculated (by means of an external traffic emission model) only after the DTA tool finds the user optimum equilibrium. Then, the emission costs are fed back to the DTA tool, which performs a new flow assignment. This process is repeated until the emission costs given as input to the DTA tool are similar to the emission costs obtained as output.

3 BI-LEVEL OPTIMIZATION METHOD TO SOLVE THE MULTI-CRITERIA ROUTING DYNAMIC TRAFFIC ASSIGNMENT PROBLEM

A simulation-based bi-level optimization method was developed to solve the multi-criteria routing dynamic traffic assignment (MCR-DTA) problem. The method requires: i) a standard single-criteria routing dynamic traffic assignment model able to incorporate fixed external link costs (FEC-DTA model); and ii) a CO_2-emission model. Route costs include travel time costs and CO_2-emission costs, but those two cost components are updated inside two different loops. The fixed-emission cost (FEC) DTA model updates the travel time costs during the traffic assignment process, while emission costs are kept constant (see Figure 1). Emission costs are computed (using the CO_2-emission model) only after the FEC-DTA model finds the user optimum equilibrium. Then, emission costs are updated and fed back to the FEC-DTA model, which performs a new flow assignment keeping those emission costs fixed (see Figure 1). A moving average is used to update the emission costs between two successive runs of the FEC-DTA model. Essentially, the MCR-DTA model includes an external emission-update loop. The MCR user optimum equilibrium is found when the emission costs given as input to the FEC-DTA model are similar to the emission costs obtained as output for all links and for all time intervals. The FEC-DTA model uses the the following equation to compute route costs:

$$C_{a,t}\left(r\right)= \sum_{i=1}^{\mathrm{I}}\delta_i^a\left(\mathrm{VoT}\cdot T_{i,t}\left(r\right)+\mathrm{VoG}\cdot E_{i,t}^{\mathrm{in}}\left(r\right)\right) \tag{1}$$

where: $C_{a,t}(r)$ denotes the composite cost of route a in time interval t in FEC-DTA model run r; I is the total number of links in the network; δ_i^a is a binary variable that is equal to one if link i is part of route a and is equalt to zero otherwise; $T_{i,t}(r)$ is the travel time on link i in time interval t in FEC-DTA model run r; and $E_{i,t}^{\mathrm{in}}(r)$ denotes the input emissions corresponding to link i in time interval t in FEC-DTA model run r (which are fixed).

Therefore, the simulation-based bi-level optimization method proposed to perform a dynamic traffic assignment with multi-criteria routing consists of the following steps (see also Figure 1):

1. Initially, run the FEC-DTA model to perform a traditional dynamic traffic assignment using travel time costs as route costs (so setting emission costs to zero).
2. Obtain relevant outputs, such as the equilibrium link traffic states.

3. Calculate the CO_2 emissions corresponding to every link i in every time interval t on the basis of the equilibrium traffic states ($E_{i,t}^{\text{out}}(1)$).
4. Update the input emissions. In the second FEC-DTA model run, $E_{i,t}^{\text{in}}(2) = E_{i,t}^{\text{out}}(1)$. In the third and subsequent runs, the input emissions are updated on the basis of the emissions given as output in the previous two FEC-DTA model runs using a moving average rule:

$$E_{i,t}^{\text{in}}(r) = (1-\beta)\cdot E_{i,t}^{\text{out}}(r-2) + \beta \cdot E_{i,t}^{\text{out}}(r-1) \qquad (2)$$

where: $E_{i,t}^{\text{in}}(r)$ denotes the input emissions corresponding to link i in time interval t in the r^{th} run of the FEC-DTA model; $E_{i,t}^{\text{out}}(r-1)$ and $E_{i,t}^{\text{out}}(r-2)$ are the output emissions on link i in time interval t in the $(r-1)^{\text{th}}$ and $(r-2)^{\text{th}}$ FEC-DTA model runs, respectively; and β is a weighting factor ($0 \leq \beta \leq 1$).

5. Run the FEC-DTA model to perform a traditional dynamic traffic assignment, defining the route costs as the sum of travel time costs and input emission costs ($E_{i,t}^{\text{in}}(r)$). The input emission costs are fixed costs imposed on links.
6. Obtain relevant outputs, such as the equilibrium link traffic states.
7. Calculate the CO_2 emissions corresponding to every link i in every time interval t on the basis of the equilibrium traffic states ($E_{i,t}^{\text{out}}(r)$).
8. Compare the output emissions with the emissions used as input to calculate the route costs in the same FEC-DTA model run. If the difference falls within the convergence threshold, stop the process. Otherwise, go back to step 4.

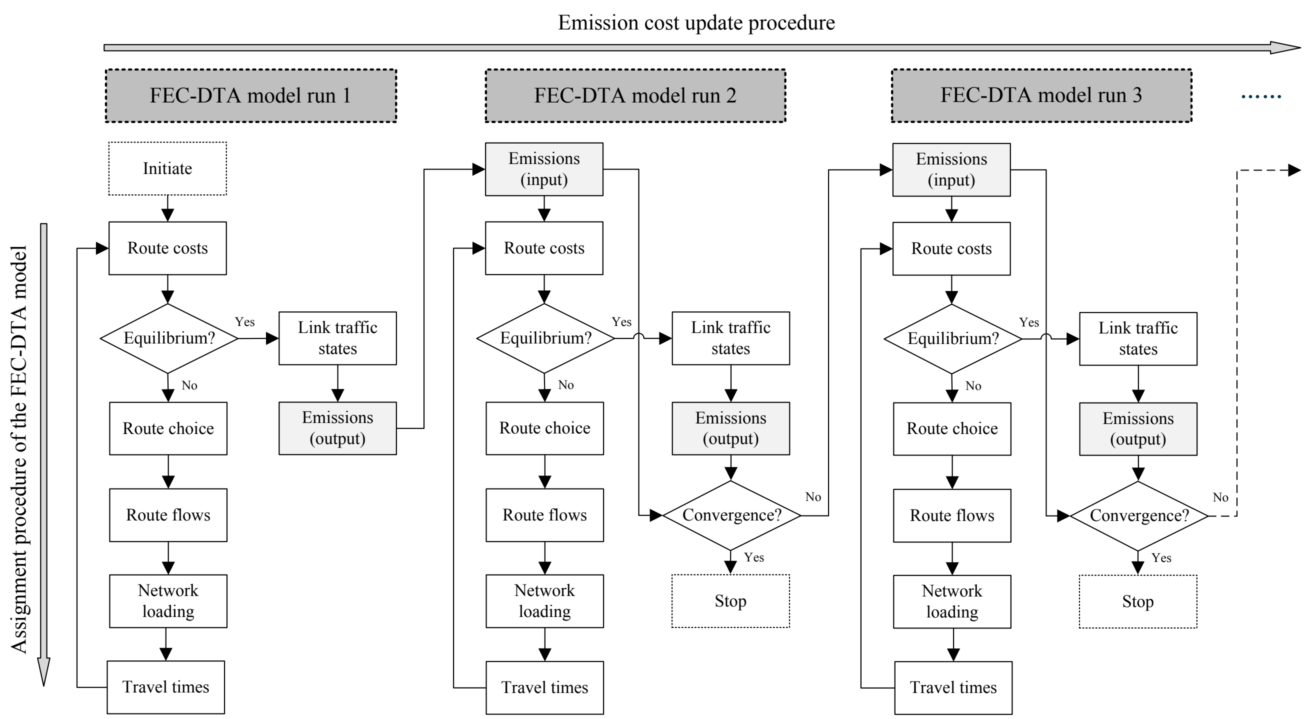


FIGURE 1 Conceptual flow chart of the bi-level optimization method used to solve the dynamic traffic assignment problem with multi-criteria routing

4 SMALL-NETWORK EXPERIMENT

A small-scale experiment was carried out to verify the effectiveness of the proposed bi-level method in solving the MCR-DTA problem before applying it to a realistic urban network. Also, it is easier to check whether the method works as intended by testing first the method on a small network. Section 4.1 describes the setup of the experiment, and Section 4.2 presents the results.

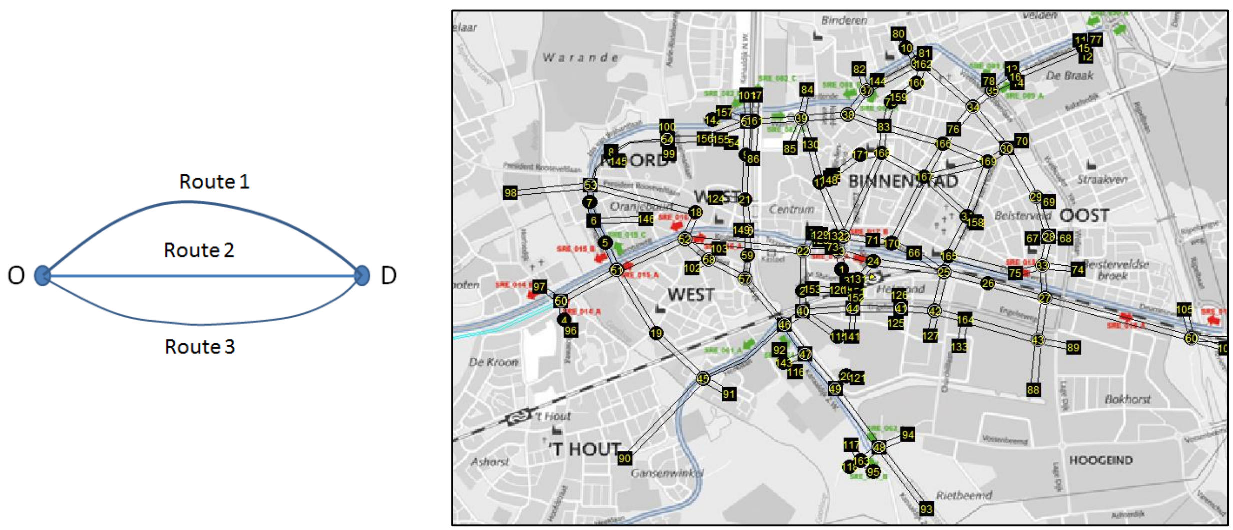
4.1. Experimental setup

A test network is defined consisting of three links between one origin and one destination (see Figure 2a). Therefore, there exist three direct routes between that OD pair (each route consists of a single link). A simple model that uses the bi-level method described in Section 3 (built in Matlab) is used to solve the multi-criteria routing DTA problem for that network. The MCR-DTA model includes: i) a fixed-emission cost (FEC) DTA model; and ii) a CO_2-emision model.

The FEC-DTA model works in a similar way to Dynasmart-P (which is the FEC-DTA model used in the medium-size urban network experiment). The FEC-DTA model uses a single-regime modified Greenshields function to model traffic flow in the network. The model determines the traffic speed on a specific link i (v_i) on the basis of the density on that link (k_i):

$$v_i = v_0 + \left(v_{\mathrm{f}} - v_0\right) \cdot \left(1 - \frac{k_i}{k_{\mathrm{jam}}}\right)^{\alpha} \tag{3}$$

The traffic flow model has four parameters: free-flow speed (v_{f}), jam density (k_{jam}), minimum speed (v_0) and a power factor (α). Note that the FEC-DTA model calculates the travel time on a link in a specific time interval by diving the link length (L_i) by the traffic speed on that link. Specifying a minimum speed in the traffic flow model prevents traffic speeds from becoming zero, which is necessary to avoid infinite link travel times. Table 1 specifies the traffic flow model parameter values for the three links.



a) Small network b) Medium-size urban network (in Dynasmart-P)

FIGURE 2 Networks.

The CO_2-emission model is based on the data-driven model presented by Barth and Boriboonsomsin *(1)*. The CO_2-emission model calculates the CO_2 emissions on link *i* in time interval *t* by means of a function of the average running speed on that link:

$$E_{i,t}^{\text{out}} = \exp\left(b_0 + b_1 \cdot v_{i,t} + b_2 \cdot v_{i,t}^{\;2} + b_3 \cdot v_{i,t}^{\;3} + b_4 \cdot v_{i,t}^{\;4}\right) \tag{4}$$

where $E_{i,t}^{\text{out}}$ is the output CO_2 emissions (in g/mi) and v_i is the traffic speed (in mi/h). The values of the coefficients in Equation 4 are: $b_0 = 7.61$ g/mi; $b_1 = –0.14$ gh/(mi^2); $b_2 = 3.9\cdot10^{–2}$ gh^2/mile^3; $b_3 = 4.9\cdot10^{–5}$ gh^3/mi^4; and $b_4 = 2.4\cdot10^{–7}$ gh^4/mi^5.

TABLE 1 Traffic flow model parameter values per link (small-network experiment).

	L (km)	v_f (km/h)	v_0 (km/h)	k_{jam} (veh/km)	α
Route 1	20	90	1	150	1.5
Route 2	24	105	1	170	1.5
Route 3	28	120	1	220	1.5

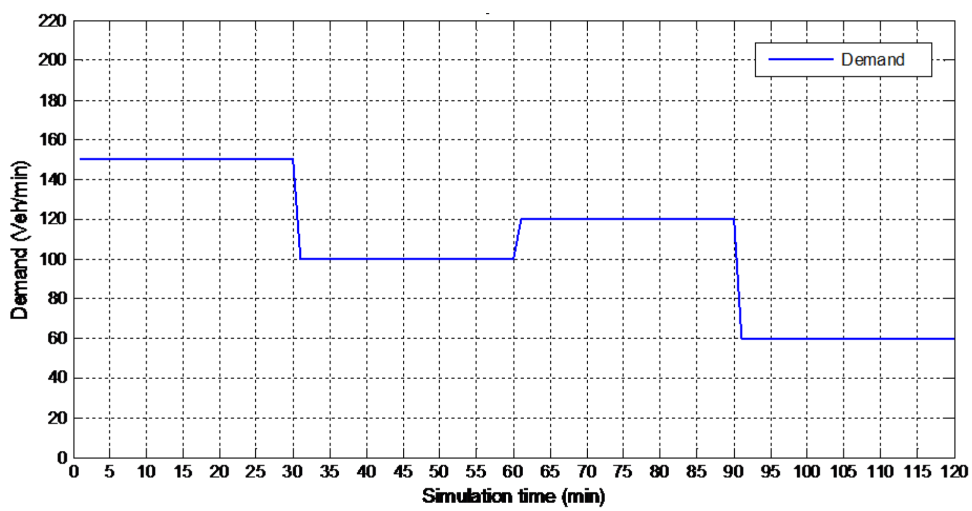


FIGURE 3 Traffic demand in the small-network experiment.

The simulation period consist of 120 time intervals, each 1 min long. The traffic demand in each time interval is shown in Figure 3. VoT and VoG are set to 10 €/h and 0.4 €/kg, respectively, in line with references (*6*) and (*8*). The value of parameter β of Equation 2 is set to 0.5. The emission convergence threshold is 5%. The maximum number of emission cost update iterations is set to 60.

To evaluate the effectiveness of the MCR-DTA model, we use the following indicators, whose input are the results of the last run of the FEC-DTA model: i) sum, mean, standard deviation and variance of the differences between CO_2 emissions given as input to the FEC-DTA model and CO_2 emissions obtained as output in every time interval per link; ii) root-mean-square error (RMSE) of the CO_2 emissions given as input to the FEC-DTA model compared with the CO_2 emissions obtained as output in every time interval per link. RMSE is frequently used to evaluate the differences between values predicted by a model or an estimator and observed values using a single indicator.

4.2. Results

The MCR user optimum equilibrium is found after the sixth run of the FEC-DTA model. Table 2 shows the total input and output emissions in each FEC-DTA model run. As seen in Table 2, the difference between total input and output emissions decreased after almost each SCR-DTA run. In the sixth MCR condition, the difference is very small (less than -0.005%).

TABLE 2 Input emissions and output emissions in each run of the FEC-DTA model

FEC-DTA model run	Input emissions (kg)	Output emissions (kg)	Absolute difference (kg)	Relative difference (%)
1	0	1763.522	1763.522	100.00
2	1763.522	1787.745	24.223	1.37
3	1775.633	1783.802	8.169	0.46
4	1779.718	1788.129	8.411	0.47
5	1783.923	1783.084	-0.840	-0.05
6	1783.504	1783.494	-0.010	-0.00

We calculated the sum, mean, standard deviation and variance of the differences between input emissions and output emissions in every time interval in the sixth FEC-DTA model run per link. As seen in Table 3, the values of all those indicators are quite small for all three routes. This indicates that the difference between input emissions and output emissions is very small in all simulation time intervals.

The RMSE was used to determine the average magnitude of the errors between input and actual emissions in every time interval in the sixth run of the FEC-DTA model per link. A lower value indicates less variance and hence a better match. As seen in Table 3, the RMSE is very small for all routes, which indicates that after the sixth run, the output emissions are very close to the input emissions in all links.

TABLE 3 Summary statistics (last run of the FEC-DTA model)

		Route 1	Route 2	Route 3
Differences between input and output CO_2 emissions in all links (kg)	Sum	0.4581	-0.0631	0.6433
	Mean	0.0038	-0.0005	0.0054
	Standard deviation	0.0133	0.0053	0.0244
	Variance	0.0002	0.0000	0.0006
Input and output CO_2 emissions in all links (kg)	RMSE	0.0136	0.0053	0.0249

To sum up, the results of the small-network experiment show that the proposed bi-level method is able to effectively solve the multi-criteria routing dynamic traffic assignment problem, at least for small networks. The method finds a user optimum equilibrium in which the composite costs of all used routes (which include travel time costs and CO_2 emission costs) are similar in all simulation time intervals.

5 MEDIUM-SIZE URBAN NETWORK EXPERIMENT

The experiment presented in Section 4 shows that the proposed bi-level method is able to solve the multi-criteria routing DTA problem for a small network. In this section, we perform a multi-criteria routing DTA for a realistic medium-size urban network, and we analyze the effects that taking into account CO_2 emission costs in the routing strategy has on network performance. Section 5.1 describes the setup of the experiment and Section 5.2 presents the results.

5.1. Experimental setup

The MCR-DTA model includes a fixed-emission cost (FEC) DTA model and a CO_2-emision model. As FEC-DTA model we use a mesoscopic DTA model based on Dynasmart-P *(16)* that was developed and calibrated for the city of Helmond (the Netherlands) by TNO (Netherlands Organisation for Applied Scientific Research) in the eCoMove project (EU Framework Programme 7). The OD demand corresponds to the morning peak (from 8:00 AM to 10:00 AM) on a workday. The simulation time interval is 6 seconds, i.e., flows and network states are updated every 6 seconds.

Figure 2b shows the features of the network in Dynasmart-P. The network is 2.0 km long from south to north and 3.8 km long from west to east. It consists of 78 zones, 171 nodes and 378 links. The links correspond to roads of the real network. Two-directional roads are represented by two links between two nodes. The characteristics of each link are described by setting parameters such as link type, length, number of lanes and speed limit. We specify 5 link types, which correspond to different types of roadways, and we assign different traffic flow models to each of them. Link type 1 (freeway) is assigned a two-regime modified Greenshields traffic flow model, whereas link types 2 to 5 are assigned single-regime modified Greenshields traffic models. The single-regime modified Greenshields traffic model is specified in Equation 3. The two-regime modified Greenshields traffic model determines the traffic speed on a specific link i (v_i) as follows:

$$v_i = \begin{cases} v_{\text{f}} & \text{if} \quad 0 \le k_i < k_{\text{c}} \\ v_0 + \left(v_{\text{f}} - v_0\right) \cdot \left(1 - \dfrac{k_i}{k_{\text{jam}}}\right)^{\alpha} & \text{if} \quad k_c \le k_i \le k_{\text{jam}} \end{cases} \tag{5}$$

where k_{c} denotes the breakpoint traffic density. The parameter values of the traffic flow models assigned to each link type are listed in Table 4.

TABLE 4 Traffic flow model parameter values per link type (urban network experiment)

	Link type				
	Type 1: Freeway	Type 2: Arterial	Type 3: Minor arterial	Type 4: Local road	Type 5: Local road
Number of regimes	2	1	1	1	1
v_{f} (mi/h)	75	62	44	31	19
v_0 (mi/h)	6	10	10	10	10
k_{c} (pcu/mi/lane)	30	N/A	N/A	N/A	N/A
k_{jam} (pcu/mi/lane)	200	160	120	90	90
α (unitless)	2.0	1.0	2.0	3.0	3.5

CO_2 emissions are calculated by means of the TNO macro emission module, which is based on the Versit+ model *(17)*. The Versit+ model calculates emissions based on average link speeds and lookup tables. Based on the findings of previous studies (*6, 8*), the value-of-time is set to 15 €/h and the value-of-green is set to 0.4 €/kg. The value of parameter β is 0.5. The emission convergence threshold is 5%. Since it may be hard to achieve complete convergence on a large-scale network, the maximum number of emission cost update iterations is set to 30.

We define a single-criterion routing (SCR) scenario (reference scenario) and a multi-criteria routing (MCR) scenario. In the reference scenario, drivers use a single-criterion routing (SCR) strategy to choose routes. That is the routing strategy used in traditional DTA models, which only includes travel time in the route cost function. In the MCR scenario, drivers use a routing strategy that takes into account travel time and CO_2 emissions. We perform ten replications of the DTA (with different random seeds) for each scenario.

In addition, we analyze the sensitivity of the DTA results in the MCR scenario to the ratio between VoT and VoG. Different ratios were specified in Dynasmart-P through different combinations of VoT and VoG. The default VoT/VoG ratio in the MCR scenario is 37.5 kg/h (15 €/h divided by 0.4 €/kg). The ratio between VoT and VoG is a relevant measure because it indicates the extent to which people may adapt their routes in order to decrease their CO_2 emissions if the travel time is longer: the VoT/VoG ratio indicates how many kilograms of CO_2 emissions a traveler should save in order to accept a one-hour increase in travel time.

Four indicators are used to evaluate the network performance in each scenario: i) average travel time per vehicle; ii) average trip distance per vehicle; iii) average CO_2 emissions per vehicle; and iv) trip completion rate.

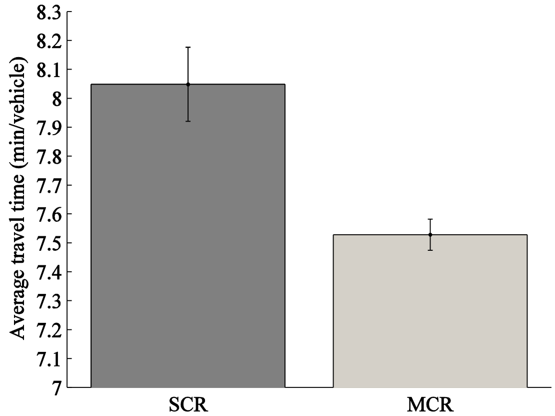
5.2. Results

5.2.1. Comparison between SCR scenario and MCR scenario

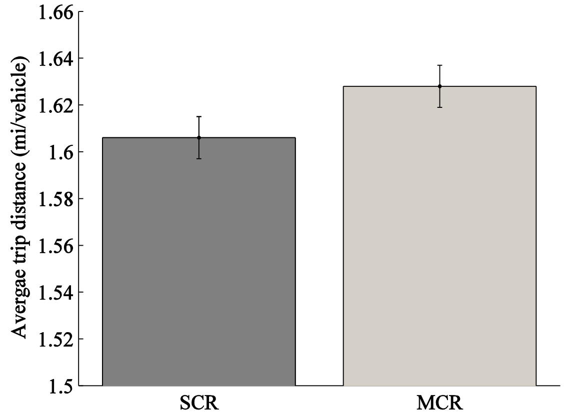
A summary of the values of the network performance indicators in the SCR and MCR scenarios (mean and standard deviation of the ten replications) is shown in Figure 4. In most replications of the MCR scenario, the input and output CO_2 emissions converge before the maximum number of runs is reached. In the remaining replications, the input and output emissions are close to convergence when the MCR-DTA model stops.

As shown in Figure 4d, the trip completion rate is considerably higher in the MCR scenario (around 94.0%) than in the SCR scenario (around 91.8%). An increased trip completion rate means that more vehicles reach their destinations within the simulation period. The reason is that the congestion level in the network is lower in the MCR scenario. Because of the lower level of congestion, in the MCR scenario the average travel time is 6.5% lower than in the SCR scenario (see Figure 4a), and the CO_2 emissions are 3.3% lower (see Figure 4c). The average trip distance is 1.4% longer in the MCR scenario than in the SCR scenario (see Figure 4b), which means that drivers choose slightly longer routes in the MCR scenario. The patterns observed in the DTA results in the SCR and MCR scenarios are similar in all replications with different random seeds.

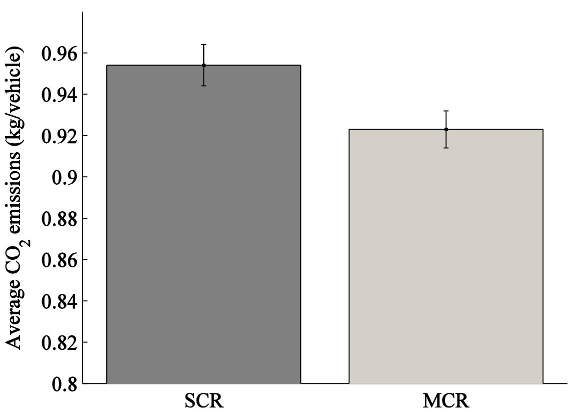
Boyce and Xiong *(18),* who conducted experiments about user-equilibrium (UE) and system-optimum (SO) route choice in a large-scale network, found that in large and congested road networks, shifting flows from UE to SO behavior can save up to 5% total travel time with a 1.5% increase in travel distance. Interestingly, our results show similar patterns: when CO_2 emissions are effectively taken into account in the route choice cost function, traffic spreads more efficiently over the network and average travel time (and average emissions) decrease, whereas the average trip distance slightly increases. Our results confirm that emissions can be used as feedback in the DTA procedure and can help improve network routing efficiency. An adequate composition of cost influences travel behaviour and, thus, route choice. Since traffic emissions are higher in congestion, adding the emission cost term mimics a marginal cost term, hence pushing the user equilibrium towards the system optimum equilibrium. Therefore, in the MCR scenario, total travel times are lower than in the SCR scenario.



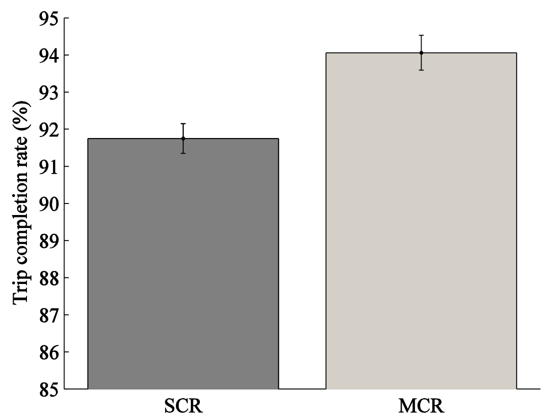
a) Average travel time: mean (bars) ± standard deviation (whiskers)



b) Average trip distance: mean (bars) ± standard deviation (whiskers)



c) Average CO_2 emissions: mean (bars) ± standard deviation (whiskers)



d) Trip completion rate: mean (bars) ± standard deviation (whiskers)

FIGURE 4 Network performance in the SCR and MCR scenarios.

5.2.2. Sensitivity analysis (MCR scenario)

The ratio between VoT and VoG indicates the extent to which people adapt their routes in order to decrease their CO_2 emissions if the travel time is longer. Figure 5 shows a summary of the values of the network performance indicators in the MCR scenario with different VoT/VoG ratios. In most cases, the input and output emissions converge before the maximum number of runs is reached. In the remaining replications, the input and output emissions are close to convergence when the MCR-DTA model stops.

The results show that modifying the VoT and VoG in the composite route cost function has significant effects on network performance (see Figure 5). Adding CO_2 emissions to the route costs with a VoT/VoG ratio equal to or lower than 1 kg/h leads to poorer network performance than in the SCR scenario (reference). However, that is a very low ratio. The default VoT/VoG ratio in the MCR scenario is 37.5 kg/h, which is considered a reasonable ratio according to the scientific literature (see Section 2). The results of the sensitivity analysis show that with a VoT/VoG ratio from 2 to 500 kg/h, adding CO_2 emissions to the route cost function improves network performance in comparison with the single-criteria routing scenario (in a similar way to what was explained in Section 5.2.1). As shown in Figure 5, within that range of VoT/VoG ratios, the average travel time and average CO_2 emissions per vehicle are lower and the trip completion rate is higher than in the SCR scenario (reference). The most satisfying network performance is observed when the VoT/VoG ratio has a value between 2 and 37.5 kg/h.

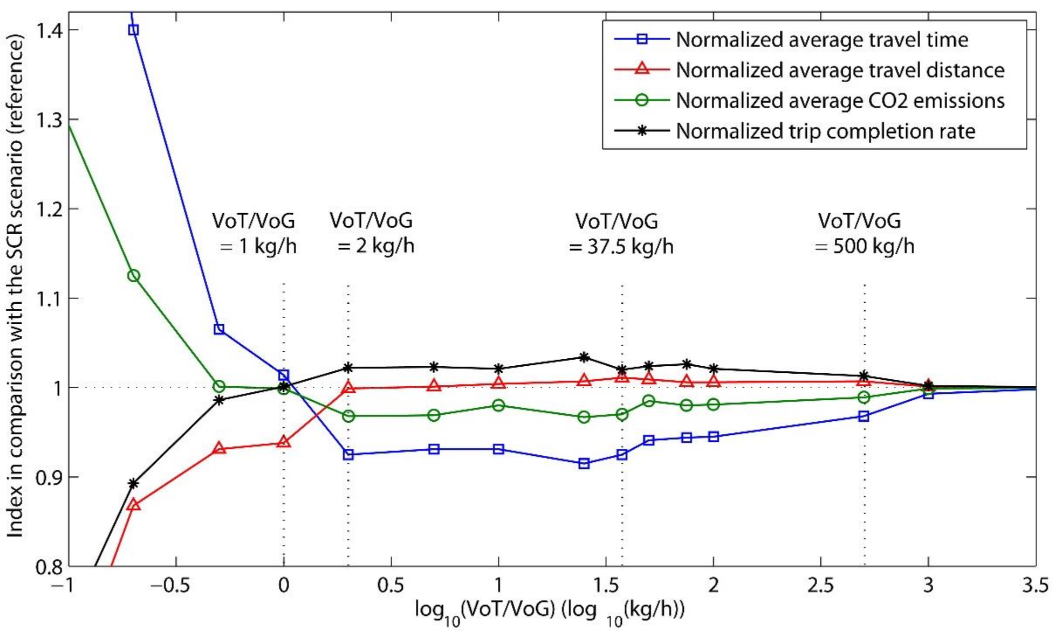


FIGURE 5 Network performance with different VoT/VoG ratios. Note that the scale of the horizontal axis is logarithmic. The reference case corresponds to the single-criteria routing scenario (in which emission costs are not included in the route cost function)

To summarize, the results of the sensitivity analysis confirm that if drivers take into account CO_2 emissions when choosing routes, network performance improves, even if we assume different values-of-time and different values-of-green (within a certain range of reasonable VoT/VoG ratios). Adding CO_2 emissions in the route choice cost function makes traffic spread more efficiently over the network and maximizes the use of the network capacity, which reduces traffic congestion and CO_2 emissions.

6 CONCLUSIONS

The aim of this research was to perform a preliminary evaluation of the effects that providing information to drivers about the emission costs of route alternatives may have on network performance. A simulation-based bi-level optimization method was developed to solve the multi-criteria routing dynamic traffic assignment (MCR-DTA) problem with route costs consisting of travel time costs and CO_2-emission costs. A small-network experiment showed that the proposed method is able to solve the MCR-DTA problem in a consistent and effective way.

The results of a medium-size urban network experiment indicated that when drivers choose routes taking into account CO_2 emissions, traffic spreads more efficiently over the network, and the average travel time and emissions per vehicle decrease. The reason why this occurs is as follows. Since traffic emissions are higher in congestion, adding the emission cost term in the route cost function is equivalent to adding a marginal travel time cost term. As a result, the user optimum equilibrium is pushed towards the system optimum equilibrium. A sensitivity analysis showed that modifying the ratio between value-of-time (VoT) and value-of-green (VoG) in the composite route cost function has significant effects on network performance. However, the analysis confirmed that network performance improves if drivers take into account CO_2 emissions when choosing routes, even if we assume different values-of-time and different values-of-green (within a certain range of reasonable VoT/VoG ratios).

This study is a starting point in the evaluation of route information measures with multi-criteria routing DTA models. Further research is necessary to understand and explain better from a theoretical point of view how multi-criteria routing strategies can improve the performance of road networks, and how route information measures can be implemented in real road network traffic control and operations. Furthermore, it is necessary to analyze the effects of more comprehensive multi-criteria routing strategies, such as strategies that consider reliability, safety, comfort and other route choice criteria. Finally another important point for further research is the development and evaluation of advanced DTA tools that are capable of updating all individual costs included in the route cost function (e.g., travel time costs and emission costs) simultaneously during the assignment process and solve the MCR-DTA problem in a consistent and effective way.

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