Is marginal emission cost pricing enough to comply with the EU CO_2 reduction targets?

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Abstract

From transport economic literature it is known that pricing (environmental) externalities can improve the efficiency of a transport system. However, in real-world politics, policy setting often follows so-called 'backcasting' approaches where predefined goals are set, and policy measures are implemented to reach those goals. This study presents, for a specific case study, an parametric approach to identify the gap between toll levels derived from environmental damage cost internalization and toll levels from the goal to reduce global greenhouse gas emissions in the transport sector until 2020 by 20% (avoidance cost approach). For this purpose, the damage costs internalization is applied to a real-world scenario of Munich metropolitan area. The results indicate that the desired reduction in CO_2 emissions is not reached. This parametric internalization approach with damage cost estimates from the literature yields toll levels that are by a factor of 5 too low in order to reach the predefined goal. When aiming at overall emission cost reductions by 20%, the damage cost estimates are even by a factor of 10 too low. Furthermore, it is shown that the major contribution to the overall emission reduction stems from behavioral changes of (reverse) commuters rather than from urban travelers; under some circumstances, the latter even increase their CO_2 emission levels. Finally, the study indicates that there might be conflicting trends for different types of pollutants, i.e. pricing emissions does not necessarily result in a reduction of all pollutant types.

Keywords: Air Pollution, Vehicle Emissions, Marginal Cost Pricing, Backcasting

1 Introduction and problem statement

Rapid urbanization has led to significant increases of transport-related negative externalities (e.g. emissions, congestion, accidents, noise etc.). The costs of these externalities can amount to a considerable share of a country's GDP (Gross Domestic Product). For example, the total external costs of transport excluding congestion costs for EU plus Norway and Switzerland in 2008 add up to more than 500 billion EUR – 4% of the total GDP – and the congestion costs of road transport ranges between 146 and 243 billion EUR, i.e. 1 to 2% of the total GDP (van Essen et al., 2011).

Transport systems operate inefficiently unless the costs of these externalities are borne by the responsible households and firms. For almost a century, it is known that internalizing external effects by a tax can change users' behavior and increase overall benefits (Pigou, 1920). Therefore, many past contributions investigated the impact of internalizing external costs. Some studies focus on finding theoretically optimal congestion tolls (see, e.g., Vickrey, 1969; Henderson, 1974; Arnott et al., 1993), and other studies examine the effect of congestion pricing strategies on emission levels (see, e.g., Daniel and Bekka, 2000; Beevers and Carslaw, 2005). Substantially less effort has been undertaken to develop exhaust emission internalization strategies, or to evaluate the impacts of environmental pricing strategies on congestion (see, e.g., Kickhöfer and Nagel, 2013; Wang et al., 2014). Very little research has focused on combined pricing schemes, even though it is well known that these different external effects of transportation are positively correlated (see, e.g., Barth and Boriboonsomsin, 2009; Beamon and Griffin, 1999). This lack of research might be explained by the fact that time losses (and in consequence congestion levels) can be obtained relatively easily from standard transport simulation toolkits, but environmental impacts other than CO_2 require rather sophisticated (post-processing) models and the *true* marginal costs (and in consequence damage levels) are hard to obtain.

In real-world politics, the focus is therefore typically on so-called 'backcasting' approaches (Geurs and van Wee, 2000, 2004; IWW et al., 1998) rather than on marginal cost pricing strategies. The idea behind backcasting is to set political goals, and implement a number of policy measures in order to achieve these goals. Consequently, this procedure implicitly defines implementation (= avoidance) costs and ignores the damage cost approach from above. A prominent example of such policy setting in the European Union (EU) is the agreement to limit global warming below 2° Celsius (European Commission, 2011). In order to achieve this goal, the directive 2008/101/EC (2008) sets the goal to reduce global greenhouse gas (GHG) emissions in the transport sector by at least 20% until 2020 with respect to 1990 levels. In this context, several regulation schemes have been set up: (1) Emission trading system, (2) Use of renewable energy sources, (3) Reduction in the energy use of buildings and industries, (4) Improvement in fuel and vehicle technology. For the road transport sector, improvements in vehicle and fuel technology might play an important role. However, most estimates indicate that innovations in vehicle and fuel technology are only able to stabilize transport-related emissions (IEA, 2014). This is due to potential rebound effects where the resulting reduction in generalized costs will yield higher demand which, in turn, can (partly) neutralize the positive impact of technological improvements (Divjak, 2009; Parry and Small, 2005). Also Edenhofer et al. (2015) highlight that omitting pricing strategies and focusing on technological changes only will forgo a major part of the potential welfare improvements. Another point of concern from these innovations is the growing divergence between "type-approved" (emission tests under laboratory conditions) and on-road CO_2 emission from the vehicles (Moch et al., 2014; EEA, 2014). This gap has increased from 8% in 2001 to 38% in 2013 (Moch et al., 2014). That is, improvements in vehicle and fuel technology might not be effective under on-road conditions what might further pull back the GHG emission targets.

In the light of the above, the questions arise (i) to what extend pricing schemes, in particular the internalization of air pollution externalities, would contribute to the political goal, and (ii) how (additional) prices would need to be set in order to reach this target. Or, in other words, how different the price levels of a (best-practice) damage cost approach are compared to the backcasting approach.

Thus, in a first step, the present study applies a marginal cost-based pricing scheme for exhaust emissions to a real-world scenario of the Munich metropolitan area in Germany similar to work by Kickhöfer and Nagel (2013); Agarwal and Kickhöfer (2015). In a second step, the paper attempts to identify the necessary additional prices, as multiples of the original damage cost estimates, in order to reach the EU 2020 CO_2 reduction targets.

The remainder of the paper is organized as follows. Sec. 2 describes the travel demand simulator MATSim briefly. Different approaches for environmental policy setting and their implementation in the MATSim framework are discussed in Sec. 3. Further, scenario set up for a real-world case study is displayed in Sec. 4 and the results are analyzed in the Sec. 5. Finally, the study is concluded and possible ways forward are shown in Sec. 6.

2 Travel demand simulator – MATSim

MATSim[1] is a transport simulation framework designed to simulate large-scale scenarios in reasonable computation time (Balmer et al., 2009). It is therefore chosen for all simulation runs. Minimal inputs to the model are network data and daily plans of all individual travelers (= agents), forming the initial demand (see Fig. 1), as well as various configuration parameters.

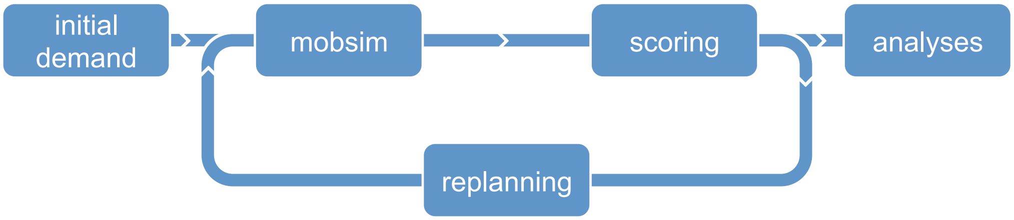

Figure 1: MATSim cycle (Horni et al., in preparationb)

Every agent in the simulation, learns and adapts to the system within an iterative process. This process is composed of the following three steps:

1. **Simultaneous execution of plans (mobsim)**: In the first step, daily plans of all individuals are executed simultaneously on the network. In this study, a state-of-the-art queuing model (Gawron, 1998; Cetin et al., 2003) is used which follows the traditional *"first-in-first-out"* queuing logic.

2. **Evaluation of plans (scoring)**: In order to model the choice between multiple potential daily plans, executed plans of all agents are evaluated using a utility function, indicating the performance (or score) of the plan. A plan's utility (S_{plan}) is represented by:

$$S_{plan} = \sum_{q=0}^{N-1} S_{act,q} + \sum_{q=0}^{N-1} S_{trav,mode(q)} \tag{1}$$

where N is the number of activities, $S_{act,q}$ is the utility from performing activity q and $S_{trav,mode(q)}$ is the (typically negative) utility for traveling to activity q. In short, the utility earned from performing an activity is given by[2]

$$S_{act,q} = \beta_{dur} \cdot \ t_{typ,q} \cdot \ln(t_{dur,q}/t_{0,q}) \tag{2}$$

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[1] See `www.matsim.org`; for detailed information, please refer to Horni et al. (in preparationa).

[2] See Charypar and Nagel (2005) and Nagel et al. (in preparation), Sec. 3.2, for a more detailed description.

where $t_{dur,q}$ and $t_{typ,q}$ are actual and typical durations of activity q, respectively. β_{dur} is the marginal utility of activity duration. $t_{0,q}$ is the minimal duration, which essentially has no effect as long as dropping activities is not allowed. The simplified mode-specific utility from traveling by car or public transport (PT) following Nagel et al. (in preparation) is described by:

$$\begin{aligned} S_{car(q)} &= \beta_{trav,car(q)} \cdot t_{trav,q} + \beta_m \cdot \gamma_{d,car(q)} \cdot d_{trav,q} \\ S_{PT(q)} &= C_{PT(q)} + \beta_{trav,PT(q)} \cdot t_{trav,q} + \beta_m \cdot \gamma_{d,PT(q)} \cdot d_{trav,q} \end{aligned} \tag{3}$$

where $t_{trav,q}$ and $d_{trav,q}$ is the travel time and distance between activity q and $q+1$. $C_{pt(q)}$ is the Alternative Specific Constant (ASC) of public transport (PT).

3. **Change of plans (replanning)**: After executing and scoring plans, a new plan is generated for a predefined share of agents. The new plan is generated by modifying an existing plan according with respect to predefined choice dimension.

3 Environmental policy setting

This section shortly describes the idea behind the principle of internalizing air pollution externalities and the implementation in the MATSim framework (Sec. 3.1), Subsequently, an idea of how to link this damage cost approach to political backcasting approaches is presented (Sec. 3.2).

3.1 Internalization

Internalization is the process in which the (damage) costs of one or several externalities are actually charged to make them relevant in the behavioral decision making of users. In literature, this is referred to as marginal social cost (MSC) pricing. These social costs are the sum of marginal private costs (MPC) and marginal external costs (MEC) (see, e.g., Walters, 1961; Turvey, 1963). By default, the MATSim utility functions only incorporate marginal private costs (MPC) which correspond to (every agent's) time and money spent for traveling between planned activities (see Eq. 1). Agents do not take into account the emission costs which they cause to other agents or the environment.

For the calculation of damage costs of exhaust emissions, an emission modeling tool is used which has been developed by Hülsmann et al. (2011) and further improved and extended by Kickhöfer et al. (2013). Exhaust emissions are categorized as warm and cold-start emission. The cold-start emissions are generated during the warm-up phase of vehicles, whereas warm emissions are generated while driving. The most relevant parameters for their calculation essentially are parking duration, distance traveled and vehicle characteristics, and engine type, road category and speed of vehicles, respectively. At the end of the every link and for every vehicle, cold-start and warm emissions are calculated based on the traffic states on the link. The essential parameters such as parking duration, traveled distance, road category, speed of vehicle etc. are derived from the simulation. With their help, the HBEFA[3] database provides the resulting exhaust emission values differentiated by type of pollutant.

In order to convert these emissions into vehicle-specific toll values, a method developed by Kickhöfer and Nagel (2013) is used. It converts the time-dependent, vehicle-specific emissions into a toll by using emission costs factors from the literature (see Tab. 1). Thus, in the simulation, every time an agent leaves a link, the agent consequently pays the toll equivalent to the emissions produced by her. As a reaction to the toll, agents learn and adapt their behavior within the iterative learning cycle (see Sec. 2). Consequently, agents' decisions are based on MSC, and the external effect is internalized.

Table 1: Emission cost factors. Source: Maibach et al. (2008).

Emission type	**Cost factor** (EUR/ton)
CO_2	70
$NMHC$	1,700
NO_x	9,600
PM	384,500
SO_2	11,000

3.2 Backcasting

The process of internalizing environmental externalities based on marginal social costs as described in Sec. 3.1 can, e.g., be used in computer models in order to identify the upper bound of possible efficiency gains in a transport system. However, the calculation of dynamic, vehicle-specific emissions is very complex and time consuming, and it remains unclear whether the cost factors (see,

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[3] 'Handbook Emission Factors for Road Transport', Version 3.1, see `www.hbefa.net`

e.g., Tab. 1) can be determined in a way that they represent damage costs.

Because of this difficulty to determine actual damage costs, real world policies often use so-called backcasting approaches, i.e. the definition of high level political goals (Geurs and van Wee, 2000, 2004; IWW et al., 1998), such as the reduction of GHG emissions in the transport sector by at least 20% until 2020 with respect to 1990 levels. Setting such goals implicitly defines implementation (= avoidance) costs if certain policy actions are undertaken to reach the respective goal.

The idea of the present study therefore is to identify the order of magnitude of price level differences between the internalization and the backcasting approach. For that purpose, emission cost factors from Tab. 1 are increased by a multiplication factor following a parametric approach. In the remainder of this paper, this factor is referred to as "emission cost multiplication factor (ECMF)". The increased emission costs are then charged to the agents who eventually consider them in their decision making. The study will report changes in agents' behavior under different levels of ECMF (see Sec. 4.2).

4 Real-world scenario: Munich

In this section, the set-up for the scenario of the Munich metropolitan area is illustrated shortly.

4.1 Inputs

The initial scenario was created by Kickhöfer and Nagel (2013) and further modified by Agarwal et al. (2015). In the present study, the latter is used.

Network The Municipality of Munich (RSB, 2005) provided network data in the form of VISUM[4] data, which is further converted into a MATSim network. It contains 17,888 nodes and 41,942 links.

Plans The demand in the Munich metropolitan area is based on four different data sources, resulting in four subpopulation groups: urban, commuters, reverse commuters and freight. A realistic activity-based demand for each of the user group is created as shown in Tab. 2. The table also shows the number of individuals for each user group. For computational reasons, 1% of total population is used for the present study. Network flow and storage capacities are adjusted accordingly. In the simulation, only car mode is simulated on the network, all other modes are

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[4] 'Verkehr In Städten UMlegung', see `www.ptv.de`

Table 2: User groups in the Munich metropolitan area

User group	Data source	No of individuals [million]	Travel modes
Urban	MiD 2002, Follmer et al. (2004)	1.4	car, PT, bike, walk,ride
Commuter	Böhme and Eigenmüller (2006)	0.3	car, PT
Reverse commuter		0.2	
Freight	(ITP and BVU, 2007)	0.15	car

assumed to run emission free and without capacity constraints. Therefore, in the present study, all modes other than car depicted as *non-car* travel modes.

Following the study by Agarwal et al. (2015), the present study also uses two different public transport (PT) modes and consequently two alternative specific constants for each PT mode. All behavioral parameters and the approximate average Values of Travel Time Savings (VTTS) are listed in Tab. 3.

Re-planning strategies As described in Sec. 2, two re-planning strategies modeled in order to let the agents react towards different pricing schemes: route choice and mode choice. In every iteration, 15% agents switch route, 15% agents switch mode[5], and rest of the agents chose a plan from their existing choice set according to multinomial logit (MNL) model. After 80% of the iteration, agents only chose from their fixed choice set.

4.2 Base case and pricing schemes

A base case simulation is run for 1000 iterations and its output is then used as input for the different policy cases:

- The base case is continued for 500 more iterations and is referred to as "Business As Usual" (BAU) case. This is the reference case for comparison.

- Six different emission cost multiplication factors (ECMF), namely 1.0, 5.0, 10,0, 15.0, 20.0 and 25.0, are considered and for each ECMF, one simulation is set up by running for 500 iterations.

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[5] In accordance to the study Agarwal et al. (2015), an urban traveler can switch mode between car and slower PT (speed 25 km/h) whereas, commuters and reverse commuters can switch mode between car and faster PT (speed 50 km/h).

Table 3: Behavioral parameters.

Parameter	**Value**	**Unit**
Source: Kickhöfer (2014)		
Marginal utility of activity duration (β_{dur})	+ 0.96	$utils/h$
Marginal utility of traveling by car ($\beta_{trav,car}$)	– 0.00	$utils/h$
Marginal utility of traveling by PT ($\beta_{trav,PT}$)	– 0.18	$utils/h$
Monetary distance rate by car ($\gamma_{d,car(q)}$)	–0.30	EUR/km
Monetary distance rate by PT ($\gamma_{d,PT(q)}$)	–0.18	EUR/km
Marginal utility of money (β_m)	– 0.0789942	$utils/EUR$
Approximate average $VTTS_{car}$	+ 12.15	EUR/h
Approximate average $VTTS_{PT}$	+ 14.43	EUR/h
Source: Agarwal et al. (2015)		
ASC for urban PT	– 0.75	$utils$
ASC for commuters/reverse commuters PT	– 0.3	$utils$

In each of the pricing schemes, emission cost factors (see Tab. 1) are increased by the above mentioned ECMF to increase the toll for the agents. The reaction of the agents under various ECMF is analyzed in the following Sec. 5.

5 Results

In this section, the impact of the different emission cost multiplication factors (ECMF) on transport-related indicators is presented. The absolute daily emission costs caused by all subpopulations amounts to 3.7 m EUR. Tab. 4 shows the share of car trips and emission costs for the different subpopulations. Though, freight car trips represent roughly 7.82% of all car trips, they contribute to approximately 68.58% of the emission costs because freight vehicles emits more emissions other vehicles and have longer travel distances (mean and median trip distances are 111 and 69 km). On the other hand, urban travelers (62.66% car trips of all car trips) contribute to only 5.47% of total emission costs.

Table 4: Share of car trips and emission costs caused by different user groups for BAU scenario

	Urban	(Rev.) commuter	Freight
% of trips	62.66	29.52	7.82
% of emission costs	5.47	25.95	68.58

5.1 Changes in emission costs

Tab. 5 shows the effect of different ECMF on emission costs caused by the respective subpopulation. As expected, overall emission costs by tendency decrease with increasing ECMF. This reduction in emission costs is a combined effect of re-routing and modal shift towards environmentally friendly modes. As Tab. 6 shows, the modal shift is the driving force behind these savings. (Rev.) commuters are better off by already shifting to PT at low values of ECMF. In contrast, emission costs caused by urban travelers' first decrease slightly, then increase for ECMF = 5 and then decrease again. The significant decrease in the car share of the (rev.) commuters has led to capacity relief (see Tab. 6). As a consequence, car share for urban travelers increases and ultimately results in higher emission costs at ECMF = 5. Afterwards, the tolls for urban travelers become so high that even after further relief in the capacities, urban travelers are better off by changing to non-car transport modes. This, in consequence, eventually diminishes the emission costs of urban travelers. For freight transport where only route choice is allowed, the decrease in emission costs is – as expected – by far smaller than for the other subpopulations.

Overall, for the whole population, ECMF and caused emission costs are inversely proportional to each other, i.e. an increase in the ECMF yields a decrease in emission costs. However, this effect stagnates at higher values of the ECMF (> 10). Thus, presumably, in order to achieve a 20% emission cost reduction target, a toll level equivalent to 10 times of the damage costs is required.

5.2 Changes in pollutant types

Following the overall interpretation from above, the effects on different types of pollutants is presented next.

5.2.1 Changes in CO_2

Fig. 2 shows the relative change in CO_2 levels for various emission cost multiplication factors. The trend is similar to emission costs, i.e. for (rev.) commuter, freight and the whole population, CO_2

Table 5: Daily change in emission costs (in percent) with respect to BAU for various ECMF

User group	Emission cost multiplication factor					
	1	5	10	15	20	25
Urban	-0.08	2.02 ↑	-3.16	-8.42	-13.22	-18.89
(Rev.) commuter	-9.87	-63.19	-83.76	-88.07	-89.45	-89.60
Freight	-0.23	-0.56	-0.67	-0.72	-0.70	-0.71
Total	-2.72	-16.67	-22.37	-23.81	-24.42	-24.77

Table 6: Change in car trips (in percentage points) with respect to BAU for various ECMF

User group	BAU	Emission cost multiplication factor					
		1	5	10	15	20	25
Urban	22.98	0.22	1.39	1.14	0.66	0.20	-0.41
(Rev.) commuter	65.57	-7.04	-44.96	-59.57	-62.71	-63.61	-63.67
Freight	100.00	No change					
Total	30.72	-0.79	-5.06	-7.29	-8.12	-8.63	-9.15

decreases with an increase in the ECMF. In contrast, for urban travelers, CO_2 remains almost same at ECMF $= 1$, increases at ECMF $= 5$ and afterwards decreases with increase in ECMF. The increase at ECMF $= 5$ is due to the capacity relief effect (see Sec. 5.1). Interestingly, the EU emission reduction target (i.e. 20% reduction in CO_2) can be achieved at ECMF $= 5$ (or slightly less). Recall that for a 20% reduction in the total emission costs, an ECMF $= 10$ or higher was necessary.

5.2.2 Changes in NMHC

Fig. 3a shows the effect of ECMF on the exhaust of Non-Methane Hydrocarbons (NMHC) for urban travelers and freight transport. For (rev.) commuters, levels of all pollutant types decrease with an increase in ECMF whereas for freight, the levels of NMHC increases with increase in ECMF. For urban travelers, similar to the total emission costs (see Sec. 5.1), the levels of all pollutants except NMHC first decreases, then increase for ECMF $= 5$ and then again decreases with an increase in the ECMF.

The emission level of NMHC mainly depends on fuel type, engine type, age of the vehicle and

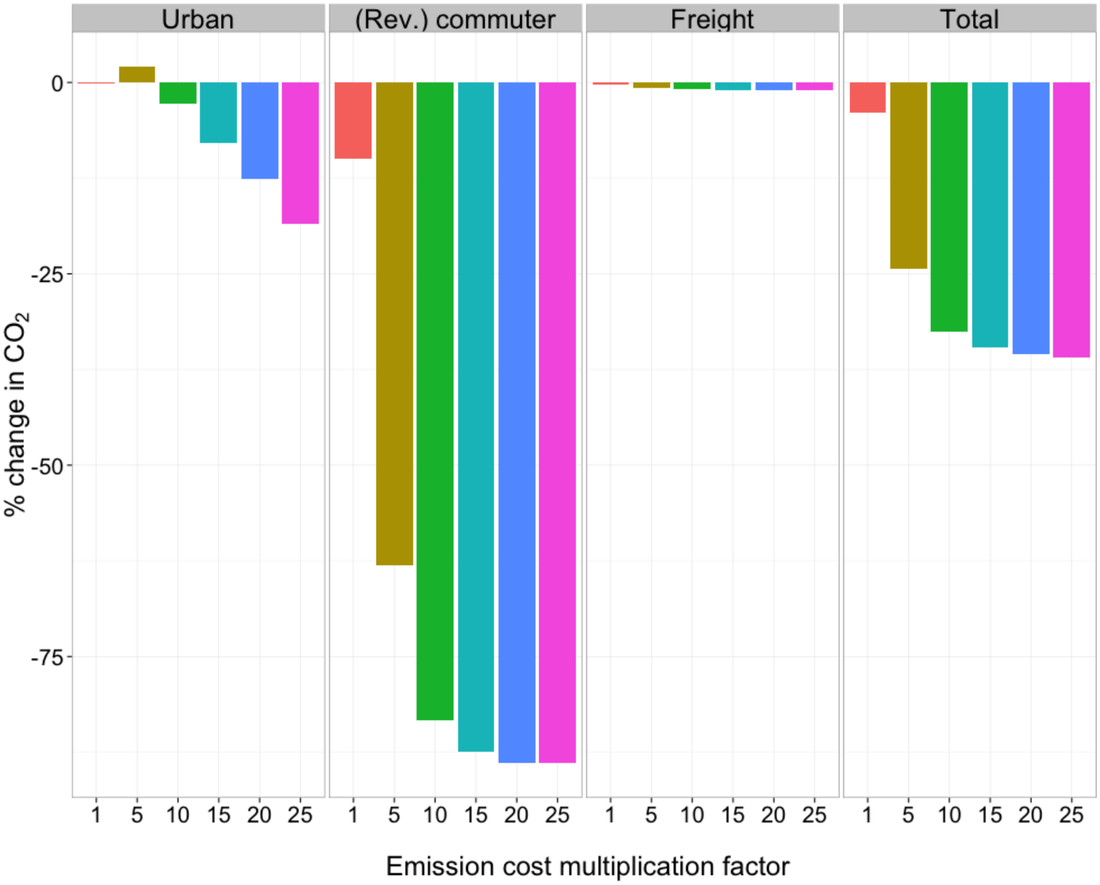
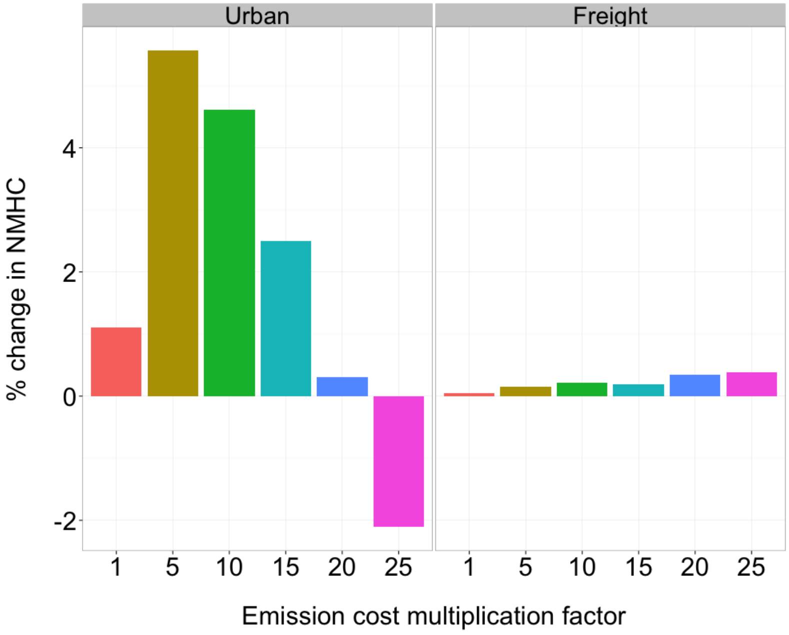


Figure 2: % Change in CO_2 levels for various ECMF

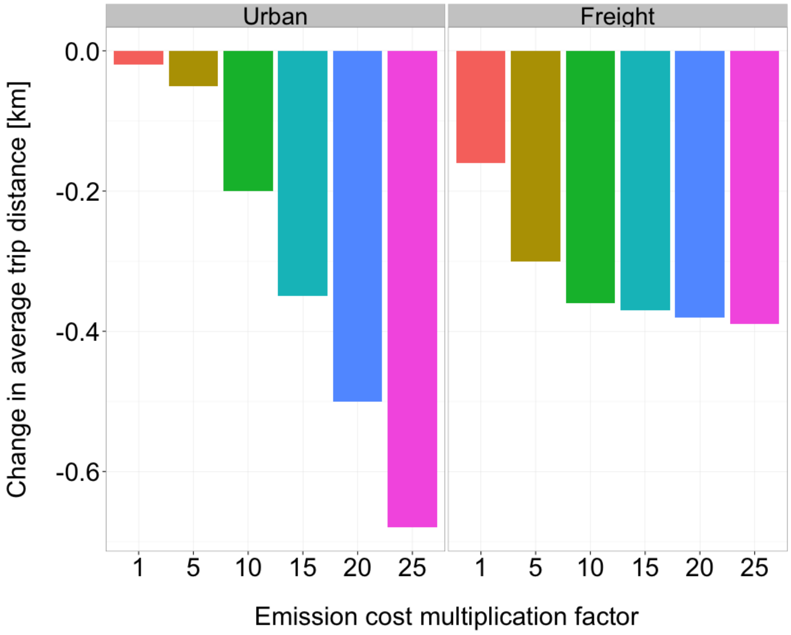
vehicle speed (Haszpra and Szilágyi, 1994). Also, NMHC emissions are higher for cold-starts than for a warmed up vehicle (Schmitz et al., 2000; Hoekman, 1992).

For the BAU scenario, urban travelers contribute to about 39% of total NMHC emissions because: (1) They travel relatively shorter distance (average distance = 6.11 km) and, (2) They perform multiple trips in a day, whereas (rev.) commuters and freight only perform 2 and 1 trips per day, respectively. From Fig. 3, the following can be observed:

1. **Urban:** Pricing emission increases the number of urban car trips (see Tab. 6) and decreases their average car distance (see Fig. 3b). It means, some of the non-car users with short trip distance are better off by shifting to car mode. This eventually result in higher NMHC emissions for urban travelers. On the contrary, at ECMF = 25, even after the decrease in the average trip distance, the NMHC costs is reduced by more than 2% due to a significant drop in car share.



(a) % Change in NMHC levels



(b) Change in average trip distance

Figure 3: Change in NMHC costs and average trip distance for urban and freight user groups with respect to BAU

2. **Freight:** The freight user group is somewhat different than all other user groups. The average trip distances decrease with increasing ECMF, but NMHC costs increase. The average trip distance of freight trips is very high (average distance = 110.9 km) and freight vehicle fleet, fuel type, age of the vehicle do not vary, thus, presumably, route shift from motorways to local roads increases the NMHC costs.

   It has been observed that total link counts increase with an increase in the ECMF and average trip distance decreases (see Fig. 3b) with an increase in the ECMF. That is, freight trips are shifted from longer links to multiple shorter links. A detailed closer analysis of these numbers show that the major shift occur from motorway (faster speed links) to local and distributor roads (slower speed links). Consequently, the level of NMHC rises with increase in the ECMF.

6 Conclusion and outlook

This study examined the gap between toll levels derived from (a) damage cost internalization and (b) avoidance costs which are needed to achieve the EU 2020 CO_2 reduction target. First, in order to obtain the damage cost levels, marginal emission pricing by Kickhöfer and Nagel (2013) was applied to a real-world scenario of the Munich metropolitan area. Second, in order to obtain the possible avoidance cost toll levels, different emission cost multiplication factors (ECMF) were used, modifying the damage cost estimates from the literature.

The results indicate that ECMF = 10 is required to reduce total emission costs by 20% whereas ECMF = 5 is enough to obtain a 20% reduction in CO_2 levels. That is, damage costs from the literature have to be multiplied by a factor of 5 to achieve the EU 2020 CO_2 reduction target. However, at ECMF = 5, a significant increase in CO_2 levels from urban travelers is observed. The highest contribution comes from (rev.) commuters and their modal shift from car to non-car mode. Urban travelers, however, shift to car mode because of the resulting relief in road capacities. Only at very high toll levels, the car share of urban travelers decreases. Furthermore, the investigation of emission levels indicates that the number of short urban car trips increases, and NMHC levels therefore increase as well for all values of ECMF except ECMF = 25. Similarly, for freight, an increase in NMHC is observed because of route shifts from motorway to local and distributor roads.

Clearly, pricing other externalities of transport as well as considering emissions by environmentally friendly transport modes is required. This study nonetheless provides an insight about potential different outcomes of internalizing damage costs or setting prices in order to reach a predefined goal. In future research, the authors aim to compare the above findings with the emission and toll levels induced by an exposure pricing approach (Kickhöfer and Kern, 2015), and to perform some kind of economic evaluation for the different pricing schemes.

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