Pricing and Incentive Strategies for Pareto-Optimal Modal Splits in a Regional Transport Network

Julian Zimmer*[1], Markus Friedrich[2]

[1] M.Sc., Chair of Transport Planning and Traffic Engineering, University of Stuttgart, Germany

[2] Prof. Dr.-Ing., Chair of Transport Planning and Traffic Engineering, University of Stuttgart, Germany

SHORT SUMMARY

Energy-efficient transport is critical to reach the climate targets. This study examines the introduction of monetary measures (toll for cars, incentives for public transport) in a regional transport network with the aim to influence the modal split, shifting travel demand from cars to public transport in order to save energy. Public transport supply is adapted for increasing demand, allowing for additional pull effects through increased frequencies. The toll rate is varied and the concept of Pareto optimality is employed to draw conclusions about the efficiency of the resulting scenarios. A distance-dependent toll and refraining from paying a bonus to public transport users outperforms the alternative scenarios. Also, the modal shifts achieved by increasing the toll rate to more extreme values turn out to be less favorable than the shifts caused by the initial introduction of toll, as the tradeoff between energy reduction and additional travel time become less advantageous.

Keywords: Energy-efficient Transport, Modal Split, Pareto Optimality, Pricing, Travel Time

1. INTRODUCTION

Unlike other sectors, the transport sector is not on track (T&E 2024) to meet the climate targets (e.g. the European goal of a 55% greenhouse gas emission reduction between 1990 and 2030 (European Commission 2020)). While the electrification of all modes of land transport can be expected in the foreseeable future, an abundance of climate-neutral energy supply can not. It is therefore reasonable to consider energy consumption instead of (direct) CO_2 emissions when researching efficient transport systems. Reducing the energy demand of the transport sector remains critical in order to reach the overall climate targets.

Cars are usually the fastest transport option for medium distances. On the other hand, public transport modes like trains, buses, and metros usually require less energy per person-kilometer than cars (Umweltbundesamt 2025). Therefore, increasing public transport usage at the expense of car usage would usually enable the handling of the same travel demand with lower energy demand, but would lead to an increase in travel time.

In this research, we want to use the concept of Pareto optimality to draw conclusions on efficient transport systems. Pareto optimality refers to a state of a system (in this case the transport system) in which one system property (e.g. travel time) cannot be improved without simultaneously

impairing another property (e.g. energy demand). If several such states exist, they form a so-called Pareto front (Zitzler and Thiele 1999). This Pareto optimality in multicriteria analysis and optimization must be distinguished from the concept of Pareto improvement in welfare economics, which improves the situation for at least one individual without impairing it for any individual (Varian 2010).

This study examines how the modal split can be influenced to reduce the overall energy demand of the transport system, while staying Pareto-optimal with respect to travel time and energy demand. We consider a travel demand model of a regional transport network with a mode choice model. The behavior of travelers is influenced by introducing a toll and further monetary measures.

2. RELATED WORK

Road pricing is an extensively and actively researched field (Munir et al. 2021). Studies include a theoretical (Cascetta and Montanino 2022) and applied perspective (Erdmenger et al. 2010) as well as works on how to achieve public acceptance (Lichtin et al. 2024). However, contributions with a clear focus on modal shift and its potential to reduce energy consumption are rare.

Explicit consideration of Pareto optimality is also rare. More commonly used in the context of road pricing is the concept of Pareto improvements, as in (Yang et al. 2025) and (Wu et al. 2011). Pareto optimality as defined above has been considered in the context of the design of the transport supply (network design), e.g. the tradeoff between average travel times and operational costs in public transport (Hartl 2020, Migl 2024). Brands and van Berkum (2012) consider a multi-objective public transport network optimization problem in a multimodal network and include explicit consideration of Pareto optimality for different combinations of objectives. The only source to our knowledge that focuses on the Pareto optimality regarding the user behavior is our own work (Zimmer et al. 2026), which does not incorporate free mode choice but enumerates all possible modal splits. Sun and Lang (2015) apply the concept of Pareto optimality to the routing of freight transport in a multimodal network.

3. METHODOLOGY

Study design

We consider a regional transport network with the two modes car and public transport (PT). In our model, every zone is served by PT at least with a frequency of one service per hour. To influence travel behavior, we introduce a toll for car traffic to disincentivize car usage and shift demand towards PT. If PT capacity is exceeded, the frequencies of the affected lines are increased in order to meet the demand. The raise in frequency might increase the attractiveness of public transport, which in turn influences the mode choice of travelers. All calculation steps (mode choice, assignment, and capacity adjustment) are therefore iteratively repeated until an equilibrium is reached. The resulting modal splits, average travel times and energy consumption (derived from vehicle kilometers) are then evaluated.

An idea to amplify the effects of shifting travelers towards public transport is to use the money collected from the toll to incentivize PT usage with a bonus, thus compensating public transport

passengers for their longer travel times. Two alternatives for the bonus are examined: a flat-rate bonus per trip ("flat bonus") and a bonus proportional to the travel time difference compared to a car trip on the same OD-pair ("disadvantage bonus"). We are considering four scenarios:

- Flat rate toll + no bonus
- Distance-dependent toll + no bonus
- Distance-dependent toll + flat bonus
- Distance-dependent toll + disadvantage bonus

Within each scenario, the calculations are performed for multiple levels of the toll rate in order to generate a large number of solutions ("toll states").

Model details

We use a simple travel demand model implemented in the Software PTV Visum (PTV GmbH 2025). The model covers the Erding district northeast of Munich in Germany with 103 zones (including Munich Airport). It contains 27 additional zones for the area around it, including a coarse representation of Munich as an important destination for commuters. The model therefore covers both urban and rural areas. As a bi-modal model, the model only incorporates the modes car and PT. The model is solely created for academic purposes, it is not calibrated and does not claim to accurately represent the actual traveler flows in the region.

The model uses a logit model for mode choice with specific parameters for each person group, which are given in Table 1. The utility functions used for the mode choice model are:

$$v_{\mathrm{Car}} = \beta_0 + \beta_t \cdot t_{\mathrm{Car}}^{\mathrm{TravelTime}} + \beta_c \cdot \left(c_{\mathrm{Car}}^{\mathrm{UserCost}} + c_{\mathrm{Car}}^{\mathrm{Toll}}\right) \tag{1}$$

and

$$v_{\mathrm{PT}} = \beta_t \cdot t_{\mathrm{PT}}^{\mathrm{PerceivedTravelTime}} + \beta_c \cdot \left(c_{\mathrm{PT}}^{\mathrm{Fare}} - c_{\mathrm{PT}}^{\mathrm{Bonus}}\right), \tag{2}$$

where $c_{\mathrm{PT}}^{\mathrm{Fare}} = 0.5\,€ + 0.1\,€/\mathrm{km} \cdot \mathrm{StraightLine\ Distance}$,
$c_{\mathrm{Car}}^{\mathrm{UserCost}} = 0.3\,€/\mathrm{km} \cdot \mathrm{Distance\ In\ Network} + c_{\mathrm{Car}}^{\mathrm{Parking}}$ with zone-dependent parking costs, and the perceived travel time in PT is:

$$\begin{aligned} t_{\mathrm{PT}}^{\mathrm{PerceivedTravelTime}} = {} & t_{\mathrm{Train}} + 1.1 \cdot t_{\mathrm{Bus}} + 1.5 \cdot t_{\mathrm{Walk}} + 1.25 \cdot t_{\mathrm{TransferWait}} \\ & + 0.25 \cdot t_{\mathrm{OriginWait}} + 10\ \mathrm{min} \cdot n_{\mathrm{Transfers}}\,. \end{aligned} \tag{3}$$

For evaluating the average travel times and for determining the bonus, we use the actual travel time and not the perceived travel time:

$$t_{\mathrm{PT}}^{\mathrm{TravelTime}} = t_{\mathrm{Train}} + t_{\mathrm{Bus}} + t_{\mathrm{Walk}} + t_{\mathrm{TransferWait}} + t_{\mathrm{OriginWait}}\,. \tag{4}$$

The model uses a frequency-based PT assignment procedure (Nökel and Wekeck 2009). Therefore, all wait-times are directly dependent on the headway. The PT supply consists of 4 train lines and 28 bus lines serving all zones in the network. In car traffic, we use a deterministic user equilibrium assignment and the following BPR volume delay function:

$$t\,(q) = t_0 \cdot \left(1 + 0.5 \cdot \left(\frac{q}{q_{\mathrm{max}}}\right)^4\right). \tag{5}$$

In our implementation of the model, the toll does not influence route choice directly. However, changes in route choice may occur due to the different saturation levels of the road network.

The total travel demand in the study area is shown in Table 2. The trip distribution is calculated for an initial state and is then not influenced by any of the measures considered in this study. In addition to the trips listed in Table 2, we consider some external demand in car traffic as a preload for the road network. It is assumed that external demand cannot be influenced and is not subject to our evaluations.

The energy consumption is directly derived from the vehicle kilometers in the network, using the values shown in Table 3. In PT, the vehicle kilometers are the service kilometers based on the chosen headway for each line. Allowed headways are 60, 30, 20, 15, 10, 7.5, 5, 2.5, 2 and 1 minute(s).

The calculation steps mode choice, assignment, and capacity adjustment are iteratively repeated until an equilibrium is reached. Figure 1 shows the general calculation procedure. For the scenarios with bonus, the amount disbursed on each OD-pair is recalculated in the inner iteration, using the the toll revenue based on the assignment result of the previous iteration. As a result, the difference between revenue and expenditure converges to zero in these scenarios.

Table 1: Person groups and their parameters for the utility function.

Person group	β_0	β_t (1/min)	β_c (1/€)
Employees	+1.2	−0.038	−0.15
Non-employed adults	+0.6	−0.038	−0.20
Pupils	−2.2	−0.027	−0.30
University students	−0.6	−0.027	−0.30
Flight passengers	+0.6	−0.038	−0.15

Table 2: Number of trips in the network, broken down by person group and trip purpose.

Person Group	Work	School	Uni-versity	Airport	Other	Back home	Total
Employees	76,030	0	0	0	72,402	148,432	296,864
Non-employed adults	0	0	0	0	101,855	101,855	203,710
Pupils	0	5,695	0	0	5,547	11,242	22,484
University students	2,194	0	8,413	0	4,555	15,162	30,324
Flight passengers	0	0	0	35,000	0	35,000	70,000
Total	78,224	5,695	8,413	35,000	184,359	311,691	623,382

Table 3: Available means of transport and their characteristics.

Vehicle type	Plannable Capacity*	Energy consumption (kWh / km)
Car	1.2	0.20
Standard bus	42	1.15
Articulated bus	63	1.60
Commuter train (200m)	750	12.00

*Car: average occupancy, PT: 65% of total capacity of a typical vehicle

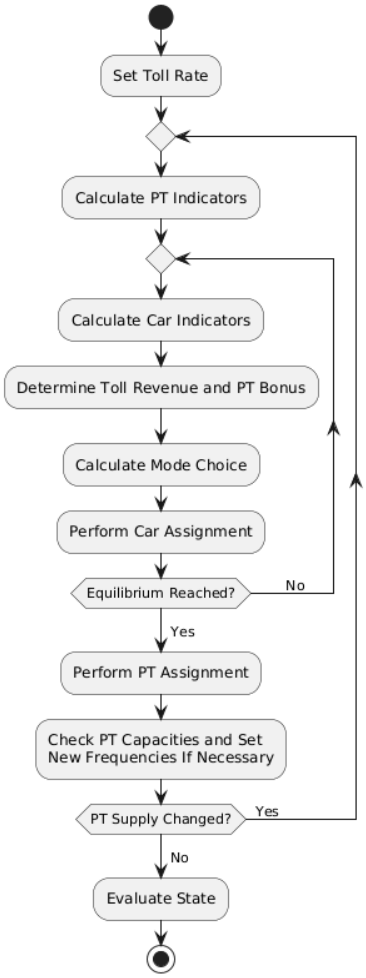


Figure 1: Iterative Calculation Procedure. The indicator calculation includes travel distance, travel time and perceived travel time.

4. RESULTS AND DISCUSSION

As a first benchmark, we turn off the mode choice model and evaluate the travel time and energy consumption for the hypothetical case, where we have the same modal split on all OD-pairs. The result is shown in Figure 2, where the two competing objectives of energy consumption and travel time are plotted against each other. As both values should be minimized, points towards the lower left are Pareto-optimal. We can see a clear tradeoff between travel times and energy consumption. We can also see jags in the curve, which are the result of extending the PT supply: the energy consumption to operate the PT network increases abruptly, and simultaneously PT travel times decrease due to higher frequencies. The initial state (status quo) without tolls using the mode choice model lies below the curve. This indicates that a supply-dependent mode choice leads to a more efficient allocation of demand than using a supply-independent mode-choice with an identical modal split for all OD-pairs. The first experiment is then to compare the distance-dependent toll (toll per kilometer) and the flat rate toll (toll per trip). The results are also shown in Figure 2, and clearly show that the distance-dependent toll outperforms the flat rate toll in terms of Pareto optimality. Therefore, all further investigations are only based on the distance-dependent toll.

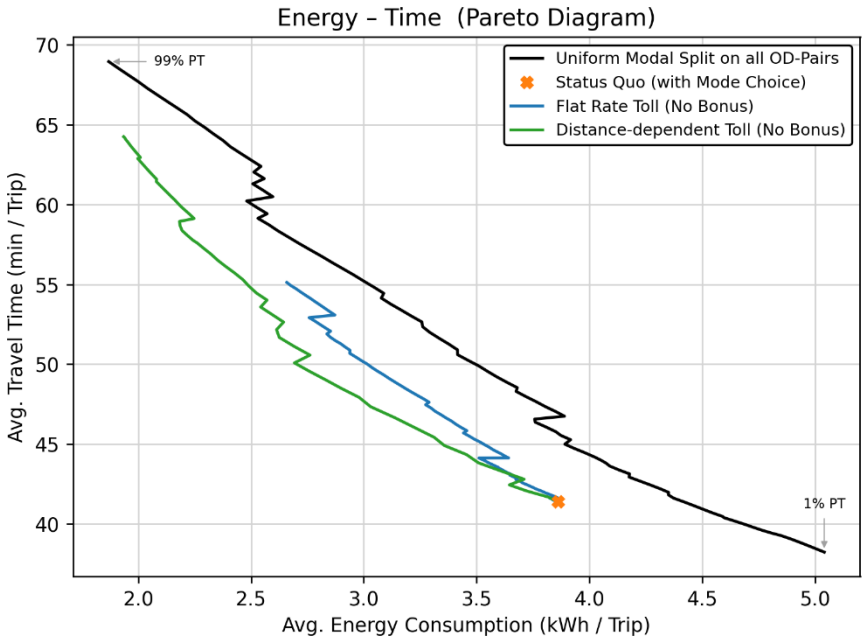
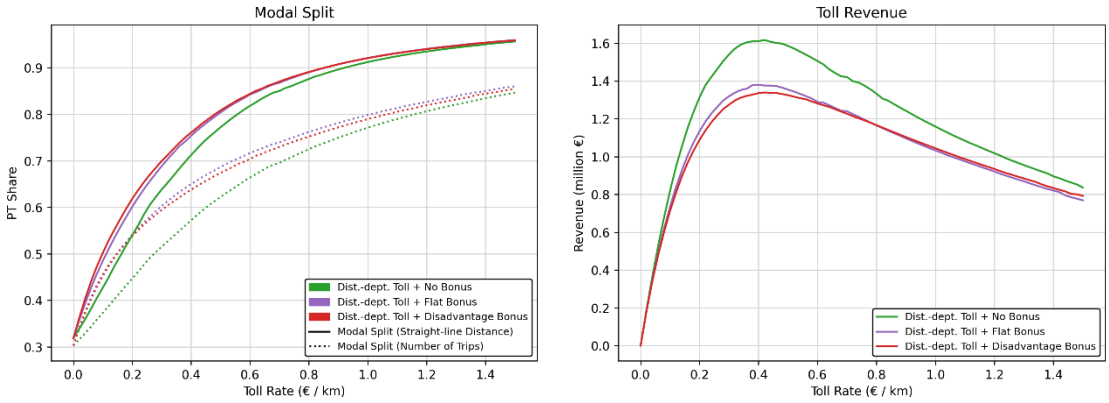


Figure 2: Pareto plot of the competing objectives (energy consumption and travel time) plotted against each other, for the status quo of the model without tolls, a flat rate and a distance-dependent toll as well as the case with equal modal splits on all OD-pairs. Solutions with high car usage are towards the lower right.

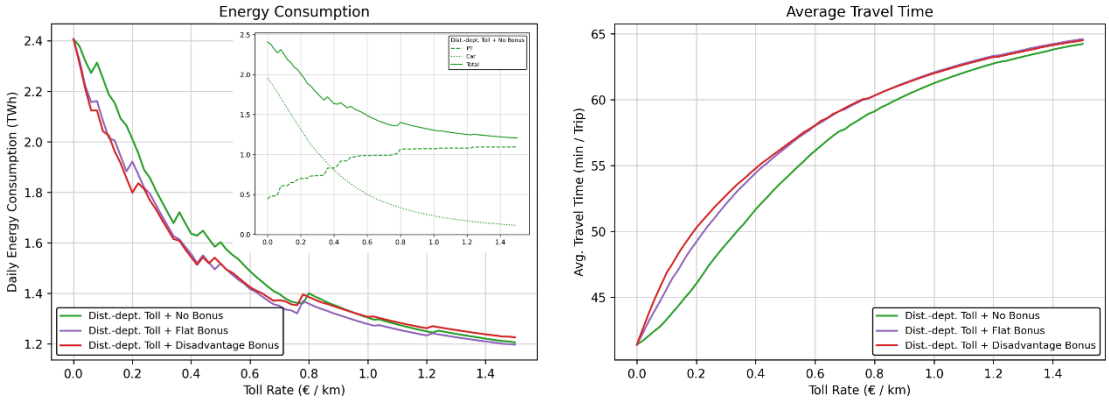
In the following, we have three scenarios: the distance-dependent toll is combined with the three cases of no bonus, flat bonus and disadvantage bonus as explained in the study design. Figure 3a shows the modal split as a function of the toll rate for the three scenarios. The increase in the modal split regarding kilometers traveled is stronger than regarding the number of trips, indicating that especially longer trips are shifted towards PT. Also, for the same toll rate, the PT share is higher in the scenarios with bonus, showing that they are effective in increasing the shift towards PT. The slope of the curves decreases with increasing toll rate, indicating that the shifting effect of further rate increases is diminishing. Figure 3b shows the total toll revenue as a function of the toll rate. After reaching a maximum, the total revenue decreases due to decreasing travel demand in the mode car. Also, the maximum revenue is highest for the case without bonus.

Figure 4a shows the energy consumption as a function of the toll rate for the three scenarios, and additionally its composition of a car and PT part for the scenario without bonus. With increasing toll rate, the energy demand required for the car mode decreases, while the energy demand of PT slightly increases due to an increase in service necessary to serve the demand. Between the three cases, the one with disadvantage bonus shows the steepest decrease in total energy consumption. On the other hand, we can see from Figure 4b that the increase of travel time is substantially lower for the case of no bonus.



(a) **(b)**

Figure 3: Modal split (a) and toll revenue(b), as they develop with increasing toll rate.



(a) **(b)**

Figure 4: Total energy consumption (a) and average travel time (b) as they develop with increasing toll rate. For the case without bonus, the energy consumption is also shown broken down by mode.

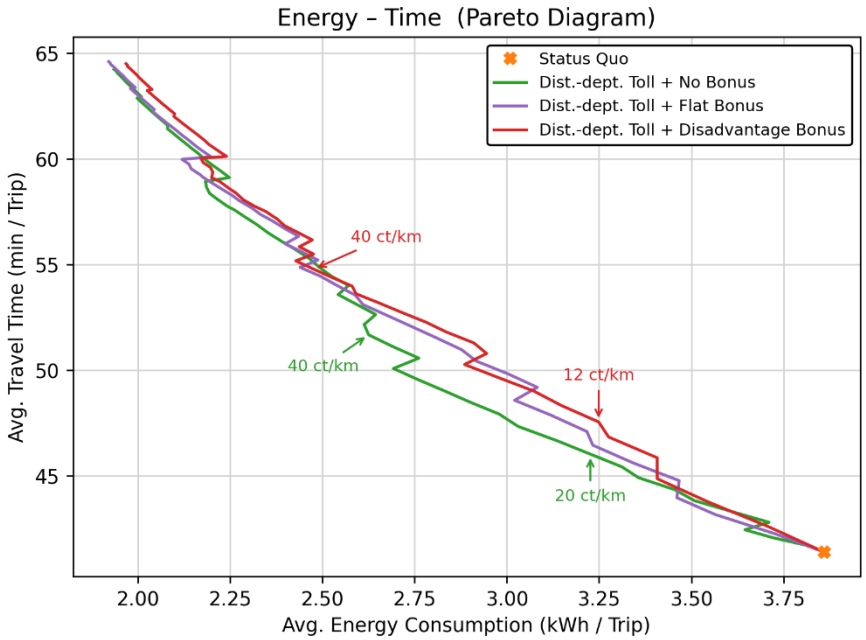


Figure 5: Pareto plot of the competing objectives (energy consumption and travel time) plotted against each other, showing the results of the three different scenarios with varying toll rate. Solutions with high car usage and low tolls are towards the lower right.

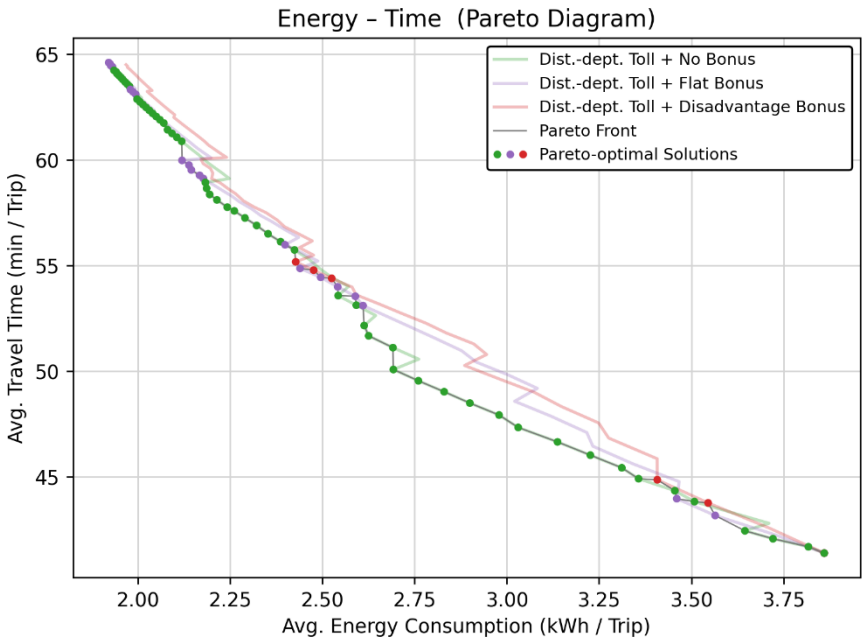
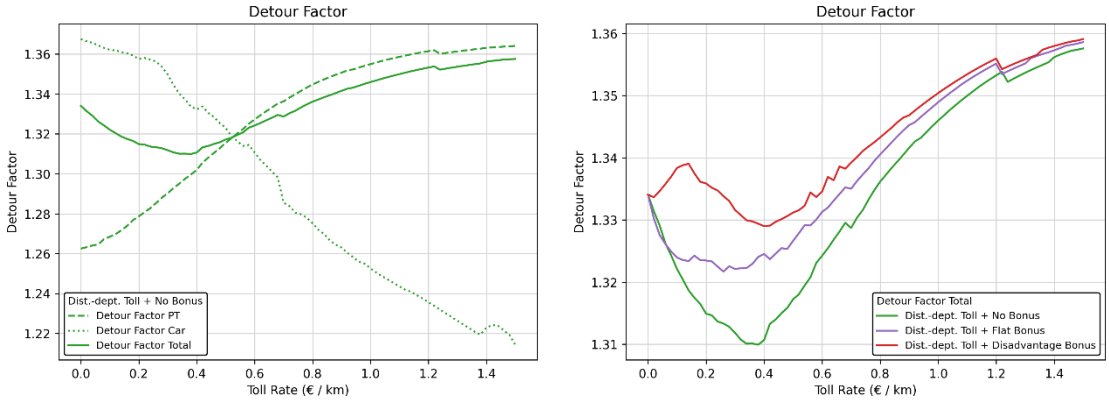


Figure 6: Pareto front with all Pareto-optimal solutions.

In Figure 5 we return to the plane of energy consumption and travel time. Figure 6 indicates which of the solutions presented in Figure 5 form the Pareto front. For a considerable (and reasonable) range of the toll rate, the solutions without bonus dominate the solutions with bonus. This effect can be explained as follows: Thanks to the choice model, PT is primarily chosen on OD-pairs where it is competitive compared to the car in terms of travel times and offers connections with few or no transfers. On other OD-pairs, the difference in utility between car and PT is much higher, leading to a low share of travelers using PT. Therefore, the selection of travelers in the network who use PT can be described as "efficient". When a bonus is offered – especially when it is based on the time difference – travelers are incentivized to use public transport even on OD-pairs where it is objectively a bad alternative (e.g. large detours or multiple transfers). The ratio of saved energy to additional travel time for these travelers is much worse than for those who would switch to public transport if the toll rate would be increased instead.

Figure 7 shows how the detour factor within each mode develops with increasing toll rate and compares the detour factors for the different scenarios. The detour factor of the mode car decreases due to the decreasing saturation of the network. The detour factor in PT increases, as with increasing toll it becomes an attractive alternative on OD-pairs where it is less and less direct. Looking at the overall detour factor, this leads to a minimum for lower toll rates before it increases and surpasses the initial value. In the scenario without bonus, the detour factor shows a distinct minimum in the range of 30 – 40 ct/km. In the scenario with the disadvantage bonus, we see a noticeable increase right at the start, indicating that the financial incentive to put up with long journey times in PT leads to inefficient behavior.

Figure 8 locates this area of 30 – 40 ct/km without bonus in the energy vs. time diagram. Around this area, the slope of the curve of the scenario without bonus – indicating the tradeoff between travel time and energy consumption – changes. With 8 min/kWh the tradeoff up until this area (on the right-hand side in the figure) is substantially better than the tradeoff of 17.1 min/kWh from here onwards. The relative increase in travel time for this area compared to the status quo (22 %) is smaller than the relative reduction in energy consumption (30 %), allowing it to argue that the measure is favorable.



(a) **(b)**

Figure 7: Detour factor by mode for the scenario without bonus (a) and over all modes for the different scenarios (b).

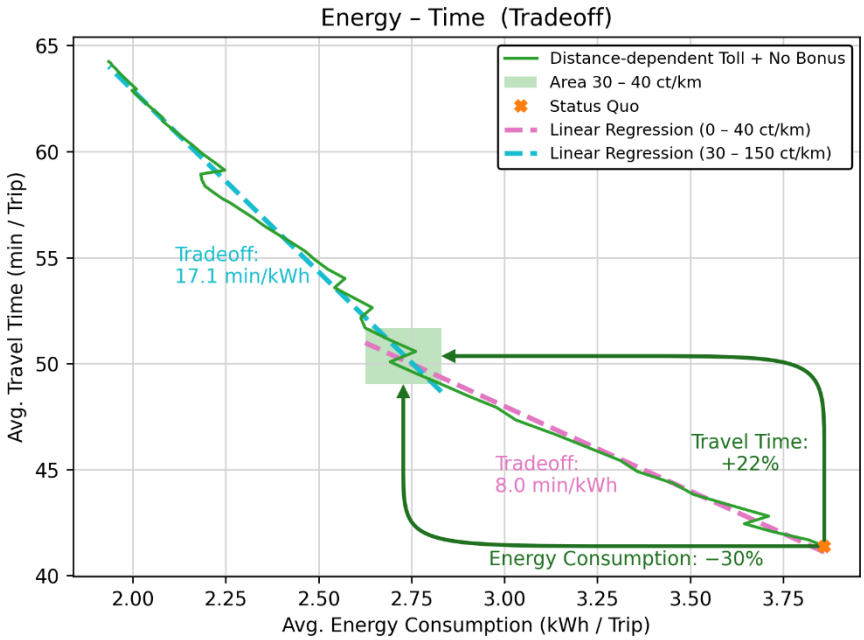


Figure 8: Tradeoff between saved energy and additional travel time for the scenario with no bonus determined using linear regression and relative change of the region with 30 – 40 ct/km compared to the status quo.

5. CONCLUSIONS

Within the travel demand model, introducing a distance-dependent toll proves effective to reduce energy usage. While offering a bonus for PT usage reinforces this effect for equal toll rates, the resulting solutions are rarely Pareto optimal, since inefficient time use is incentivized.

For the case with no bonus, the tradeoff between saved energy and increased travel time is favorable for lower toll rates. At some point, the shifts from car to PT accompanying further increases in toll rate become increasingly unfavorable, as they occur on OD-pairs where the PT travel times are much higher and the potential for energy savings is low.

For the network and parameters considered in this study, a distance-dependent toll of 30 – 40 ct/km and no bonus appears to be a good choice, roughly doubling the price of the mode car. The numerical values of the point where the tradeoff changes and the development of the detour factor can vary depending on land-use, transport supply, and behavioral parameters. The insights that the scenario without bonus outperforms scenarios with bonus in terms of Pareto optimality and that the tradeoff is good for lower toll rates and deteriorates for more extreme cases can be expected to hold true regardless of the network. Ultimately, which variant of monetary measures and which points of the Pareto front are to be preferred should be subject to a social debate.

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