Research paper

Ending the myth of mobility at zero costs: An external cost analysis

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ABSTRACT

Although transport externalities are known to be substantial, their estimates are uncertain, especially when comparing modes. This paper presents a comprehensive approach to assess the external costs of various modes of transportation, including public transport, motorized individual transport, sharing services, and active mobility. The methodology also covers multiple external cost categories, namely air pollution, climate, noise, land use, congestion, accidents and barrier costs, as well as the health benefits of active mobility. The city of Munich, Germany, serves as a case study to calculate the total external costs of transportation per year. Furthermore, the developed approach allows the assessment of transport policy scenarios to investigate the impacts of changes in the mobility system, such as modal shifts or electrification. In Munich, diesel and gasoline cars cause almost 80% of all external costs. Increasing the active mobility share is more beneficial in terms of external cost reductions than increasing the public transport share or electrification rate.

1. Introduction

Human mobility is linked to multiple negative impacts such as air pollution, greenhouse gas emissions, noise, and land consumption. At the same time, there are positive impacts on fitness and health through active mobility, more precisely, walking and cycling. In other words, mobility causes externalities – costs and benefits that have an impact on others but are not fully reflected in the price paid by the user (OECD, 2003). Uncompensated costs are borne by society (Mayeres, Ochelen, & Proost, 1996), which can be considered a subsidy for unsustainable modes: Users are not only exempt from paying the full costs of their mobility behavior but are also typically unaware of the hidden costs. As a result, external costs barely have an impact on the mobility decisions of individual travelers (van Essen et al., 2020, p. 332). Achieving transport-related sustainability aims thus requires suitable planning and policymaking to overcome this market inefficiency (Axhausen et al., 2021, p. 244; Lindsey & Santos, 2020). Knowledge and transparency of the full costs of mobility, both internal and external, enable steering of mobility behavior toward increased sustainability via information-based and economic instruments (Axsen, Plötz, & Wolinetz, 2020; Kaddoura & Nagel, 2019; Molloy, Tchervenkov, & Axhausen, 2021; Taniguchi, Hara,

Takano, Kagaya, & Fujii, 2003). App-based services play an increasing role in the transport sector and have the potential to largely impact mobility behavior. Pricing mechanisms can help to internalize the external costs of mobility, for example by means of a mobility-as-a-service platform informed by calculations of the full costs of mobility (Axhausen et al., 2021, p. 244; Schröder, Kinigadner, Loder, & Rothfeld, 2022). It should be noted that transport systems are complex and different means of travel have not only costs, but also benefits that should be taken into consideration. At the same time, externalities are highly dynamic and depend on numerous, sometimes uncertain system variables (both endogenous and exogenous). Despite some uncertainties, neglecting external costs in mobility pricing can lead to undesired traffic outcomes (Loder, Bliemer, & Axhausen, 2022).

Existing literature sheds light on the full costs of mobility from various perspectives. For example, Pisoni et al. (Pisoni, Christidis, & Navajas Cawood, 2022) address the societal benefits of active mobility. A study by Molloy et al. (Molloy et al., 2021) highlights the importance of considering pollution and congestion costs of car travel at a detailed spatial and temporal resolution. Air pollution costs of road traffic can be linked to pricing schemes and policy interventions, as done by Kickhöfer and Kern (Kickhöfer & Kern, 2015, p. 22). While König et al. (König

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et al., 2021) focus on the internal costs of battery electric vehicles, Clerck et al. (Clerck et al., 2018) compare the external costs of electric and conventional vehicles. A wider perspective in terms of transport modes is adopted by Gössling et al. (Gössling, Choi, Dekker, & Metzler, 2019) who consider walking and cycling in addition to the car and compare these modes by various cost categories. A more recent study by Gössling et al. (Gössling, Kees, & Litman, 2022), which received substantial media attention, uncovers the full costs of private car ownership for both the individual and society.

This paper builds on previous work and introduces a methodology to calculate the external costs of mobility as a basis for status quo analysis as well as for assessing the impacts of policy scenarios. The unique contribution lies in the large number of transport modes (including public transport, motorized individual, sharing, and active mobility), propulsion types (including diesel, gasoline, hybrid, and electric) and cost categories (including air pollution, climate, noise, land use, congestion, accidents, barrier costs, and health benefits) considered. Using the city of Munich, Germany as an example, this paper addresses the following questions:

- How do different transport modes and propulsion types compare in terms of their external costs (external costs per person kilometer and total external costs per year)?
- How do potential policy measures targeting mode share impact the total external costs per year?

Section 2 outlines our understanding of transport-related external costs, thus providing the basis of the methodology described in Section 3. Results of the external costs calculation for the City of Munich, both status quo and scenario analysis, follow in Section 4. While the transferability of specific results might be limited, the methods used in our study can be adapted to other regions worldwide. Methodology, assumptions and results are discussed in Section 5. This paper closes with critical reflections as well as an outlook on further research in Section 6.

2. Theoretical background

External costs or externalities are a concept in economics "central to the neo-classical critique of market organization" (Buchanan & Stubblebine, 1962). They emerge when one's economic activity (negatively) affects an uninvolved third party, thus being an unwanted side-effect or an unpriced good in a missing market. Externalities are commonly expressed as the difference between the social cost and the private cost of an economic activity. This concept was first introduced by Pigou (Pigou, 1920). It is important to note that externalities are commonly understood as negative external costs, but there can be positive externalities, too. These can be, for example, agglomeration effects, where higher levels of accessible economic density increase productivity disproportionally (Rosenthal & Strange, 2004). In this context, Rietveld (Rietveld, 1994) highlights that producer and consumer surplus are the largest benefits of a transport project. These are not an external benefit, though, and should hence not be subtracted from the negative external costs. In this paper, externality or external cost mainly refers to negative consequences, except for the health benefits from active mobility. Although external costs emerge in various economic activities, we focus on the transport sector only.

Three different scales of external costs can be distinguished: the total external cost (e.g., referring to an entire country), average external cost (expressed per performance unit), and marginal external cost (for one additional performance unit). There are several commonly used external cost categories in the transport sector, including accident costs, air pollution costs, climate change costs, noise costs, congestion costs, costs of well-to-tank emissions, and costs of habitat damage (van Essen et al., 2020, p. 332). Calculation methods of external costs have been formalized over the years and the results are regularly published. For example, current figures of the total external costs in the transport sector

are available for every member state of the European Union (van Essen et al., 2020, p. 332). Also, methods to derive the marginal external cost curves, relevant for policy making as seen below, have been developed and are frequently applied to quantify especially the marginal costs of congestion (e.g., (Mayeres et al., 1996) and (Sen, Tiwari, & Upadhyay, 2010) and (Russo, Adler, Liberini, & van Ommeren, 2021)).

The fact that external costs distort the market constitutes an interest in correcting this distortion in order to achieve a more efficient outcome. Next to command-and-control policies, which rely on direct regulation, two very prominent market-based instruments for internalizing external costs have emerged in the literature. These can be categorized into price and quantity control schemes, respectively (Santos, Behrendt, Maconi, Shirvani, & Teytelboym, 2010): (i) charging a tax equivalent to the difference between the marginal social and the marginal private cost, which shifts the market equilibrium to a more efficient point (Pigou, 1920), the so-called Pigouvian tax; (ii) limiting the total quantity of external costs, e.g., emissions, and allowing affected parties to trade emission rights with each other to achieve the most efficient outcome, the so-called cap-and-trade schemes (Dales, 1968). Importantly, as there are many different categories of external costs, there are many ways to internalize them. (Musso & Rothengatter, 2013) Musso and Rothengatter highlight the challenges when "bundling" instruments to internalize external costs, as there can be both desired and counterproductive side effects. Many countries have adopted schemes to internalize external costs in the transport sector, such as fuel or emission taxes. The European Union not only publishes external cost levels, but also the status of internationalization in each member state (van Essen et al., 2020, p. 332). Sound calculations are the basis for any kind of planning and policymaking aiming to minimize negative externalities from transport activities. The following section presents a comprehensive methodology for this purpose.

3. Methodology

The methodology of this work includes two parts. First, a general quantification of externalities is pursued to compare external cost rates in Euros per person kilometer (€/Pkm) for all transport modes (Sections 3.1 and 4.1). Second, these cost rates are used to illustrate how total external costs would change in a chosen city due to assumed changes in modal split (Sections 3.2 and 4.2).

3.1. External cost calculation

This study focuses on passenger transport only. Since the calculation basis is the urban environment, an application of the developed calculation model to other areas is only possible to a limited extent. A review of current literature was conducted to identify the relevant external cost categories. Perhaps surprisingly, the scopes of studies differ substantially, where the cost categories considered largely depend on the study aims. For example, Saighani (Saighani, 2020) calculates and examines external costs against the background of possible internalization by municipalities. In contrast, van Essen et al. (van Essen et al., 2020, p. 332) calculate and compare the external costs of transport in the individual countries of the European Union, while Ecoplan and INFRAS (Ecoplan and INFRAS, 2014) consider the situation in Switzerland with regard to cost recovery ratios in road and rail transport and for the calculation of the performance-based heavy vehicle charge. The cost categories considered in this work were selected based on the purpose of the study and include the following:

1. Air pollution
2. Climate
3. Noise
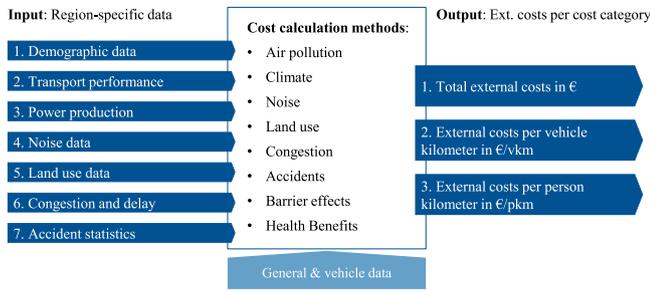4. Land use
5. Congestion
6. Accidents

Fig. 1. External cost rate calculation tool.

Table 1
Overview about region specific input data.

No	Region-specific data	Explanation	Tables in Appendix (data for Munich)
1	Demographic data	Number of citizens in different age groups	Table A1
2	Transport performance	Annual mileage in vkm/year and annual transport performance in pkm/year for every transport mode; number of vehicles	Table A2
3	Power production	Share of electric power generation types for different transport modes	Table A3
4	Noise data	Residents affected by noise levels LDEN	Table A4
5	Land use data	Investments for infrastructure; number of parking spaces; profit per parking space	Table A5
6	Congestion and delay	Average delay of public transport modes; delay costs per hour, number of trips with public transport	Table A6
7	Accident statistics	Police data about all accidents with causer, involved transport modes and degree of injury of involved modes	(not included in Appendix)

Table 2
Overview about overall input data.

No	Overall data	Explanation	Tables in Appendix (data for all regions in Europe)
8	General data	Climate and air pollution cost factors; noise cost rates; noise weighting factors; barrier effects; kinetic energy; overall land use and parking costs and space requirements; health benefits data and value of statistical life	Table A7 – A22
9	Vehicle data	Fuel consumption, power consumption of all transport modes	Table A23

7. Barrier effects
8. Health benefits

The methodology for all modes and cost categories is presented in Sections 3.1.1 to 3.1.8. Two types of input data are needed: (i) region-specific input data, which needs to be adapted to the region under analysis and (ii) overall input data, which does not need to be changed because it is applicable for all cities (preferably in Europe as most input

values rely on European sources). With the adapted region-specific data, the tool calculates total external costs, external costs per vehicle kilometer (Vkm) and external costs per person kilometer (Pkm) for any chosen city (Fig. 1).

Region-specific data include demographic data, transport performances, power production data, noise data, land use data, congestion and delay and accident statistics. All of them are further explained in Table 1 and collected in Table A1 to A.6 in the appendix.

The accident data set from the police department is not included in the appendix. It is included in the attached calculation models. The overall input data set is explained in Table 2 and summarized in Table A7 to A.23 in the appendix. The following paragraphs elaborate the detailed calculation methodology for each cost category.

3.1.1. Air pollution

The calculation of air pollution costs includes several aspects. These include material damage, crop failure, biodiversity loss, and health damage. Due to the special emission situation in transport, where emissions occur at a short distance from the ground (0–3 m), the German Federal Environment Agency, Umweltbundesamt (UBA), gives adjusted cost rates for transport-induced emissions depending on population density in 2016 in €$_{2020}$ (Matthey & Bünger, 2020). Table A7 provides an overview of the cost rates in transport by air pollutant and emission environment. For air pollutants in transport, the UBA summarizes the non-health damage (crop losses, material damage and biodiversity losses) in one category. The health damage category includes both material and immaterial damage. A slight underestimation of the immaterial share of the air pollution costs can be assumed, since according to Matthey and Bünger (Matthey & Bünger, 2020), the willingness to pay to avoid the immaterial part of health damage, i.e., pain and suffering, increases with rising income. The calculation of the costs is done according to Eq. (1) and (2) depending on the propulsion type of the vehicle:

where:

PCV_{ijm} Cost of air pollution by a vehicle class I with fuel type j on a road of category m in €/Vkm

EF_{ik} Emission factor of pollutant k and vehicle class I in g/Vkm (Calculations with Table A23)

APC_{mk} Monetary cost of pollutant k for a road of category m in €/g (Table A7)

PPC_j Fuel production pollution costs for a fuel type j in €/l (Table A11)

FC_i Fuel consumption of vehicle class I in l/100Vkm (Table A23)

SP_l Share of electric power generation type l in power mix without unit (Table A3)

$EPPC_l$ Air pollution costs of electric power generation type l in power mix in €/kWh (Table A13)

PC_i Power consumption of vehicle class I in kWh/100Vkm (Table A23)

The method includes air pollution costs from operation of the vehicle as well as from the fuel and power production. Based on the handbook for emission factors (HBEFA) and the corresponding calculation tool (TREMOD), UBA has calculated average cost rates for environmental costs per vehicle kilometer for different traffic situations and vehicle categories, which are listed in Table A8 for urban traffic (Matthey & Bünger, 2020). The calculation methodology from EU Directive 2011/76/EU given in Eq. (1) and (2) is used. For subways, regional

Combustion engines:
$$PCV_{ijm} = \underbrace{\sum_k EF_{ik} \cdot APC_{mk}}_{\text{Operation}} + \underbrace{PPC_j \cdot FC_i \cdot 10^{-2}}_{\text{Fuel production}} \qquad (1)$$

Electric power:
$$PCV_i = \underbrace{PC_i \cdot 10^{-2} \cdot \sum_l SP_l \cdot EPPC_l}_{\text{Power production}} \qquad (2)$$

Combustion engines:
$$CCV_{ij} = \underbrace{FC_i \cdot GHGE_j \cdot GHGC \cdot 10^{-8}}_{\text{Operation}} + \underbrace{CCP_j \cdot FC_i \cdot 10^{-2}}_{\text{Fuel production}} \qquad (3)$$

Electric power:
$$CCV_i = \underbrace{PC_i \cdot 10^{-2} \cdot \sum_l SP_l \cdot EPCC_l}_{\text{Power production}} \qquad (4)$$

trains and trams, the emission values of local trains were assumed. For plug-in hybrid electric vehicles (PHEV), a proportional cost rate was used in relation to the fuel consumption of the gasoline vehicle. Abrasion from bicycle, e-scooter and pedestrian traffic are disregarded in this work.

3.1.2. Climate

Two methods are available for the economic valuation of climate costs, namely the damage cost approach and the abatement cost approach. The damage cost approach requires estimating and monetizing all damages caused by climate change today and in the future, which are associated with uncertainties (Ecoplan and INFRAS, 2014, p. 295). Previous studies mainly resort to the abatement cost approach, where an explicit abatement target must be given and the costs of the measures to achieve this target are assessed (Ecoplan and INFRAS, 2014, p. 295; Saighani, 2020, p. 213). This approach is also associated with large uncertainties (Ecoplan and INFRAS, 2014). UBA recommends using the damage cost approach based on recent scientific findings on climate change damage costs with more robust damage cost estimates (Matthey et al., 2020, p. 9). The calculations in this paper also follow this recommendation. The climate change damage costs applied by UBA are listed in Table A10. The calculcation of the climate costs done according to Eq. (3) and (4) depending on the propulsion type of the vehicle. Again, the method includes climate costs from operation of the vehicle as well as from the fuel and power production.

where:

CCV_{ij} Climate cost by vehicle class I with fuel type j in €/Vkm
FC_i Fuel consumption of vehicle class I in l/100Vkm (Table A23)
$GHGE_j$ Greenhouse gas emissions in CO2 equivalent per fuel type in g CO2eq/l (Table A9)
$GHGC$ Cost rate per unit of CO2 equivalent in €/t CO2eq (for 1% or 0% time preference rate) (Table A10)
CCP_j Climate cost for the production of a fuel type j in €/l (Table A12 and Table A10)
SP_l Share of electric power generation type l in power mix without unit (Table A3)
$EPCC_l$ Climate costs of electric power generation type l in power mix in €/kWh (Table A13)
PC_i Power consumption of vehicle class I in kWh/100Vkm (Table A23)

In economics, the preference of consumers to consume a good in the present rather than in the future is described by the concept of time preference. Here, the utility (or welfare) at the present time is compared with the utility or welfare at a future time via the so-called time

preference rate (Beck, 2014, pp 205, p. 416). This concept can also be applied to the monetization of future damages at the present time. With a pure time preference rate of 1%, the welfare of current generations is weighted higher than that of future generations; with a rate of 0%, the welfare is weighted the same. The cost rate at a time preference rate of 1% along with a sensitivity analysis at the higher cost rate is recommended. Cost rates for years not listed in the table can be calculated using linear interpolation (Matthey et al., 2020, p. 8). The values were calculated using Equity Weighting, because the consequences of climate change cause damage globally, regardless of where the greenhouse gases are emitted. Calculations by the Austrian Federal Environment Agency (Umweltbundesamt GmbH) were used, in which the direct emission factors in CO$_2$ equivalent were determined for diesel and gasoline. CO$_2$, CH$_4$, NO$_2$ and other greenhouse gases were included, taking into account their climate impact (Umweltbundesamt GmbH, 2020). The emission factors used are listed in Table A9. Essentially, the calculations of climate costs follow the calculations in Ecoplan and INFRAS (Ecoplan and INFRAS, 2014), Saighani (Saighani, 2020), and van Essen et al. (van Essen et al., 2020, p. 332). For this purpose, the specific greenhouse gas emissions per vehicle kilometer are first calculated for the various means of transport based on their fuel consumption (listed in Table A23) and the emissions of the individual fuel types, and then total costs and average costs per person-kilometer are derived through travel and transport performance. Additionally, the internalization of climate costs via vehicle or energy taxes on fuels can be considered. However, in Germany, these taxes are not for a specific purpose and a rather low percentage of the overall tax income (Bundesfinanzministerium, 2022). Energy taxes were even used for subsidy of coal mining in Germany until 1988 (Bund der Steuerzahler Deutschland e.V., 2018). This is why, those taxes were not considered in this work. If these taxes are used to mitigate climate change in other cities, the amount of taxes has to be subtracted from the overall external climate costs. For example, CO$_2$ pricing for fossil fuels was introduced in January 2021 in Germany. It is not considered in this work due to the late introduction after the reference year, 2020, of this paper.

3.1.3. Noise

The effects of noise are noticeable in various areas of life. Thus, traffic noise causes costs for a national economy in several respects. The threshold above which noise is to be considered harmful is disputed in the literature; the limit values 50 dB (A), 55 dB (A), and 60 dB (A) are frequently mentioned (van Essen et al., 2020, p. 92, p. 332). Persons affected by more than 55 dB (A) traffic noise are included in the monetization for this study due to the corresponding data situation of the affected person statistics for Munich according to the European Union (EU) Environmental Noise Directive. The statistics for rail, road, and subway/tram traffic can be found in Table A4. The UBA proposes

$$LCV_{ijp} = \underbrace{INV_j \cdot \frac{SC_i}{\sum_l SC_{lj} \cdot FL_{lj}}}_{\text{Infrastructure}} \left(+\underbrace{PAC \cdot \frac{ST_i}{\sum_k ST_k \cdot FL_k}}_{\text{Parking (only cars)}} \right) + \underbrace{OC_p \cdot SC_i \cdot NV_i \cdot \frac{ST_i}{24h} \cdot \frac{1}{FL_i}}_{\text{Opportunity costs for parking (all other vehicles)}} \qquad (7)$$

the cost rates listed in Table A14 for specific traffic noise classes, depending on the cause of the noise. These include immaterial costs, costs for the health care system, and costs for production losses that are the result of annoyance, cognitive and psychological impairments, and physical health consequences (Matthey & Bünger, 2020, pp. 25–26).

The calculation of noise costs in this study is analogous to van Essen et al. (van Essen et al., 2020, p. 332). Accordingly, the two factors listed above, i.e., the number of people affected and the cost rate per noise level class, are multiplied by each other and summed up to determine the total costs of road traffic and rail traffic noise, respectively. In the next step, the calculated total costs must be allocated to the individual modes of transport. For this purpose, so-called noise weighting factors (NWF) and mileage are used in the literature (Maibach et al., 2008, p. 336; Saighani, 2020; van Essen et al., 2020, p. 332). NWFs are used to consider the different levels of noise emitted by different modes of transport. An overview of NWFs by traffic situation can be found in Table A15. The data of Bäumer et al. (Bäumer et al., 2017, p. 110) for road traffic and van Essen et al. (van Essen et al., 2020, p. 332) for rail traffic are used to determine the mileage of non-passenger transport modes. The calculation is performed according to Eqs. (5) and (6) (Saighani, 2020, p. 242).

$$NCV_{ij} = \lambda NOIST_{ij} \bullet \frac{1}{FL_i} \sum_k RAN_{jk} \bullet CNL_{jk} \qquad (5)$$

with $\quad \lambda NOIST_{ij} = \dfrac{NWF_i \bullet FL_i}{\sum_l \left(NWF_{lj} \bullet FL_{lj}\right)} \qquad (6)$

where:

NCV_{ij} Noise cost by vehicle class I and infrastructure type (street or rail) j in €/Vkm

$\lambda NOIST_i$ Allocation key of traffic noise per means of transport

RAN_{jk} Residents affected by noise level k and infrastructure type j in number of residents (Table A4)

CNL_{jk} Cost rate per noise level k and infrastructure type j in €/resident (Table A14)

NWF_i Noise weighting factor per vehicle I (no unit) (Table A15)

FL_i Annual mileage per vehicle I in Vkm/a (Table A2)

NWF_{lj} Noise weighting factor per vehicle l of infrastructure type j (no unit) (Table A15)

FL_{lj} Annual mileage per vehicle l of infrastructure type j in Vkm/a (Table A2)

3.1.4. Land use

Transport uses land in two different traffic situations. Land is used for moving traffic via streets or rail systems. At the same time, vehicles that are not moved occupy space for parking. The costs for street, bicycle and public transport infrastructure (Landeshauptstadt München, 2021a) can be estimated by the investments of the responsible municipality and then divided by the different transport modes using that infrastructure. Parking for cars causes costs through construction, maintenance, operation (Ulrich et al., 2017) and missed opportunity (Landeshauptstadt München, 2021b; Welling, 2021, p. 2) of those spaces. Besides car parking, other private and shared vehicles consume space on sidewalks while parking. This also causes opportunity cost. All of these aspects are summarized in the following two equations (7) and (8).

with $\quad PAC = NP \bullet \left(\dfrac{CCP}{LTP} + OCP \bullet PSS + MCP - PP\right) \qquad (8)$

where:

LCV_{ij} Land use cost by vehicle class I, parking type p and infrastructure type (street, public transport or bicycle) j in €/Vkm

INV_j Annual investments of municipality for infrastructure type j in €/a (Table A5)

PAC Total annual parking costs for cars in €

ST_i Daily standing time per vehicle class I (difference between sharing and private) in hours (Table A21)

ST_k Daily standing time per car type k (difference between sharing and private) in hours (Table A21)

SC_i Space consumption per vehicle I in m2 (only for street vehicle) (Table A19 and Table A21)

SC_{lj} Space consumption per vehicle l of infrastructure type j in m2 (only for street vehicle) (Table A19 and Table A21)

FL_{lj} Annual mileage per vehicle l of infrastructure type j in Vkm/a (Table A2)

FL_k Annual mileage per car type k in Vkm/a (Table A2)

OC_p Opportunity costs per parking type p (parking slots or side walk) in €/m2 (Table A21)

NV_i Number of vehicles per vehicle class I (Table A2)

NP Number of parking slots (Table A5)

CCP Construction costs per parking slot in € (Table A21)

LTP Lifetime of a parking slot in a (Table A21)

OCP Opportunity costs of parking slot in €/m2 (Table A21)

PSS Size of a parking slot in m2 (Table A21)

MCP Annual maintenance costs per parking slot in €/a (Table A21)

PP Annual profit per parking slot in €/a (Table A5)

Table A5 in the appendix collects all data that is region-specific for the calculation such as annual investments for infrastructure, number of public parking slots and the profit while operating these spaces. In Table A21, all constant values for parking are summarized. Similarly to the climate cost section, it can be argued that vehicle taxes are used for road construction and thus a part of the land use costs are already internalized. For same reasons as before, it is not considered in this calculation because the purpose of those taxes is not clearly specified in some countries (Bundesfinanzministerium, 2022).

3.1.5. Congestion

Congestion is mostly known for blocked streets by cars and other road users. However, there are also a lot of congested public transport networks which lead to delays. For both cases, time is lost and thus costs are generated. "*In transport economics, the value of time is the opportunity cost of the time that a traveler spends on their journey. In essence, this makes it the amount that a traveler would be willing to pay in order to save time, or the amount they would accept as compensation for lost time.*" (Small, 2012). This concept is applied by the INRIX traffic scorecard (INRIX, 2019) which calculates congestion costs for many cities all over the world. This value is taking for the congestion calculation method of this study and distributed to the different road users via space consumption and annual mileage weighting (Equation (9)). For public transport, the average delay of a trip for different public transport modes is needed. For example, Martin et al. (Martin, Wittmann, & Li, 2021) have collected public transport data in Munich and calculated the average delay for each trip. This will be multiplied with number of the trips and the average amount for value of time (Equation (10)).

For street vehicles : $COCV_i = CONC \bullet \dfrac{SC_i}{\sum_l SC_l \bullet FL_l}$ (9)

For public transport : $COCV_i = \dfrac{AD_i}{60} \bullet NT \bullet 365 \bullet SPT \bullet VT \bullet \dfrac{1}{FL_i} \bullet \dfrac{TP_i}{\sum_k TP_k}$ (10)

where:

$COCV_i$ Congestion cost by vehicle class I in €/Vkm
$CONC$ Total congestion costs in € (Table A6)
SC_i Space consumption for vehicle class I at 30 km/h in m2 (Table A21)
FL_l Annual mileage per vehicle l in Vkm/a (Table A2)
AD_i Average delay for vehicle class I in min (Table A6)
NT Number of trips per day (Table A6)
SPT Share of public transport of these number of trips (Table A6)
VT Value of time in €/h (Table A6)
TP_i Transport performance of the vehicle class I in Pkm/a (Table A2)

3.1.6. Accident

The following paragraph explains the methodology used to determine external accident costs. Analogous to Becker et al. (Becker, Gerike, Rau, & Zimmermann, 2002, p. 214), this study only considers the costs of personal injury, since physical damage to cars and infrastructure is predominantly covered by motor vehicle insurance or borne by the parties causing the damage themselves (Böttger, 2017, p. 18, p. 22) and are considered internal costs. Humanitarian costs of causer are also considered internal costs and thus not added up to total external accident costs. The cost rates for personal injury are based on Saighani (Saighani, 2020), Neumann (Neumann, 2014, p. 71) and Becker et al. (Becker, Rau, & Zimmermann, 2001, p. 114) and are largely in line with the calculation methods and values of the German Federal Highway Research Institute (BASt). Table A18 provides an overview of the cost rates used. All cost rates were adjusted to the price level of €2020 used in this paper via the consumer price index of the German Federal Statistical Office (Destatis) (Statistisches Bundesamt, 2021).

For the evaluation of external accident costs, various approaches can be found in the literature, according to which the accident costs are assigned to the involved means of transport. The monitoring principle, the costs-by-cause principle and the damage potential approach are commonly mentioned in the literature (Saighani, 2020, p. 168). The monitoring principle maps the accident event, and the external accident costs are assigned to the vehicle class in which the victim was traveling. In contrast, the costs-by-cause principle decides to whom the costs are to be allocated according to the question of guilt of each traffic accident. Here, the guilty party bears the full costs of the accident (Ecoplan and INFRAS, 2014, p. 385). The damage potential approach is based on the consideration that heavier and larger vehicles carry a greater intrinsic risk for severe accident consequences, especially in collisions with weaker road users (Vermeulen et al., 2004, p. 149, p. 187). In this study, accident costs are calculated using the costs-by-cause principle and the damage potential approach.

To calculate the costs according to the *costs-by-cause principle,* the number of lightly and seriously injured persons, as well as fatalities for each accident are multiplied by the respective cost rate and added up. The total costs are then calculated as the sum of all individual accident costs of a vehicle class. Only the vehicle class of the person causing the accident is used for classification.

The calculation of accident costs according to the *damage potential approach* differs greatly depending on the study. For allocation in this study, a calculation is made using the kinetic energy in the accident (Saighani, 2020, p. 181). Kinetic energy, and hence the vehicle mass in urban traffic with its low speeds, has a large impact on accident severity (Aarts & van Schagen, 2006). Since the allocation of accident costs via kinetic energy best reflects the damage potential of an accident

participant, this approach was chosen for the present work. An overview of the assumed vehicle masses and speeds as well as the kinetic energies is given in Table A20. The mass is composed of the vehicle mass and the mass of passengers by average occupancy. The mass of pedestrians is calculated using the average weights of men and women in Germany. For bus and tram, the vehicle masses were weighted using the vehicle types used. The calculation follows Eqs. (11)–(13).

Costs $-$ by $-$ cause principle : $ACV_i = \dfrac{1}{FL_i} \bullet \sum_k AC_{ki}$ (11)

Damage potential approach : $ACV_i = \dfrac{1}{FL_i} \bullet \sum_p \dfrac{E_{kin\ i}}{\sum_l E_{kin\ l}} \bullet AC_{pi}$ (12)

with : $AC = \sum_j \left(n_j \bullet c_j \right)$ (13)

where:

ACV_i Accident cost by vehicle class I in €/Vkm
FL_i Annual mileage per vehicle class I in Vkm/a (Table A2)
AC Accident costs of one accident
AC_{ki} Accident costs for accidents where vehicle class I is causer
AC_{pi} Accident costs for accidents where vehicle class I is part of accident
n_j Number of injured persons according to degree of injury j of an accident event (without unit) (Police data)
c_j Specific cost rate by degree of injury j in €/person (Table A18)
$E_{kin\ i}$ Kinetic energy for vehicle class I in J (Table A20)
$E_{kin\ l}$ Kinetic energy of vehicle l involved in the accident in J (Table A20)

3.1.7. Barrier effect

The barrier effect describes the time delay that motorized transport imposes to active mobility forms (Victoria Transport Policy Institute, 2022). This could be in form of big streets pedestrians have to cross or circumvent to reach their destination. Benefits for active mobility forms can be reached by infrastructure improvements for pedestrians and cyclists or reduction of motorized traffic in general. In this study, values of a previous study were adapted to the currency rate of 2020 (Victoria Transport Policy Institute, 2022). The used values are collected in Table A16 in the appendix.

3.1.8. Health benefits from biking and walking

Cycling and walking play a major role as a form of mobility in urban environments due to the short distances involved. Health benefits through active mobility should therefore be included in a comprehensive observation of externalities in urban mobility. To determine this health benefit, the World Health Organization (WHO) has developed the "Health Economic Assessment Tool (HEAT) for Walking and Cycling", which can be used to calculate and monetize this benefit in cycling and walking (World Health Organization, 2019). The calculation methodology of HEAT is used in this study and is based on a comparison of the mortality risk of persons who regularly walk or cycle with that of persons who do not regularly use active forms of mobility. A reduction in mortality risk of 10% for bicyclists at 87 h of activity per year (100 min per week) and 11% for walkers at 146 h per year (168 min per week) is assumed. With more (or less) physical activity, a linear change in mortality risk is postulated (World Health Organization, p. 29). In HEAT, the risk assessment is based on the combined results of seven studies on cycling and 14 studies on walking (World Health Organization, p. 5). The calculation is conducted using the parameters listed in Table A22 according to Eqs. (14) and (15).

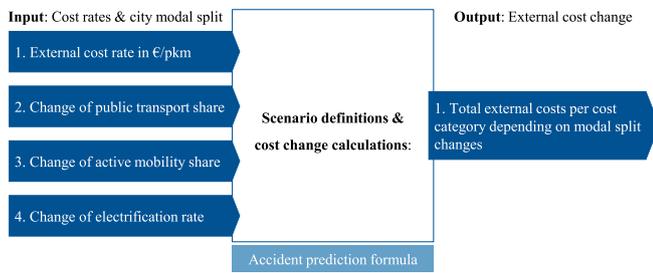$HB_{ij} = \dfrac{1}{FL_i} \bullet \Delta RISK_{Mort,i} \bullet MR_j \bullet NR_j \bullet VL$ (14)

Fig. 2. Scenario analysis calculation tool.

with $\quad \Delta RISK_{Mort} = (1 - RR) \bullet \dfrac{t}{t_{ref}}$ (15)

where:

> HB_{ij} Health benefits by vehicle class I (only bicycle and pedestrian) dependent on age group j in €/Vkm
> FL_i Annual mileage per vehicle class I in Vkm/a (Table A22)
> $\Delta RISK_{Mort,i}$ Reduced mortality risk (without unit)
> RR Relative mortality risk (without unit) (Table A22)
> t Daily travel time per person in min/week (Table A22)
> t_{ref} Daily travel time per person in the reference scenario in min/week (Table A22)
> MR_j Mortality rate in age group j (Table A1)
> NR_j Number of residents in age group j (Table A1)
> VL Statistical value of life in € (Table A22)

In the equation, the number of inhabitants in each age group (20–64 years for cycling, 20–74 years for walking) is multiplied by the mortality rate to calculate the mortality of the population group. The annual deaths in this period are then multiplied by the reduced mortality risk due to active mobility to calculate the deaths prevented in this group. The avoided deaths are monetized using the value of statistical life (VSL). A mortality rate of 264.968 deaths per 100,000 population is used for the 20–64 age group, and a mortality rate of 483.235 deaths per 100,000 population is used for the 20–74 age group (World Health Organization, 2019).

3.2. Scenario analysis

While the first part of the methodology helps to quantify the external costs of different transport modes, the second part relies on scenario analysis to illustrate how external costs could be reduced. The various scenarios correspond to a change in modal split for the whole city compared to the status quo, which reflect a difference in the total external costs. Three characteristics can be changed for a scenario: the modal share of public transport, the modal share of active mobility and the electrification rate of cars, buses and mopeds (Fig. 2). An increased modal share of active mobility or public transport automatically results in a decrease of diesel and gasoline cars in this model and vice versa. The total amount of travelled kilometers stays the same for all changes in modal share. Clearly, this simplification does not reflect the true complexity of mobility decisions. For example, selling a car will cause a shift to other modes of transport, such as public transport and the bicycle. This in turn will likely result in a change in destination choice and reduced trip lengths if nearer points of interest are selected. Due to the high complexity of these interdependencies and lack of data on trip length elasticity for mode changes in Germany, this aspect is however not considered in this paper.

Furthermore, a change in modal split would likely cause a relative change in the external cost factors given in €-ct/Pkm. For example, with less cars on the street, less accidents with bicycles would occur. To address these dynamics, the relative external cost value for pedestrians and bicycles is adapted based on existing studies that estimate accident numbers. First Brüde and Larsson (Brüde & Larsson, 1993) and later Elvik (Elvik, 2009) and Schepers (Schepers & Heinen, 2013) predict the number of accidents for pedestrians and cyclists depending on the number of motor vehicles on the street. the street. The following relation is assumed in this study (based on the initial coefficients from (Brüde & Larsson, 1993)):

Number of pedestrian accidents $= 0.0000734 \bullet MV^{0.5} \bullet PED^{0.72}$ (16)

Number of bicycle accidents $= 0.0000180 \bullet MV^{0.52} \bullet CYC^{0.65}$ (17)

where

> MV Number of motor vehicles (AADT = annual average daily traffic)
> PED Pedestrian volume
> CYC Cyclist volume

Volume is considered as transport volume in vehicle kilometers (Vkm) per day. These equations were implemented in the calculation model, so that the relative change of accidents according to the modal shift in the scenarios causes a change in the accident costs per Pkm for walking, bicycle and pedelec. While acknowledging that similar effects might apply to modal split and other external cost factors, these could not be considered in this study.

4. Application to munich

4.1. Status quo assessment

The calculations follow the territorial principle, i.e., only external effects caused by passenger transport activities within the boundaries of the city of Munich are estimated. Costs are allocated according to the place of cause, regardless of where the effects of the externalities occur. For example, not only those climate impacts are considered that (will) occur within the municipal boundaries, but all damages that occur globally as a result of the transport activity under consideration. The transport performance data on car, bicycle and pedestrian traffic, which are taken from the Munich-specific part of the study "Mobility in Germany" (Belz et al., 2020) are an exception. Here, travel distances of 15,693 persons from 8,195 households were recorded according to the resident principle, i.e., all passenger transport activities of persons living in the reference area are included. The reference year is set to 2020 with some exceptions where data was not available. Price values from other years were inflation-adjusted. For data related to transport performance and travelled trips, the most recent available data sets until 2019 are used to represent pre-COVID conditions. All relevant transport modes that significantly contribute to the total transport performance in the urban area of Munich are considered and categorized as:

- Public transport: bus, tram, subway, regional train
- Motorized individual: electric and gasoline mopeds; gasoline motorcycles; cars (battery electric vehicle (BEV), plug-in hybrid electric vehicle (PHEV), diesel and gasoline)
- Sharing: electric mopeds, cars (electric and gasoline free-floating), e-scooter
- Active mobility: walking, bicycle, pedelec

For the status quo calculations, the actual share of electric buses (1% in 2019) (Münchner Verkehrsgesellschaft mbH) is neglected and all buses are assumed to be diesel buses. However, the share of electric cars in car sharing is considered at around 20% in 2019 (Thomas Pentzek, 2019).

Applying the calculation methods for each external cost category (Section 3.1) and summing up the monetary values by transport mode
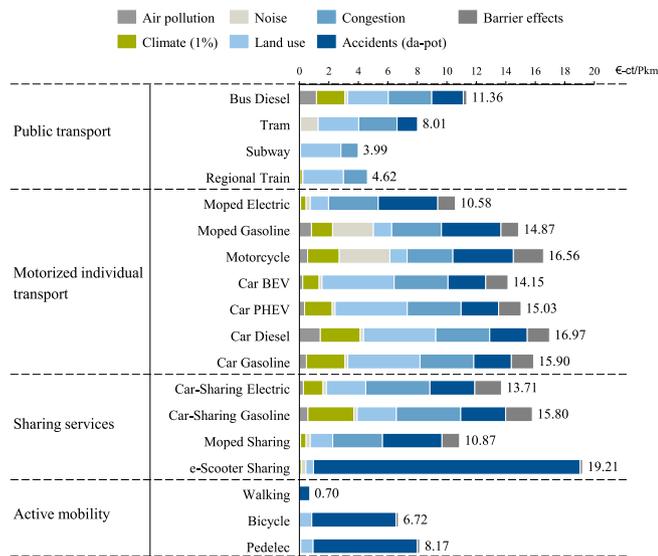
Fig. 3. Overview of external costs per Pkm for each transport mode in Munich.

Table 3
Overview of the health benefits of cycling and walking in Munich.

Transport mode	Total benefits in Mn. €$_{2020}$/a	Benefits per Pkm in €-ct$_{2020}$/Pkm	Benefits per resident in €$_{2020}$/RES
Walking	1,202.02	193.72	807.70
Bicycle	578.56	51.13	388.76
Total	1,780.57		1,196.46

Fig. 4. Why are accident costs for bicycle and e-scooter so high despite damage potential approach? Detailed analysis of accidents statistics for e-scooter and bicycle.

results in the external costs per transport mode in €-ct/Pkm. The overview in Fig. 3 depicts the external costs according to the stated boundary conditions and calculation methods, using the damage potential approach for accident costs and 1% pure time preference rate for climate costs. The considered powertrain types of cars include battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV), diesel and gasoline. The positive health benefits of active mobility are not considered in the overview due to a low comparability to the negative cost factors. Table 3 shows health benefits for walking and bicycle in Munich based on the HEAT approach.

The overall external costs of e-scooter sharing exceed all other transport modes. This is due to the high share of accidents costs which are based on accident statistics from 2019. In that year e-scooters were first introduced in Munich and, especially in the beginning, high numbers of accidents occurred compared to the low number of kilometers travelled with this mode (one accident every approx. 350,000 Pkm compared to one accident every 2,800,000 Pkm for cars, Fig. 4). Additionally, most accidents of e-scooters were either alone or with active mobility so that the damage potential approach allocates most costs of the accidents to e-scooters in almost 75% of all cases (Fig. 4). Diesel cars have the second highest external costs per kilometer due to higher air pollution and climate costs compared to other car types. Furthermore, motorcycles have the third highest external costs per kilometer due to high accident and noise costs.

Besides walking, public transport modes such as subway and regional train have the lowest external costs per kilometer. Bicycles only rank fourth lowest, as they are involved in a lot of dangerous accidents, where the share of bicycle-only accidents or accidents with pedestrians is rather high (Fig. 4). However, it should be stated that the positive health benefits (see Table 3) by far exceed the caused accident costs for walking and bicycles. Active mobility also does not cause any costs in air pollution, noise and climate. Other than accidents that occur without involvement of other road users (around 17% of all bicycle accidents)
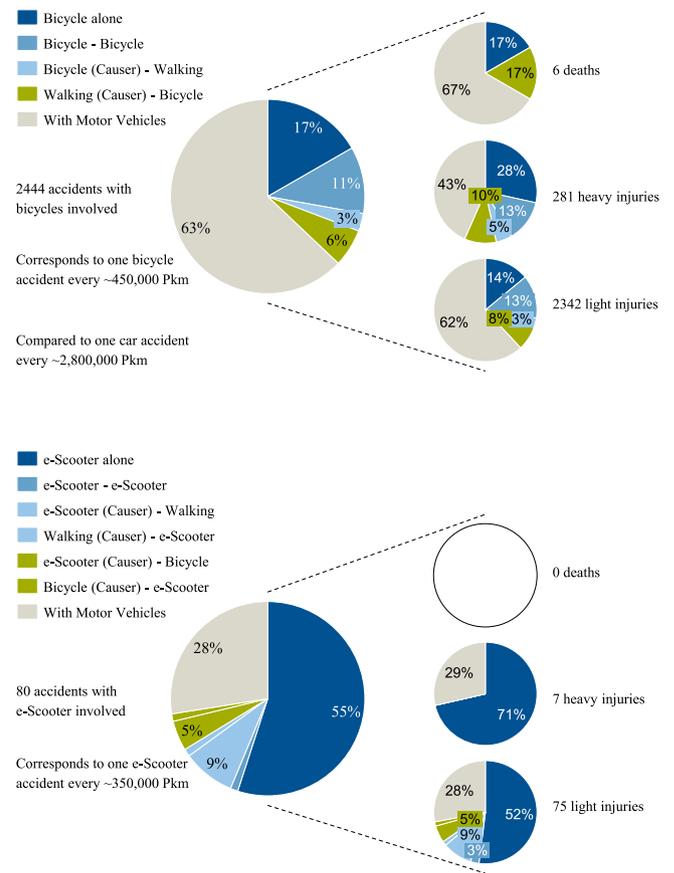
(Fig. 4), the accident costs of active modes are dependent on the amount of motor vehicles on the streets. With less cars on the road, the number of accidents with bicycles and pedestrians will also be reduced (see Equations 16 and 17). Consequently, the external costs of each active transport mode can be reduced by more than 50% when reducing the motor vehicle share. Fig. 5 shows the distribution of external costs for different transport modes (left) and cost categories (right), representing the status quo of external costs in Munich. The results are based on the external cost factors per transport mode (Fig. 3) and the transport performances in Munich (Table A2). The total amount of all costs is around 2,135 Mn. €. Around 79% of all external costs are caused by diesel and gasoline cars due to two reasons: first, the high amount of these vehicles on the street, and second, the high external costs per km. Land use (31%) and congestion (22%) costs have the highest shares among all external cost categories.

4.2. Scenario analysis

Section 4.1 and especially Fig. 5 shows that air pollution and climate emissions only account for a small share in total external costs. Nevertheless, most cities focus their transport system strategies on emission reduction only. The city of Munich recently published their mobility strategy which aims to have 80% "emission-free" passenger transport in Munich by the year 2025 (Landeshauptstadt München, 2021c). This section presents different modal share scenarios to achieve this goal of emission reduction and shows that different strategies can lead to substantial differences in external costs. The total transport performance in each scenario remains the same as in the status quo analysis. For the purpose of this study, the following transport modes are considered "emission-free": electric bus, tram, subway, regional train, electric
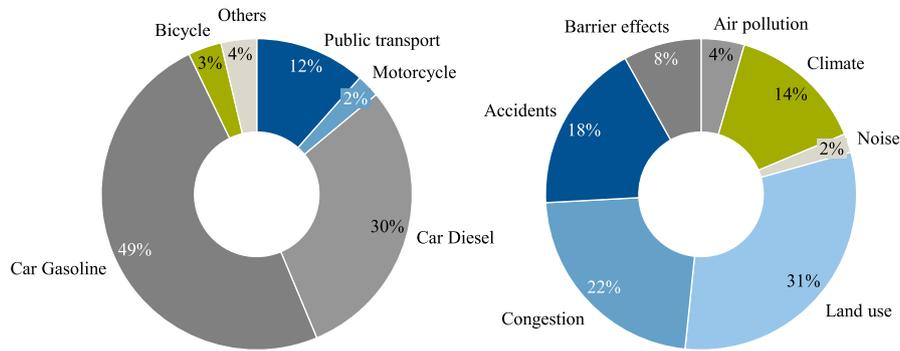
Fig. 5. Distribution of external costs for different transport modes (left) and cost categories (right) in Munich.
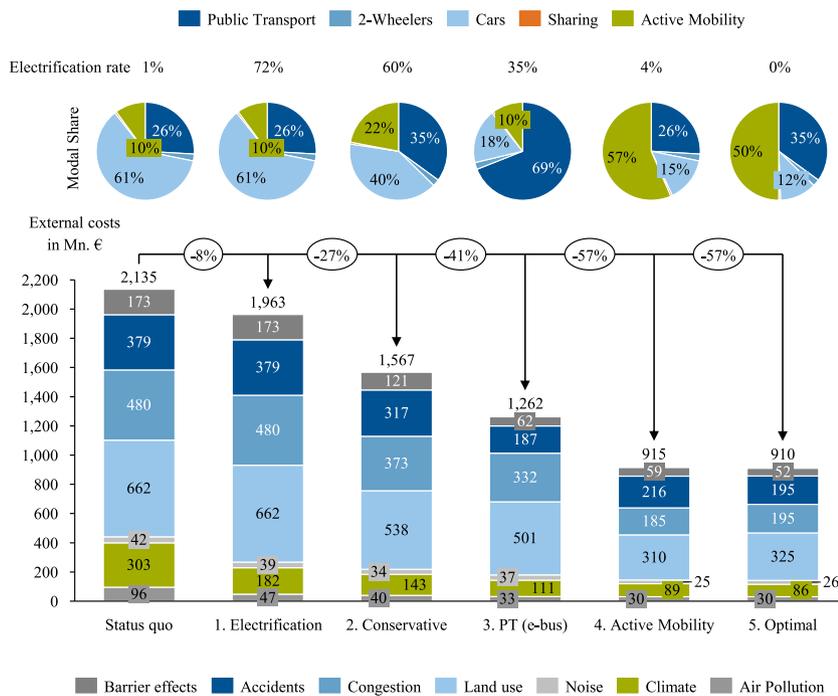

Fig. 6. Scenario analysis of modal split change and impact on total external costs in Munich.

moped, car BEV, electric car-sharing, moped sharing, e-scooter sharing, walking, bicycle, pedelec. These modes can only be emission-free if emissions from tire abrasion are not considered and if electric power generation is 100% renewable. However, since the EU power-generation-mix of 2020 is used for both the status quo and scenario analysis, "emission-free" vehicles might still have climate costs in their balance. With this definition the current share of "emission-free" vehicles in Munich is 33.6%.

Five scenarios are used to reduce external costs and reach 80% "emission-free" transport (Fig. 6). The scenarios are illustrative for choosing only one featured mode to reach the 80% "emission-free" transport. The realistic evaluation of the resulting modal shares is done in the scenario description:

1. Scenario 1 – Electrification: Electrification ratio for cars, buses, car-sharing and mopeds are increased equally. An electrification ratio of 72.2% is needed to reach 80% of "emission-free" transport. This leads to a decrease in climate costs and air pollution and an overall drop of external costs of 8%.

2. Scenario 2 – Conservative: A conservative approach for reaching 80% "emission-free" transport was chosen as a comparison to the

other scenarios that maximize either electrification, public transport or active mobility. AM increased by 12%, PT by 9% and the electrification rate was raised up to 60%.

3. Scenario 3 – Public transport (PT) (electric-bus): The share of public transport in modal split (share between PT modes stays the same) is increased equally. A PT share of 69% is needed with 100% electric buses in order to reach 80% of "emission-free" transport. This is not realistic, when looking at other European cities, e.g., Moscow or Budapest with a PT share of around 50% (Kodukula, Rudolph, Jansen, & Amon, 2018). This scenario results in an external cost reduction of 41%.

4. Scenario 4 – Active mobility (AM): The share of active mobility in modal split (share between AM modes stays the same) is increased equally. An AM share of 57% is needed to reach 80% of "emission-free" transport. This is a realistic number, when looking at other European cities, e.g., Amsterdam with an AM share of around 60% (Kodukula et al., 2018). Compared to the status quo, this leads to an external cost reduction of 57%.

5. Scenario 5 – Optimal combination: With a parameter variation for the three control levers above – Electrification, Active Mobility and Public Transport – many different scenarios were calculated, and an

optimal combination was identified by choosing the scenario with the lowest external costs of these scenarios. At the same time, maximum levels of PT (35%) and AM (50%) were considered. With these measures an external cost reduction of 57% can be reached.

5. Discussion

This section puts the methodology and results of this paper into perspective and critically reflects on potential inaccuracies. Regarding the quantification of external costs for the city of Munich, simplifications and assumptions cause uncertainties in the results:

- The values for air pollution in this study are based on average values and calculations by the UBA and thus do not represent the actual fleet composition in Munich.
- The climate costs are based on average fuel consumption data for the individual vehicles. For motorized individual transport, a more detailed analysis is recommended, analogous to the consideration of air pollutant costs.
- Noise costs strongly depend on total traffic volumes – not just passenger traffic. Thus, detailed knowledge of all mileage is necessary for the exact calculation of these costs per mode of transport. The basis of the calculation in this study is Germany-wide average mileage in urban traffic.
- The land use cost calculations of this work rely on parking cost data from a Swiss study. Differences between parking costs in Switzerland and Germany can be assumed, and thus inaccuracies might occur. Additionally, opportunity costs for parking spaces strongly differ in the literature, based on the replacement purpose of those spaces.
- Congestion cost calculations in this study depend on congestion cost results from INRIX. Some cities might not have results from INRIX. This limits the adaptation to other cities.
- Accident costs are based on exact data for Munich traffic and the methodology enables an exact breakdown of the costs. The damage potential approach seems to be more suitable for the evaluation of external accident costs in urban areas, since it better represents savings potentials of a traffic shift from one vehicle category to another. In contrast, the results of the costs-by-cause principle can be used to evaluate the relevance of concrete measures to increase road safety (e.g., improvement of infrastructure or information campaigns) compared to the damage potential approach.
- Barrier effect costs again depend on results of an American study and are constant for all cities in this methodology. This is a strong simplification because barrier effect costs are depending on the modal share and infrastructure conditions in the city.

Considering all the limitations above, a validation with consolidated methods is necessary. The literature varies significantly in the transport modes and cost categories considered. The most common transport mode in the research of external costs is the gasoline combustion engine car. In this study, an external cost value of about 15.9 €-ct/Pkm was calculated. For example, Gössling et al. calculated a value of 10.8 €-ct/Pkm for the year 2017 (Gössling et al., 2019) and used another value for different car sizes between 31 and 35 €-ct/Vkm in 2022 (Gössling et al., 2022) (With a occupancy rate of 1.5 this results in 20.7–23.3 €-ct/Pkm). Compared to those two studies the result of this paper is clearly in the middle of those other studies. For a complete validation of the method used in this paper, a review and comparison of all external cost studies is recommended. However, this exceeds the scope of this work.

Methodological uncertainties play an important role in the evaluation of the results. There are several aspects that cause these uncertainties: Firstly, there might be a misalignment between method used and expected results. In the past, several studies have highlighted the uncertainties in the estimation and quantification of externalities with regards to the expectations of the authors. Review studies show that in general higher costs for externalities are estimated when the amount of

Table 4
Comparison of external costs for 1 %- and 0 %-time preference rate.

Transport mode	External costs for 1 %-time preference rate in €-ct/Pkm	External costs for 0 %-time preference rate in €-ct/Pkm	Cost increase between 1 %- and 0 %-time preference rate in %
Bus Diesel	11.36	16.18	42%
Tram	8.01	8.09	1%
Subway	3.99	4.06	2%
Regional Train	4.62	5.04	9%
Moped Electric	10.58	11.50	9%
Moped Gasoline	14.87	18.41	24%
Motorcycle	16.56	21.90	32%
Car BEV	14.15	16.90	19%
Car PHEV	15.03	19.68	31%
Car Diesel	16.97	23.71	40%
Car Gasoline	15.90	22.38	41%
Car-Sharing Electric	13.71	17.00	24%
Car-Sharing Gasoline	15.80	23.55	49%
Moped Sharing	10.87	11.79	8%
e-Scooter Sharing	19.21	19.53	2%
Walking	0.70	0.70	0%
Bicycle	6.72	6.72	0%
Pedelec	8.17	8.36	2%

uncertainties in the method is higher (Bastani, Heywood, & Hope, 2012; Delucchi, 2000; Tol, 2005).

Another discussion of uncertainties is necessary for the economic valuation of externalities. Different methods are highlighted in the literature such as estimations of damage, avoidance or replacement costs (Dyr, Misiurski, & Ziółkowska, 2019; Nocera & Cavallaro, 2014; Verhoef, 1994). To show the variation of the results, a sensitivity analysis for a variation of the economic value of GHG emissions is discussed in the following. Changing the time preference rate from 1% to 0% (Section 3.1.2) would increase the climate costs for one ton of CO_2 equivalent from 195 € to 680 € (Table A10). The comparison of external cost results for both inputs is shown in Table 4.

The sensitivity is highest for vehicles with combustion engines (Diesel and Gasoline Cars and Car-Sharing, Motorcycle) or propelled with electric power from high shares of non-renewable energy sources (Car BEV). These transport modes show a change between 20% and 50% in external costs when increasing the economic valuation of GHG emissions.

The third uncertainty is caused by a possible misalignment between adopted policy and results obtained. Studies have shown that policies that try to implement the polluter-pays-principle could lead to unexpected or undesirable results such as social injustice or even increased externalities (Cavallaro & Nocera, 2022; Jephcote, Chen, & Ropkins, 2016). Additionally, the behavior of the people and their willingness-to-pay could differ from the expected result of the planned policy. This needs to be considered when implementing pricing mechanisms. This is why, cities (such as Munich) should interpret the results more cautiously and take it as a rough roadmap for long-term strategies. Furthermore, stakeholders should take additional studies and recommendations into consideration.

The focus of this paper is on passenger transport only due to data availability and the focus on policy recommendations for people's travel behavior. However, freight transport has an essential share in the generation of externalities in the transport sector. The method developed in this paper in addition to a different data base on freight traffic could be used to quantify external costs of commercial transport. The effect of logistic hubs, cargo bikes, etc. could be measured in terms of external

costs. Although trends for urban last mile delivery seems to be going in the direction of using electrified vehicles and bikes, freight transport in urban areas is still dominated by trucks and smaller commercial vehicles with low electrification rates. This is why, on a qualitative level fright transport is expected to have much higher external costs than passenger cars per vehicle kilometer.

Due to the macro level view of this model and many simplifications in the modelling, these results should not be used for highly detailed or spatial- and time-specific investigations in terms of external costs. Additionally, the scenarios shown in section 4.2 would – in reality - lead to a substantial change of the transport system which is not realized in a short-term development. This is why, the scenario analysis shows a theoretical estimation of external cost developments and recommends a strategic direction in transport planning for external cost reductions.

6. Conclusion

This paper proposes an extensive, exploratory analysis of external costs for mobility in Munich. The suggested methodology and results consider all relevant transport modes available in Munich, including subgroups of public transport, motorized individual transport, sharing services and active mobility. Therefore, it is more detailed on the level of transport modes compared to recent literature. The main contributions are (i) the development of a methodology to calculate the external costs of different transport modes, (ii) computation and comparison of external costs for Munich, and (iii) potential impacts of modal shifts on external costs.

The results show that almost 80% of all external costs are caused by diesel and gasoline cars in Munich and a massive increase in modal shares of active mobility and public transport is recommended in order to reduce external costs. Electrification of the vehicle fleets reduces the overall external costs only to a limited extent compared to mode shifts to more sustainable transport modes.

Transparency of external costs allows for planning and policy implications: The overall objective of a future-oriented, sustainable, environmentally friendly, resource efficient and more social transport policy should be a usage-related charge of costs according to the "polluter-pays principle". An essential element is the internalization of external costs since external costs are typically disregarded by consumers when taking economic decisions. On the other hand, subsidization of high external cost modes must be eliminated. This methodology can act as a decision-support tool in order to transform mobility towards a more sustainable future. Cost transparency enables and encourages a fact-based public discourse about critical topics such as car-free city centers. The external costs analysis for Munich has shown that a reduction of individual motorized transportation, mainly including cars, results in a significant reduction of external costs. Only an all-encompassing view allows good decisions for society, the economy and the environment.

Several important aspects have been identified but remain insufficiently explored. Parameter and input values can be refined for different modes and forms of mobility. Ultimately, the development of a comprehensive cost calculator is projected, a multimodal routing tool for relevant transport modes in Munich, including internal and external costs. Further strategic scenarios including full cost-based pricing schemes can be derived and implemented in agent-based simulation tools. The results can show how citizens and the modal share might react to potential price changes and hence how overall internal and external costs might change in the city. For this purpose, further surveys and data about price sensitivity of people are needed.

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CRediT authorship contribution statement

Daniel Schröder: Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft. **Lukas Kirn:** Data curation, Formal analysis, Investigation, Methodology, Visualization. **Julia Kinigadner:** Conceptualization, Validation, Writing – original draft, Writing – review & editing. **Allister Loder:** Validation, Writing – original draft, Writing – review & editing. **Philipp Blum:** Investigation, Resources, Writing – original draft. **Yihan Xu:** Investigation, Resources, Writing – original draft. **Markus Lienkamp:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare no conflicts of interest, and the funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Data availability

Data is published at https://nam11.safelinks.protection.outlook. com/?url=https%3A%2F%2Fzenodo.org%2F&data=05%7C01% 7Ca.begum%40elsevier.com%7C67a64db9ccb54f7bbc6b 08dac65a1728%7C9274ee3f94254109a27f9fb15c10675d%7C0% 7C0%7C638040387538998520%7CUnknown%7CTWFpbGZsb3 d8eyJWIjoiMC4wLjAwMDAiLCJQIjoiV2luMzIiLCJBTiI6Ik1haWwwiLC JXVCI6Mn0%3D%7C3000%7C%7C%7C&sdata=IQlq9EhH% 2Faj88L5MqVPNfVXgbykzR0D%2BZXhi2OLvnMM%3D& reserved=0 with same title and DOI as the paper.

Appendix

Abbreviation list

a	annual (in the formula)
AADT	Annual Average Daily Traffic (in the formula)
AM	Active Mobility
BASt	Federal Highway Research Institute Bundesanstalt für Straβenwesen
BEV	Battery Electric Vehicle
BMBF	German Ministry of Education and Research
CO2 eq	Carbon Dioxide Equivalent CO_2-Äquivalente
CYC	Cyclist Volume (in the formula)
Destatis	Federal Statistical Office of Germany Statistische Bundesamt

EU	European Union
GDP	Gross domestic product
HBEFA	Handbook Emission Factors for Road Transport
HEAT	Health Economic Assessment Tool
ICE	Internal Combustion Engine
INFRAS	Swiss Consulting Company for Sustainable Development
INRIX	American Company for Data Analytics
KBA	Federal Motor Vehicle Office of Germany Kraftfahrtbundesamt
kWhel	Kilowatt hour electric Kilowattstunden elektrisch
l	liter
L(DEN)	Day–Evening–Night Noise Level
MiD	Mobility in Germany Mobilität in Deutschland
MJ	Megajoule
Mn. €	Million Euros
MV	Motor Vehicles
NWF	Noise Weighting Factor
OECD	Organization for Economic Co-operation and Development
PED	Pedestrian Volume (in the formula)
PHEV	Plug-in Hybrid Electric Vehicle
Pkm	Person kilometer
PT	Public Transport
TREMOD	Transport Emission Model
UBA	Federal Environment Agency of Germany Umweltbundesamt
Vkm	Vehicle kilometer
VSL	Value of a Statistical Life
WHO	World Health Organization

Table A.1

Citizens and mortality rate in Munich urban Area

Description	Value	Year
Total	1,488,202 citizens[1]	2020
20–74 years	1,085,496 citizens[1]	2020
20–64 years	965,590 citizens[1]	2020
20–74 years	0.004832 deaths/citizen[2]	2021
20–64 years	0.002650 deaths/citizen[2]	2021

Sources: [1]Bayerisches Landesamt für Statistik, GENESIS-Online: Bevölkerung: Gemeinden, Stichtage (letzten 6). Ergebnis 12411-001. [Online]. Verfügbar unter: https://www.statistikdaten.bayern.de/genesis/online;jsessionid=6CB3363574391F9435FD661D9125B699?sequenz=tabelleErgebnis&selectionname=12411-001#abreadcrumb (Zugriff am: 15. Juli 2021).; [2]Statistisches Bundesamt, „Fortschreibung des Bevölkerungsstandes: Bevölkerung: Kreise, Stichtag, Altersgruppen", 2021. World Health Organization, Health Economic Assessment Tool (HEAT) for walking and cycling: v. 4.2. [Online]. Verfügbar unter: https://www.heatwalkingcycling.org/#homepage (Zugriff am: 16. Februar 2021).

Table A.2

Annual transport performance per means of transport in Munich

Transport mode	Annual mileage in Mn. Vkm/a	Transport service in Mn. Pkm/a	Number of vehicles
Public Transport	70.40[1]	approx. 4500	
Bus	37.36[2]	A[3]	675[2]
Tram	8.87[2]	A[3]	134[2]
Subway	12.00[2]	A[3]	702[2]
Regional Train	7.64[5]	1585.08[4]	
Motorized Individual Transport	7811.00	12,191.00	
Moped	86.57[11]	88.30[13]	
Electric	0.78[11]	0.79[13]	181[14]
Gasoline	85.01[11]	86.71[13]	19788[14]
Sharing	1.54[12]	1.57[13]	1000[15]
Motorcycle	278.20[11]	308.80[13]	64755[16]
Car	7446.23[8]	11,169.34[13]	
BEV	85.16[11]	127.75[13]	8284[17]
Hybrid	316.77[11]	475.16[13]	
PHEV	109.59[11]	164.39[13]	10660[17]
Diesel	2495.82[11]	3743.73[13]	242771[17]
Benzin	4401.09[11]	6601.63[13]	428099[17]
Carsharing	65.44[12]	91.61[13]	2400[10]

(continued on next page)

Table A.2 (*continued*)

Transport mode	Annual mileage in Mn. Vkm/a	Transport service in Mn. Pkm/a	Number of vehicles
Others			
Walking	620.50[13]	620.50[6]	
Bicycle	1131.50[13]	1131.50[6]	
Classic	1103.21[13]	1103.21[11]	975000[6]
Pedelec	28.29[13]	28.29[11]	25000[6]
e-Scooter	11.61[7]	11.61[13]	5401[7]

Sources: [1]Statistisches Bundesamt, 2019. Verkehr: Personenverkehr mit Bussen und Bahnen. 2017. Fachserie 8 Reihe 3.1, 87 pp. https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Transport-Verkehr/Personenverkehr/Publikationen/Downloads-Personenverkehr/personenverkehr-busse-Bahnen-jahr-2080310177004.pdf?_blob=publicationFile. Accessed 3 March 2021.; [2]Münchner Verkehrs- und Tarifverbund GmbH, 2020. Der MVV in Zahlen und Fakten, München, 11 pp. https://www.mvv-muenchen.de/fileadmin/Servicedownloads/MVV-Statistikbroschuere-20S-Online.pdf. Accessed 12 March 2021.; [3]Leiter Mobilitätsforschung MVG, 2021. Beförderungsleistung MVG 2019. per e-Mail, München.;[4]Leiter Produktionsplanung S-Bahn München, 2021a. Beförderungsleistung S-Bahn München. e-Mail.[5]Leiter Produktionsplanung S-Bahn München, 2021c. Fahrleistung S-Bahn München. e-Mail.;[6]Follmer, R., Belz, J., 2019. Mobilität in Deutschland – MiD: Kurzreport Stadt München, Münchner Umland und MVV-Verbundraum. infas; DLR; IVT; infas 360, Bonn, Berlin, 24 pp. https://www.muenchen-transparent.de/dokumente/5499206/datei. Accessed 26 February 2021.;[7]Tack, A., Klein, A., Bock, B., 2019. E-Scooter in Deutschland. https://scooters.civity.de/. Accessed 3 March 2021.;[8]Calculated via domestic mileage according to Bäumer et al.: Bäumer, M., Hautzinger, H., Pfeiffer, M., Stock, W., Lenz, B., Kuhnimhof, T.G., Köhler, K., 2017b. Fahrleistungserhebung 2014 - Inlandsfahrleistung und Unfallrisiko. Fachverlag NW, Bremen, 103 pp.; [9]Statistisches Amt der Landeshauptstadt München, „Personenkraftwagenbestand 2018 - 2020 nach Kraftstoffart", 2021. [Online]. https://www.muenchen.de/rathaus/dam/jcr:9caf4e7e-cb8e-4734-87fc-6397f91d050f/jt210706.pdf. Accessed 26. July 2021.; [10]Bundesverband CarSharing e.V. (bcs), "CarSharing Städteranking 2019," Dez. 2019. [Online] Verfügbar: https://carsharing.de/sites/default/files/uploads/tabelle_staedteranking_2019_0.pdf. (Accessed: March 10 2021).; [11]Calculated via share of vehicles in Munich; [12]Own calculation according to expert estimate; [13]Calculated via average occupancy rate;[14]M. Allekotte, K. Biemann, C. Heidt, M. Colson, und W. Knörr, "Aktualisierung der Modelle TREMOD/TREMOD-MM für die Emissionsberichterstattung 2020 (Berichtsperiode 1990-2018): Berichtsteil "TREMOD"," Dessau-Roßlau, Texte 116, Jun. 2020. [Online] Verfügbar: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-06-29_texte_116-2020_tremod_2019_0.pdf. Gefunden am: Mrz. 03 2021.[15]G. Harlander, "Fahrleistung Sharing-Fahrzeuge München", e-Mail, Apr. 2021.[16] Statistisches Amt der Landeshauptstadt München, Monatszahlen-Monitoring München: Kfz-Bestand. [Online] Verfügbar: https://www.mstatistik-muenchen.de/monatszahlenmonitoring/export/export.php. Gefunden am: Feb. 26 2021.[17] Statistisches Amt der Landeshauptstadt München, „Personenkraftwagenbestand 2018 - 2020 nach Kraftstoffart", 2021. [Online]. Verfügbar unter: https://www.muenchen.de/rathaus/dam/jcr:9caf4e7e-cb8e-4734-87fc-6397f91d050f/jt210706.pdf. Zugriff am: 26. Juli 2021.[A]values are confidential, but were available for calculation

Table A.3

Power mix for different areas in Germany and Munich area

Power generation type	Power mix country (for all private vehicles)[1]	Power mix public transport[2]	Power mix trains[3]
Water power	4%	100%	25%
Wind energy	27%	0%	10%
Solar power	11%	0%	12%
Bio mass	9%	0%	10%
Brown coal	17%	0%	7%
Black coal	7%	0%	18%
Gas	12%	0%	8%
Oil	0%	0%	0%
Nuclear energy	13%	0%	9%

Sources: [1]B. Burger und K. Schneider, Nettostromerzeugung in Deutschland 2020: erneuerbare Energien erstmals über 50 Prozent. [Online] https://www.ise.fraunhofer.de/de/presse-und-medien/news/2020/nettostromerzeugung-in-deutschland-2021-erneuerbare-energien-erstmals-ueber-50-prozent.html. (Accessed: Apr. 28 2021).; [2]Landeshauptstadt München, Ökostrom für Tram und U-Bahn. [Online]. https://www.muenchen.de/aktuell/2018-01/oekostrom-fuer-muenchner-tram-und-u-Bahn.html (Accessed: 9. March 2021).; [3]Deutscher Bundestag, „Drucksache 19/10121: Antwort der Bundesregierung auf die Kleine Anfrage der Abgeordneten Matthias Gastel, Lisa Badum, Dr. Julia Verlinden, weiterer Abgeordneter und der Fraktion BÜNDNIS 90/DIE GRÜNEN".; en:former, Der Bahnstrommix soll grüner werden: Europäische Eisenbahnbetriebe wollen klimafreundlicher werden – mit sehr unterschiedlichen Ambitionen. [Online]. https://www.en-former.com/klimaziele-und-projekte-von-bahnunternehmen-in-europa/ (Accessed: 4. August 2021).

Table A.4

Affected person statistics for road and rail traffic noise in Munich[1]

L_{DEN} in dB (A)	Street	Subway/Tram	Train (EBA)
55–59	95,000	15,200	65,810
60–64	69,400	13,600	21,890
65–69	66,400	10,900	9270
70–74	21,900	1700	3570
≥75	1500	0	1350

Source: [1]Eisenbahn-Bundesamt, o.J. Lärmstatistik: Gemeinde: München. http://laermkartierung1.eisenbahn-bundesamt.de/mb3/app.php/statistik?id=7914&br=false&gemeinde=M%C3%BCnchen. Accessed 22 July 2021.

Table A.5

Infrastructure investments and number and profit of parking spaces for Munich

Description	Value
Street infrastructure investments for 5 years	621 million €[1]
Public transport infrastructure investments for 5 years	619 million €[1]
Investment for bicycle infrastructure per person per year	2.30 €[2]
Number of public parking spaces	82000[3]
Profit per parking space	240 €[4]

Sources: [1]https://stadt.muenchen.de/infos/haushalt-finanzen.html; [2]https://www.sueddeutsche.de/muenchen/greenpeace-studie-muenchen-gibt-pro-kopf-2-30-euro-fuer-radverkehr-aus-in-berlin-ist-es-doppelt-so-viel-1.4108087; [3]Referat für Stadtplanung und Bauordnung der Landeshauptstadt München, 2017. Parkraummanagement in München – Fortschreibung Sektor V, 104 pp. https://www.muenchen-transparent.de/dokumente/4747147/datei.; [4]Becker, S., 2008. Landeshauptstadt München: Parkraummanagement Wirtschaftlichkeitsuntersuchung. Endbericht zum Projekt Nr. 0649, Hannover, 61 pp.

Table A.6

Congestion costs and delay data for Munich

Description	Value
Total congestion costs for Munich	405 million €[1]
Average delay for subway	0.837 min[2]
Average delay for regional train	1.168 min[2]
Average delay for bus	2.101 min[2,3]
Average delay for tram	1.861[2,3]
Number of trips with public transport per day	1152000[4]
Costs per hour delay	9 €[5]

Sources: [1]https://inrix.com/press-releases/2019-traffic-scorecard-german/; [2]Martin, L., Wittmann, M., Li, X., 2021. The Influence of Public Transport Delays on Mobility on Demand Services. Electronics 10, 379. 10.3390/electronics10040379.;[3]own calculations based on punctuality values from https://www.mvg.de/services/fahrgastservice/mvg-puenktlichkeitswerte.html [4]https://muenchenunterwegs.de/content/657/download/infas-grossraummuenchen-regionalbericht-mid5431-20201204.pdf; [5]own calculations based on INRIX method: https://media.bizj.us/view/img/10360454/inrix2016trafficscorecarden.pdf

Table A.7

Cost rates for the air pollutant emissions in transport considered in this work by emission environment in €$_{2020}$ per ton of emission according to Methodological Convention 3.1 - Cost rates of UBA[1]

	Damage to health in €				Non-health damage
Area	Unknown	Urban	Suburban	Rural	
PM$_{2.5}$	62,900	255,300	73,600	43,200	0
PM$_{coarse}$	1000	4900	1200	600	0
PM$_{10}$	7200	30,000	8500	4900	0
NO$_x$	15,800	15,800	15,800	15,800	3700
SO$_2$	14,900	14,900	14,900	14,900	1500
NMVOC	1200	1200	1200	1200	1000
NH$_3$	24,200	24,200	24,200	24,200	10,900

Assumption: PM10 consists of 10% PM2.5 and 90% PMcoarse.

Source:[1]Matthey, Astrid, Bünger, B., 2020. Methodenkonvention 3.1: Kostensätze. Stand 12/2020, Dessau-Roßlau, 69 pp. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-12-21_methodenkonvention_3_1_kostensaetze.pdf. Accessed 3 March 2021.

Table A.8

Cost rates for direct air pollutant emissions in urban traffic in €$_{2020}$ per vehicle kilometer according to Methodological Convention 3.1 - UBA cost rates[1], own calculations.

Vehicle class	Emission concept	Exhaust in €	Abrasion in €
Bus	Diesel	14.63	0.86
Tram	Electric	0	1.45
Subway	Electric	0	1.45
Regional train	Electric	0	1.45
Moped	Gasoline	0.68	0.03
Moped	Electric	0	0.03
Motorcycle	Gasoline	0.38	0.03
Car	BEV	0	0.11

Table A.8 (*continued*)

Vehicle class	Emission concept	Exhaust in €	Abrasion in €
Car	PHEV	0.13	0.11
Car	Diesel	1.68	0.11
Car	Gasoline	0.27	0.11

Source:[1]Matthey, Astrid, Bünger, B., 2020. Methodenkonvention 3.1: Kostensätze. Stand 12/2020, Dessau-Roßlau, 69 pp. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-12-21_methodenkonvention_3_1_kostensaetze.pdf. Accessed 3 March 2021.

Table A.9

Emission factors of direct greenhouse gas emissions in CO2 equivalent for diesel and gasoline[1]

Fuel type	Direct greenhouse gas emissions in kg $CO_{2\,eq}$/l
Diesel	2.458
Gasoline	2.131

Source:[1]Umweltbundesamt GmbH, 2020. https://secure.umweltbundesamt.at/co2mon/co2mon.html. Accessed 22 April 2021.

Table A.10

Climate damage costs in $€_{2020}$/t $CO_{2\,eq}$ for the years 2020, 2030 and 2050[1]

	2020	2030	2050
0% pure time preference rate	680	700	765
1% pure time preference rate	195	215	250

Source:[1]Matthey, Astrid, Bünger, B., 2020. Methodenkonvention 3.1: Kostensätze. Stand 12/2020, Dessau-Roßlau, 69 pp. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-12-21_methodenkonvention_3_1_kostensaetze.pdf. Accessed 3 March 2021.

Tabel A.11

Air pollution costs of fuel production in €-ct$_{2020}$ per liter fuel, own calculations[1]

Fuel type	Air pollution costs of upstream process in €-ct$_{2020}$/l
Diesel	4.75
Gasoline	4.34

Source:[1]own calculations based on: Matthey, Astrid, Bünger, B., 2020. Methodenkonvention 3.1: Kostensätze. Stand 12/2020, Dessau-Roßlau, 69 pp. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-12-21_methodenkonvention_3_1_kostensaetze.pdf. Accessed 3 March 2021

Tabel A.12

Greenhouse gas emissions of fuel production for Diesel and gasoline[1], own calculations

Fuel type	g CO2 eq/MJ	kg CO2 eq/liter
Diesel	18.9	0.592
Gasoline	17.0	0.673

Source:[1]Prussi, M., Yugo, M., Prada, L. de, Padella, M., Edwards, R., Lonza, L., 2020. JEC Well-to-Tank report v5: Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context. EUR 30269 EN. Publications Office of the European Union; Joint Research Center, Luxemburg, 248 pp. https://doi.org/10.2760/959137. Accessed 26 July 2021.

Table A.13

Air pollution costs and greenhouse gas emissions of electricity generation in Germany including upstream chains[1], own calculations

	Air pollution costs (in €-ct$_{2020}$/kWh$_{el}$)	GHG emissions (in kg $CO_{2\,eq}$/kWh$_{el}$)
Fossile energies		
Lignite	2.05	1.056
Hard coal	1.68	0.975
Natural gas	0.87	0.435
Oil	5.18	0.847

Table A.13 (*continued*)

	Air pollution costs (in €-ct$_{2020}$/kWh$_{el}$)	GHG emissions (in kg CO$_{2\ eq}$/kWh$_{el}$)
Renewable energies		
Hydropower	0.06	0.013
Wind energy	0.11	0.010
Photovoltaics	0.43	0.069
Biomass	3.94	0.247

Note: Biomass and wind energy are weighted averages according to generation shares (gaseous/liquid/solid and offshore/onshore, respectively).

Source: [1]Matthey, Astrid, Bünger, B., 2020. Methodenkonvention 3.1: Kostensätze. Stand 12/2020, Dessau-Roßlau, 69 pp. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-12-21_methodenkonvention_3_1_kostensaetze.pdf. Accessed 3 March 2021.

Table A.14

Cost rates for environmental noise by noise cause and sound level in €$_{2020}$ per affected person per year[1]

L$_{DEN}$ in dB (A)	Street in €	Train in €
35–39	0.00	0.00
40–44	0.00	0.00
45–49	29.46	9.40
50–54	62.65	23.13
55–59	116.38	54.42
60–64	196.34	107.85
65–69	306.27	185.35
70–74	454.91	293.21
≥75	650.74	437.38

Source:[1]Matthey, Astrid, Bünger, B., 2020. Methodenkonvention 3.1: Kostensätze. Stand 12/2020, Dessau-Roßlau, 69 pp. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-12-21_methodenkonvention_3_1_kostensaetze.pdf. Accessed 3 March 2021.

Table A.15

Overview of noise weighting factors (NWF) for allocating noise costs by mode of transport[1,2,3], Electric moped: own assumptions

Vehicle class	Urban (50 km/h)	Rural (80 km/h)
Car Others	1.0	1.0
Car Gasoline	1.0	1.0
Car Diesel	1.2	1.0
Moped	9.8	3.0
Electric Moped	1.0	
Motorcycle	13.2	4.2
Bus	9.8	3.3
Transport Vehicle	1.5	1.2
Small Truck	9.8	3.0
Large Truck	13.2	4.2
Semi-trailer	16.6	5.5
Passenger Train	1	
Freight Train	4	

Sources:[1]Maibach, M., Schreyer, C., Sutter, D., van Essen, H., Boon, B.H., Smokers, R., Schroten, A., Doll, C., Pawlowska, B., Bak, M., 2008. Handbook on estimation of external costs in the transport sector: Internalisation Measures and Policies for All external Cost of Transport (IMPACT). INFRAS; CE Delft; Fraunhofer ISI; University of Gdansk, 336 pp.[2]Saighani, A., 2020. Bewertungsverfahren für einen ökonomischen Vergleich städtischer Verkehrssysteme. Dissertation. Universität Kassel, Kassel, 387 pp. 10.17170/kobra-202009241843.[3]van Essen, H., Fiorello, D., El Beyrouty, K., Bieler, C., van Wijngaarden, L., Schroten, A., Parolin, R., Brambilla, M., Sutter, D., Maffii, S., Fermi, F., 2020. Handbook on the external costs of transport: Version 2019–1.1. Publications Office of the European Union, Luxemburg, 332 pp. 10.2832/51388.

Table A.16
External barrier effect costs

Transport mode	Costs in €-ct$_{2020}$/vkm
Car	2.27[1]
Bus	3.73[1]
Motorcycle	2.27[1]
Bicycle	0.16[1]
e-Scooter	0.16[2]
Moped	1.22[2]

Sources: [1]Victoria Transport Policy Institute, 2022. Transportation Cost and Benefit Analysis II – Barrier Effect. https://www.vtpi.org/tca/tca0513.pdf. Accessed 1 July 2022.[2]own assumptions / calculations

Table A.17
Correction factors to account for the number of unreported traffic accidents with personal injury[1,2]

Traffic participation type	Injury severity		
	Lightly injured	Seriously injured	Killed
Motorized*	2.00	1.82	1.00
Bicycle	5.00	3.33	1.00
Walking	2.86	2.00	1.00

* without participation from public transport.

Sources: [1]Hautzinger, H., Dürholt, H., Hörnstein, E., Tassaux-Becker, B., 1993. Dunkelziffer bei Unfällen mit Personenschäden. Berichte der BASt Heft M13. Bundesanstalt für Straßenwesen, Bremerhaven.[2]Saighani, A., 2020. Bewertungsverfahren für einen ökonomischen Vergleich städtischer Verkehrssysteme. Dissertation. Universität Kassel, Kassel, 387 pp. 10.17170/kobra-202009241843

Table A.18
Accident cost rates in €$_{2020}$ per person involved in an accident according to injury severity[1,2,3,4,5], own calculations

	Injury severity in €		
	Lightly injured	Seriously injured	Killed
Reproduction costs[3]	1274	24,923	19,775
Resource downtime costs[4]	979	64,726	129,913
Extra-market costs[4]	525	33,506	529,059
Total causers	**2778**	**123,155**	**678,747**
Intangible costs[5]	37,300	496,090	3,730,000
Total non-causers	**40,078**	**619,245**	**4,408,747**

Sources: [1]Becker, U., Rau, R.G.A., Zimmermann, F., 2001. Ermittlung der Kosten und Nutzen von Verkehr in Sachsen: Hauptstudie. Arbeitsstand 11/2001. Technische Universität Dresden, Dresden, 114 pp. 10.1007/3-8350-5713-8_4.[2]Becker, U.J., Gerike, R., Rau, A., Zimmermann, F., 2002. Ermittlung der Kosten und Nutzen von Verkehr in Sachsen: Hauptstudie. Abschlussbericht. Lehrstuhl für Verkehrsökologie, Technische Universität Dresden, Dresden, 214 pp.[3]Baum, H., Kranz, T., Westerkamp, U., 2010. Volkswirtschaftliche Kosten durch Straßenverkehrsunfälle in Deutschland: Bericht zum Forschungsprojekt FP 82.321/2007: Ermittlung der volkswirtschaftlichen Kosten durch Straßenverkehrsunfälle in Deutschland. Berichte der Bundesanstalt für Straßenwesen M, Mensch und Sicherheit FP-82.321/2007, Bremerhaven, 96 pp.[4]Neumann, A., 2014. Ermittlung der externen Kosten des Verkehrs in Sachsen. Diplomarbeit, Dresden, 71 pp.[5]World Health Organization, 2019. Health Economic Assessment Tool (HEAT) for walking and cycling: v. 4.2. https://www.heatwalkingcycling.org/#homepage. Accessed 16 February 2021.

Table A.19
Assumed space requirement for parking spaces in m^2 according to means of transport

Transport mode	Space requirement
Moped	2.30[1]
Motorcycle	2.76[2]
Car	11.27[3]
Bicylce/Pedelec	1.60[4]
e-Scooter	1.40[5]

Sources: [1]Author's estimate[2]Stadt Zürich, 2007. Gestaltungs-Standards: Stadträume: Parkierung. Stadträume 2010 - Umsetzung der Strategie für die Gestaltung von Zürichs öffentlichem Raum, Zürich, 26 pp.[3]Basler Zeitung, 2018. Autos werden immer breiter und länger. https://www.bazonline.ch/auto/autos-werden-immer-breiter-und-laenger/story

/25635086. Accessed 30 April 2021.[4]Steger-Vonmetz, C., Reis, M., 2018. leitfaden FAHRRAD-PARKEN. Energieinstitut Vorarlberg; Amt der Vorarlberger Landesregierung, 32 pp. https://ec.europa.eu/transport/sites/transport/files/cycling-guidance/leitfaden_fahrradparken.pdf. Accessed 7 May 2021. [5]Geis, I., Díaz, A.V., Wagner, N., Lietz, S., 2019. Analyse heutiger und zukünftiger Anwendungsfelder: Steckbriefe mikromobiler Fahrzeugtypen. Zukunftsfeld Mikromobile. Fraunhofer-Institut für Materialfluss und Logistik, 30 pp.

Table A.20
Masses, velocities and kinetic energies in urban traffic[1-9],own calculations

Transport mode	Mass in kg	Average velocity in m/s	Kinetic energy in J
Bus	17,185	6.70	385,719
Tram	37,874	6.70	850,091
Moped	189	9.60	8695
Motorcycle	291	9.60	13,393
Car	1588	9.70	74,690
Walking	77	1.47	84
Bicycle	93	3.89	704
Pedelec	100	3.89	754
E-Scooter	108	3.89	818
Truck	16,000	8.60	591,680
Transporter	3500	8.60	129,430
Others	16,000	8.60	591,680

Sources: [1]Mensink, G.B.M., Schienkiewitz, A., Haftenberger, M., Lampert, T., Ziese, T., Scheidt-Nave, C., 2013. Übergewicht und Adipositas in Deutschland: Ergebnisse der Studie zur Gesundheit Erwachsener in Deutschland (DEGS1). Bundesgesundheitsblatt, Gesundheitsforschung, Gesundheitsschutz 56, 786–794. 10.1007/s00103-012-1656-3.[2]World Health Organization, 2019. Health Economic Assessment Tool (HEAT) for walking and cycling: v. 4.2. https://www.heatwalkingcycling.org/#homepage. Accessed 16 February 2021.[3]Geis, I., Díaz, A.V., Wagner, N., Lietz, S., 2019. Analyse heutiger und zukünftiger Anwendungsfelder: Steckbriefe mikromobiler Fahrzeugtypen. Zukunftsfeld Mikromobile. Fraunhofer-Institut für Materialfluss und Logistik, 30 pp.[4]Mein Fahrradträger, 2020. Wie schwer ist ein Fahrrad? https://mein-fahrradtraeger.de/wie-schwer-ist-ein-fahrrad/. Accessed 10 May 2021.[5]Saighani, A., 2020. Bewertungsverfahren für einen ökonomischen Vergleich städtischer Verkehrssysteme. Dissertation. Universität Kassel, Kassel, 387 pp. 10.17170/kobra-202009241843. [6]mobitool, 2021. mobitool-Faktoren v2.1: Die Excel-Datenbank mit aufbereiteten ecoinvent-Umweltdaten und Emissionsfaktoren (Update 2020). SBB CFF FFS; swisscom; Der Verban für nachhaltiges Wirtschaften; energie schweiz; Schweizerische Eidgenossenschaft - Bundesamt für Umwelt. https://www.mobitool.ch/de/tools/mobitool-faktoren-v2-1-25.html. Accessed 26 July 2021.[7]Münchner Verkehrsgesellschaft mbH, 2021. U-Bahn, Bus und Tram: Unsere Fahrzeuge. Münchner Verkehrsgesellschaft mbH. https://www.mvg.de/ueber/das-unternehmen/fahrzeuge.html. Accessed 10 May 2021.[8]Kraftfahrt-Bundesamt (KBA), 2021b. Neuzulassungen von Pkw in den Jahren 2010 bis 2019 nach technischen Merkmalen. https://www.kba.de/DE/Statistik/Fahrzeuge/Neuzulassungen/Motorisierung/fz_n_motorisierung_archiv/2019/2019_n_motorisierung_pkw_zeitreihe_techn_merkmale.html?nn=2601598. Accessed 10 May 2021.[9]MOTORselling, 2021. Motorroller 25km/h 45km/h 125 cc. https://www.motorselling.de/www-motor-selling-de. Accessed 10 May 2021.

Table A.21
Overall land use data including parking costs and space requirements

Description	Value
Land use per person for car	[2]65.2 m^2
Land use per person for bicycle/motorcycle/moped	[2]41 m^2
Land use per person for bus (20% occupancy)	[2]8.6 m^2
Construction costs per parking space	17,644 €[1]
Lifetime of a parking space	25 years[1]
Maintenance costs per year for a parking space	4,037 €[1]
Opportunity costs for parking space per m^2	36.50 €[4]
Size of parking space	[4]11.5 m^2
Standing time per day for sharing cars	20 hours[3]
Standing time per day for private cars	23 hours[3]
Opportunity costs for side walk parking per m^2	4.00 €[5]

Sources: [1]Ulrich, Axhausen, Fuhrer, 2017. Eine Kosten-Nutzen-Analyse für den Parkplatz. Institut für Verkehrsplanung und Transportsystem - ETH Zürich.[2]Randelhoff, M., 2019. Vergleich unterschiedlicher Flächeninanspruchnahmen nach Verkehrsarten (pro Person). https://www.zukunft-mobilitaet.net/78246/analyse/flaechenbedarf-pkw-fahrrad-bus-strassenbahn-stadtbahn-fussgaenger-metro-bremsverzoegerung-vergleich/. Accessed 5 July 2022.[3]Abarzúa, T., 2015. CARSHARING UND ELEKTROMOBILITÄT. https://www.sonnenenergie.de/sonnenenergie-redaktion/SE-2015-06/Layout-fertig/PDF/Einzelartikel/SE-2015-06-s040-Mobilitaet-Carsharing_und_El

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Table A.22
Calculation parameters used in HEAT[1]

	Bicycle traffic	Pedestrian traffic	Unit
Relative mortality risk (*RR*)	0.903 (0.87–0.94)*	0.886 (0.83–0.96)*	-
Reference duration	100	168	minutes/week
Reference speed	14	4.8	km/h
Applicable age group	20–64	20–74	years
Upper limit for risk reduction	45	30	% minutes/week
	450	458	
Value of statistical life	3,730,000		€$_{2020}$

*95 %- Confidence interval.
Source: [1]World Health Organization. Health economic assessment tool (HEAT) for walking and for cycling: Methods and user guide on physical activity, air pollution, injuries and carbon impact assessments, 86 pp. https://www.euro.who.int/_data/assets/pdf_file/0010/352963/Heat.pdf.

Table A.23
Gasoline, diesel and electricity consumption by mode of transport. Where necessary, the consumption values were converted to the fleet used as a basis in the work.

Transport mode	Propulsion type	Fuel consumption in l/100 km	Energy consumption in kWh/100 km
Bus	Diesel	51.7[1]	
Bus	Electric		151.3[2]
Tram	Electric		428.4[3]
Subway	Electric		1649.6[3]
Regional train	Electric		400.0[4]
Moped	Gasoline	2.9[5]	
Moped	Electric		3.5[5]
Motorcycle	Gasoline	4.8[5]	
Car	Gasoline	7.8[6]	
Car	Diesel	5.5[6]	
BEV	Electric		15.4[5]
PHEV	Gasoline a. Electric	3.8[5]	8.3[5]
Carsharing	Gasoline a. Electric	6.2[5,6]	3.1[5,6]
Pedelec	Electric		0.7[5]
e-Scooter	Electric		1.2[5]

Source: [1]Schmied, M., Mottschall, M., 2019. Berechnung des Energieverbrauchs und der Treibhausgasemissionen des ÖPNV, 60 pp. https://www.bmvi.de/SharedDocs/DE/Anlage/G/energieverbrauch-treibhausgasemission-oepnv.pdf?_blob=publicationFile.[2]ViriCiti. Report E-Bus Performance: 100+ e-buses, 7 pp. https://viriciti.com/wp-content/uploads/2020/07/ViriCiti-E-Bus-Performance-Report-July2020.pdf. Accessed 9 August 2021.[3]Stadtverwaltung München, 2020. Strommix und Stromverbrauch der MVG. https://fragdenstaat.de/anfrage/strommix-und-stromverbrauch-der-mvg/. Accessed 22 July 2021[4]Leiter Produktionsplanung S-Bahn München, 2021b. Energieverbrauch S-Bahn München. e-Mail, München.[5]König, A., Nicoletti, L., Schröder, D., Wolff, S., Waclaw, A., Lienkamp, M., 2021b. An Overview of Parameter and Cost for Battery Electric Vehicles. WEVJ 12, 21. 10.3390/wevj12010021.[6]Bundesministerium für Verkehr und digitale Infrastruktur, 2020. Verkehr in Zahlen 2020/2021. Verkehr in Zahlen, Flensburg, 372 pp. https://www.bmvi.de/SharedDocs/DE/Publikationen/G/verkehr-in-zahlen-2020-pdf.pdf. Accessed 13 March 2021.

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