

# Decarbonizing urban transport in European cities: four cases show possibly high co-benefits

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## Abstract

Cities worldwide are increasingly becoming agents of climate change mitigation, while simultaneously aiming for other goals, such as improved accessibility and clean air. Based on stakeholder interviews and data analysis, we assess the current state of urban mobility in the four European cities of Barcelona, Malmö, Sofia and Freiburg. We then provide scenarios of increasingly ambitious policy packages, reducing greenhouse gas emissions from urban transport by up to 80% from 2010 to 2040. We find significant concurrent co-benefits in cleaner air, reduced noise ambience, fewer traffic-related injuries and deaths, more physical activity, less congestion and monetary fuel savings. Our scenarios suggest that non-motorized transport, especially bicycles, can occupy high modal shares, particularly in cities with less than 0.5 million inhabitants. We think that this kind of multi-criteria assessment of social costs and benefits is a useful complement to cost–benefit analysis of climate change mitigation measures.

**Keywords:** urban transport, climate change mitigation, co-benefits, synergetic policy packages, multi-criteria assessment, Europe

 Online supplementary data available from [stacks.iop.org/ERL/7/044042/mmedia](http://stacks.iop.org/ERL/7/044042/mmedia)

## 1. Introduction

European cities are framed by their long history and often display attractive urban cores. With the 20th century's rise of the automobile, European cities became subject to investments into massive road infrastructure and increasing settlement catchment area. As a consequence of this spatial extension, cities provided more settlement area and associated housing benefits for its citizens. But urban sprawl and

automobility also put environmental, public health and social concerns onto the agenda, notably air pollution, noise-induced stress and climate change, injuries from traffic accidents and social exclusion. Per capita greenhouse gas (GHG) emissions from urban transport alone are often above 2 tCO<sub>2</sub>e/cap, and hence compromise sustainable and equitable levels of GHG emissions (Baer *et al* 2000). To respond to the overarching challenge of climate change, municipalities are willing to aim for large-scale reduction in their urban transport emissions, collectively possibly achieving significant emission reductions (Lutsey and Sperling 2008). The scale of this ambition and the nature of the transport system imply high impact on behavioral change of urban inhabitants (Semenza *et al* 2008). A transition to a low-carbon



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system must hence firmly be embedded in a participatory and deliberative approach and simultaneously address local ambience, environmental quality, and quality of life (Kahn Ribeiro *et al* 2012, Bongardt *et al* 2013).

In this paper, we present an assessment and scenario study of four European cities: Barcelona, Freiburg, Malmö and Sofia. The approach chosen was participatory and recursive and resulted in sustainable urban transport scenarios from 2010 until 2040, quantitatively assessing sustainable transport dimensions and concurrent policies based on aggregate data and municipal stakeholder input.

The sustainability assessment was motivated in the co-benefit approach of Creutzig and He (2009), evaluating a congestion charge for Beijing. Notably, the following dimensions were quantitatively estimated: (A) greenhouse gas emissions; (B) air pollution; (C) noise inconvenience; (D) traffic-related injuries; (E) physical activity benefits; and (F) fuel expenditure.

The sustainability scenarios were evaluated in these dimensions with a focus on GHG emissions. Each city was subjected to four escalating policy packages, adapted to the situation of each city. The first policy packages included current policy programs and technological advancement of fuel efficiency as envisaged by EU regulation. The second policy package, complementary to the first one, focused on 'pull' policies, i.e. policies that make cycling, walking and public transit more attractive. The third additional policy package focuses on 'push' policies, which make car traffic less attractive, comprising both physical and pricing measures. Finally, the fourth policy package attempts to evaluate the long-run potential of land-use policies to reduce greenhouse gas emissions in transportation.

We demonstrate that all four cities can achieve notable reductions in greenhouse gas emissions up to below 0.4tCO<sub>2</sub>/cap if city infrastructures are adapted for pedestrians, cyclists and efficient public transit. We find that Sofia and Barcelona, having more than 1 million inhabitants, will need to rely on public transit for >50% of modal share. In contrast, the smaller cities of Freiburg and Malmö, having less than 500 000 inhabitants, might aim to have up to or more than 50% modal share in cyclists and pedestrians, reflecting shorter distances. The most challenging task for every city is accommodating for car-dependent commuters. This can only be achieved by rail-transit oriented development, careful densification, prohibition of green-field development of retailers, and safe infrastructure for cyclists and e-bikes for intermediate distances.

## 2. Methods and data

### 2.1. Process

Four distinct stages shaped the process: (1) stakeholder self-assessment on transport-related challenges and existing policies; (2) stakeholder meetings and interviews in cities evaluating the current situation and the existing set of policies; (3) quantitative evaluation of key sustainability dimensions and construction of low-carbon and sustainability scenarios

of increasing ambition; and (4) a stakeholder workshop to communicate the quantitative scenarios and integrate stakeholder feedback into these scenarios (Creutzig *et al* 2012).

The four cities self-evaluated their climate change related transport policies, as summarized in figure 1. The cities display a relatively strong commitment to public transit provision. With the partial exception of Sofia, cities monitor and communicate climate change related data and policies. The cities only weakly rely on 'push' instruments. The accompanying interviews of municipality policy makers revealed that the coordination with the surrounding regions on land-use planning is generally regarded as an important but also difficult policy dimensions.

### 2.2. Data

Data were obtained from municipal transport documents and consulting reports. Urban transport officials and modelers were interviewed on available data. Where possible data from journal articles were included, e.g. Muñoz and Galindo (2005) in the case of Barcelona. The GHG emission data were obtained from a regional input–output model with local downscaling (city level consumer spending databases; regional environmental accounts; transport; road transport data on household levels) (Minx *et al* 2009). In the case of Sofia, the GHG data were estimated by triangulation from modal split data, fleet consumption estimates, and national gasoline and diesel consumption data. An overview of the key background data is given in table 1.

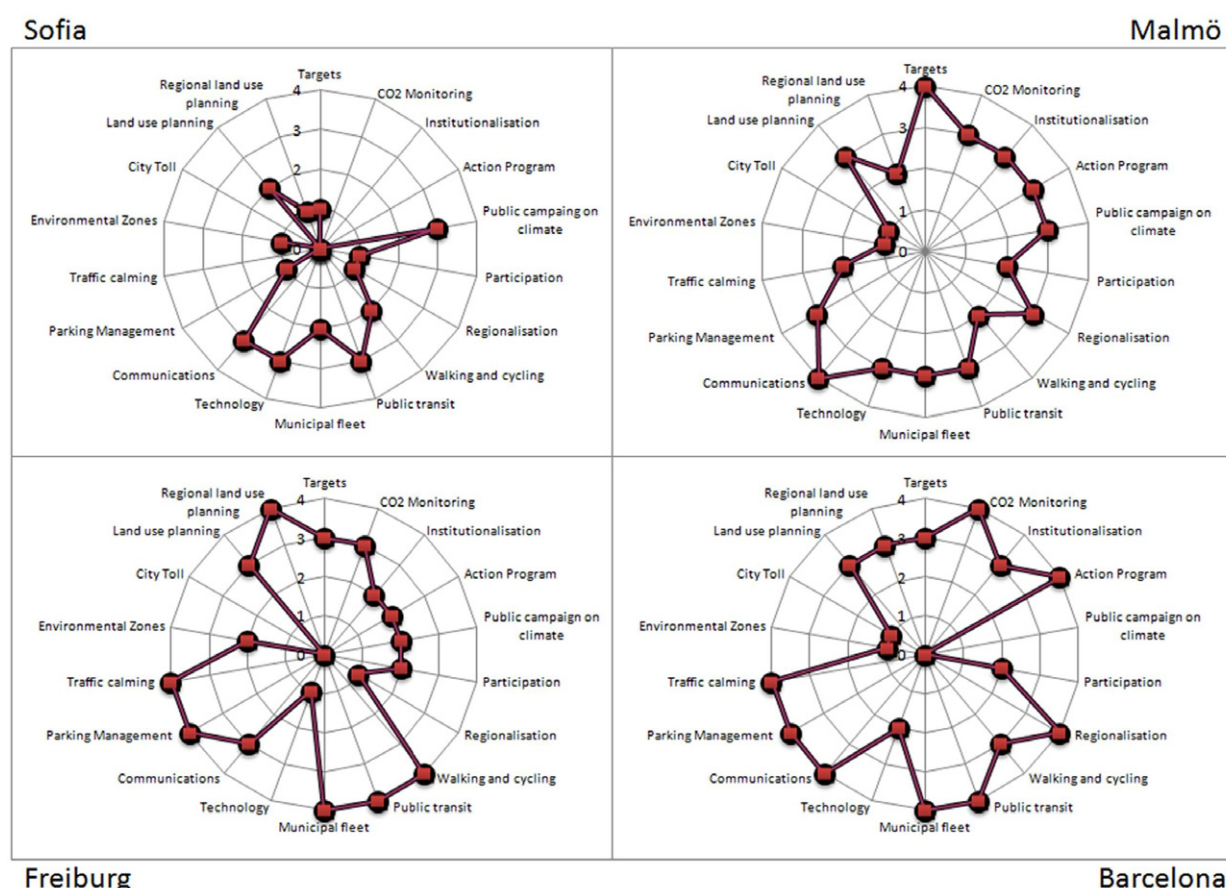
### 2.3. Scenario simulation

The scenarios were simulated based on three sets of parameters: intensity of policies, mode-specific demand elasticity and associated cross-modal elasticities, and the temporal dynamics of phasing in the policies (for details on the mathematical use of elasticities, see supplementary material A, available at [stacks.iop.org/ERL/7/044042/mmedia](http://stacks.iop.org/ERL/7/044042/mmedia)).

The policies and their intensities were determined iteratively by stakeholder workshops and interviews in each of the corresponding cities and by comparison to benchmark policies in other cities. An overview of policies and their intensities is given in table 2, displaying values for all four scenarios.

As prerequisite for all scenarios, population growth dynamics and technological advances in vehicle fleets are modeled. The expected population growth is given in table 1. On the technology side, the implementation of EU fuel efficiency policies is assumed, with the average new car emitting nominally 130 g CO<sub>2</sub> km<sup>−1</sup> in 2015 and 95 g CO<sub>2</sub> km<sup>−1</sup> in 2020<sup>3</sup> (Creutzig *et al* 2011). Assuming an average turnover rate of 15 years per vehicle, this policy alone results in 46% reduction in distance specific GHG emissions.

<sup>3</sup> The new European driving cycle systematically underestimates emissions under real driving conditions. Hence, we use EU regulation only to model the relative reduction in GHG emissions per vehicle rather than absolute reduction.



**Figure 1.** Self-evaluation of climate transport policies of four European cities. Level 0: zero policies in this domain. Level 1: minimum quality of policies. Level 2: medium. Level 3: advanced. Level 4: state-of-the-art. The self-assessment was guided by a detailed questionnaire, which can be downloaded as supplementary material ([stacks.iop.org/ERL/7/044042/mmedia](http://stacks.iop.org/ERL/7/044042/mmedia)).

**Table 1.** City characteristics. Data are from municipal documents. MIT: motorized individual transport. PT: public transport; NMT: non-motorized transport.

	Barcelona	Freiburg	Malmö	Sofia
Population	1.6 m. urban/4.8 m. metrop.	224 000 urban	300 000 urban/630 000 metrop.	1.27 m. urban/1.49 m. metrop.
Pop. growth 2010–40 (%)	35	25	52	0
Urb. pop. density (km <sup>-2</sup> )	16 000	1450	3651	944
GDP/cap	35 400 € (2004)	32 397 € (2004)	36 975 € (2004)	24 000 €
Modal share urban + regional (% number of trips)				
MIT (%)	24	48	41	34
PT (%)	36	18	16	54
NMT (%)	40	34	43	12
Transport volume/cap	28.7 v km/cap/day	32.5 v km/cap/day	26.8 v km/cap/day	29.2 v km/cap/day
Transport CO <sub>2</sub> emissions/cap.	1.8 tCO <sub>2</sub> /cap/a	2.0 tCO <sub>2</sub> /cap/a	1.6 tCO <sub>2</sub> /cap/a	2.3 ± 0.3 tCO <sub>2</sub> /cap/year
Public transport infrastructure	Extension of bus, tram, metro services ongoing	Extensions of tram network in progress	Introduction of tram network	Good tram network/need to modernize

The first scenario (S1) represents baseline trends, as identified by the stakeholders, building conservatively on current policies, labeled business-as-usual scenario. The second scenario (S2) focuses on ambitious pull scenarios, i.e. extension of public transport networks and non-motorized transport infrastructures, identified by stakeholders as scenarios currently considered within municipalities. In the

cases of Freiburg and Malmö this included the modeling of planned tramway constructions until 2020 (partially already under implementation). Additional measures have already been implemented in Barcelona and Sofia. In Barcelona, for example, the provision of bicycle lanes and the introduction of the bike sharing system Bicing has already led to notable modal shift (Rojas-Rueda *et al* 2011). With a little further

**Table 2.** Policy intensities for all four cities. The four entries in each box correspond to the four increasingly ambitious scenarios. BCN stands for Barcelona and FRBG stands for Freiburg. Percentage values indicate the change of the respective parameter relative to the status quo in 2010 for each of the four scenarios. For example the first entry for ‘PT speed and service quality’ in the BCN column indicate that the first scenario (baseline trend) assumes a 5% increase in public transit speed and service quality, making it more attractive in a relevant non-monetary dimension.

Policy	BCN (%)	FRBG (%)	Malmö (%)	Sofia (%)	Comment
PT speed and service quality	+5	—	—	+12	BCN: way-of-right and pre-boarding ticketing for inner city bus system & expansion of metro; FRBG: tram expansion in progress; Malmö: new trams in progress; Sofia: refurbishing of tram vehicle stock & add. metro line.
	+35	+20	+22	+37	
	+35	+25	+22	+37	
	+35	+25	+22	+37	
Bicycle infrastructure & other NMT measures	—	—	—	—	Freiburg and Malmö have already extensive bicycle infrastructure and are relatively pedestrian friendly. The margin of improvement is much higher in BCN, and especially in Sofia where hardly any bicycle lanes exist. With bicycle infrastructure expansion and additional area for pedestrians the available area for cars shrinks. Sofia still expands its road network.
	+50	+6	+27	+150	
	+50	+10	+27	+150	
	+50	+10	+27	+150	
Street area/total area	—	—	—	+37	Some neighborhoods in BCN and Sofia could reduce car traffic externalities by traffic calming measures.
	−10	−3	−8	+22	
	−40	−8	−20	+16	
	−40	−8	−20	+16	
Traffic calming	—	—	—	—	A global 30 km h <sup>−1</sup> street limit is particularly effective to reduce the health effects of noise along main arteries in inner cities. Such measures were discussed in FRBG and Malmö but were deemed as not realistic in BCN and Sofia.
	—	—	—	—	
	+30	—	—	+27	
	+30	—	—	+27	
Global 30 km h <sup>−1</sup> speed limit	—	—	—	—	A congestion charge can be implemented in the most progressive scenario. High quality NMT and PT infrastructure is precondition for a congestion charge, as they offer viable alternatives for car drivers.
	—	✓	✓	—	
	—	✓	✓	—	
	—	✓	✓	—	
Congestion charge	—	—	—	—	All cities offer significant potential to increase parking fees to decrease inner city cruising and induce some modal shift.
	—	—	—	—	
	—	—	—	—	
	40	30	30	40	
Parking fees	—	—	—	—	Densification and land-use measures are most effective where population growth is highest, in particular in Malmö where the high accessibility to Copenhagen leads to high inflow.
	—	+25	—	—	
	100	+100	+100	+100	
	100	+100	+100	+100	
Densification and land use	—	—	—	—	
	—	—	—	—	
	—	—	—	—	
	35	27	50	—	

addition, particular on the side of non-motorized transport, this second scenario is on track to be realized. The third scenario (S3) explores the effect of push measures, i.e. measures that limit car traffic, e.g. by higher prices of parking, traffic calming and reduction of street space (transferred to non-motorized transport instead). The fourth scenario (S4) is most ambitious and included congestion charging (another push measure) and aggressive land-use policies, restricting new development to car-free areas with bicycle infrastructure and public transport access, and prohibiting green-field development of human settlements and big boxes in the wider urban region. The third and fourth scenarios included policies that were only considered by some stakeholders, and mostly not under consideration by the municipal governments, but judged to be plausible.

In the model, policies modify transport demand and modal share proportional to their intensities. The reaction of modal demand to policy implementation is technically modeled by demand elasticities and modal cross-elasticities. Values of elasticities were adapted from the literature and are displayed in table 3.

The evaluation of scenarios focuses on various social costs and resulting co-benefits (reduction in social costs)

and follows Mayeres and Proost (2001) and Litman (2011) but has now an explicit temporal dimension: scenario outcomes in the year 2040 are compared to measured data in 2010. In economics, these social co-benefits are often called externalities. However, this notion supposes that the satisfaction of transport demand is the only purpose of a transport system. In contrast, here we perform a multi-criteria assessment, and describe the changes of social co-benefits. We refrain from weighting and aggregating these dimensions (e.g. in monetary terms) to allow for varying and changing preferences of policy makers and their constituencies. The following co-costs and co-benefits were evaluated: GHG emissions, air quality, noise ambience, physical activity, congestion, traffic-related injuries and fatalities, and fuel spending. All values were calculated from modal shares. Total km demand of car transport and public transport results in GHG emissions. The EU fuel efficiency policies determined the average GHG emissions of new cars (with Sofia assumed to lag in adoption); efficiency of public transit was equivalently supposed to increase moderately, reflecting new public transit investment in all four cities. For estimates of congestion, air pollution, noise ambience and



**Table 3.** Assumed elasticities of policies on modal trip share.

Policy	Elasticity value	Source
Public transport speed and service quality improvement	0.75 on PT	Fearnley and Bekken 2005
Slow modes infrastructure provision	0.5 on NMT	Litman 2011
Street area conversion from roads to bike lanes	0.65 on cars	Mayeres and Proost 2001, Litman 2011
Slow traffic zones (30 km h <sup>-1</sup> )	−0.115 on cars; 0.125 on NMT; 0.245 on PT	TRACE 1999
Fuel prices	−0.19 on cars; 0.13 on NMT; 0.13 on PT	TRACE 1999
Parking prices	−0.16 on cars; 0.03 on NMT; 0.02 on PT	TRACE 1999
Public transport fare	−0.85 on PT	Litman 2011, García-Ferrer <i>et al</i> 2003, Holmgren 2007
Car travel time	−0.23 on car; 0.25 on NMT; 0.49 on PT	TRACE 1999
Congestion charge	−0.6 on cars	Creutzig and He 2009

injuries, data from municipal transport reports were used, specifying stratified effects in inner city and metropolitan region (Freiburg, Barcelona) or in different quarters (Malmö for instance has eight quarters). The effects of shifting transport demand and modal shares on these dimensions were estimated by relying on factors of Maibach *et al* (2008). The saving in fuel spending costs were calculated for each scenario, considering two cases. In the first case, fuel prices double from 2010 until 2040, representing average fuel price growth rate from 1946 to 2010. In the second case, fuel prices grow six-fold, extrapolating fuel price trends from 2000 to 2010<sup>4</sup>.

The use of motorized transport rather than walking and cycling can be seen as transport-related inactivity. Transport-related inactivity has been linked to decreases in healthy life years and increased mortality, with the greatest impacts on chronic diseases, notably heart disease, stroke, colon cancer diabetes mellitus type 2, obesity, breast cancer and osteoporosis (WHO 2002). Transport-related physical activity can hence produce health benefits relative to the reference case. Health benefits from physical activity were estimated by feeding pedestrian and bicycling modal shares into the health economic assessment tool (HEAT)<sup>5</sup>, which is a robust and conservative model to estimate the maximum and mean annual mortality reduction benefits of walking or cycling. While HEAT gives results in monetary savings, the results were translated into statistical live savings. More details on the co-benefit methodology and a contextualization with recent public health literature is given in supplementary material B, available at [stacks.iop.org/ERL/7/044042/mmedia](http://stacks.iop.org/ERL/7/044042/mmedia).

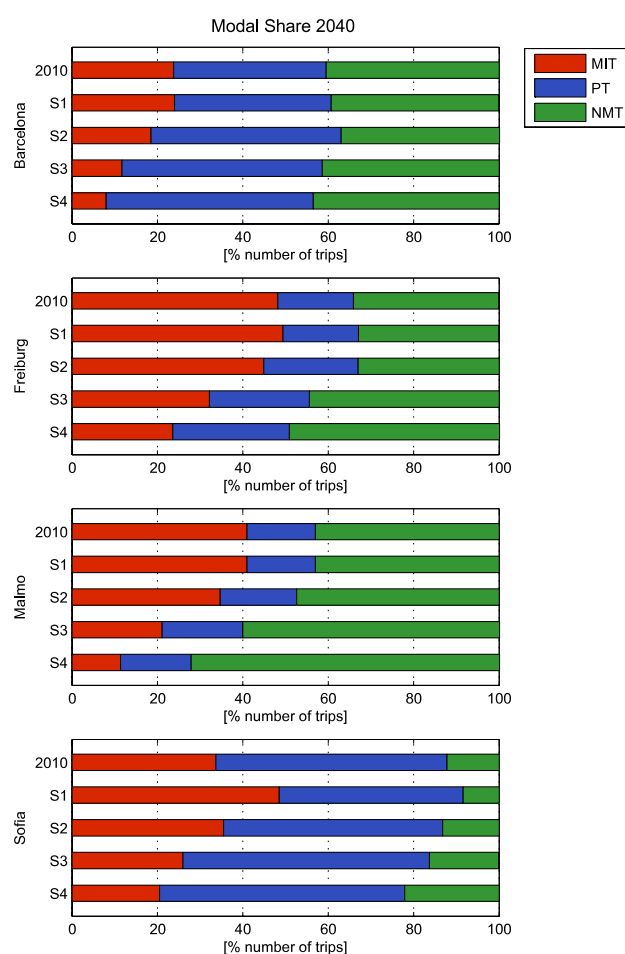
### 3. Results

#### 3.1. Modal share

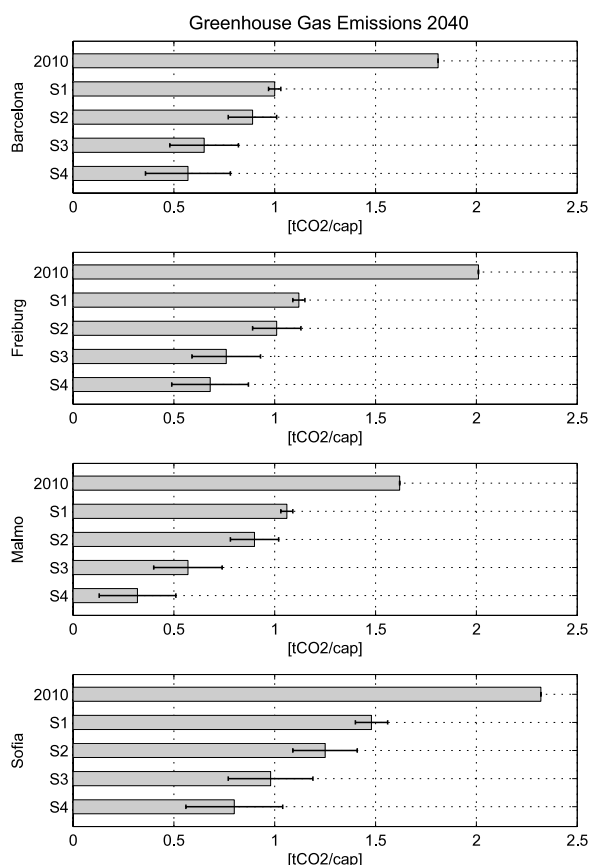
Figure 2 displays the modal shares of the four cities in 2040 for all four scenarios. In the scenarios for Barcelona,

<sup>4</sup> The second case represents a conservative high oil price scenario. Extrapolating fuel price increase from 1998 until 2008, an average annual increase of 19%, would suggest a 200-fold price increase from 2010 to 2040.

<sup>5</sup> [www.heatwalkingcycling.org/](http://www.heatwalkingcycling.org/).

**Figure 2.** Modal shares in scenarios S1–S4.

more ambitious policy scenarios results in increasingly relevant shift from motorized transport to public transport. In the scenarios for Sofia, relative demanding pull policies are already required to keep the relatively high share of public transport from deteriorating. Further push and land-use policies can however increase non-motorized and public transport modal shares. In the scenarios for Freiburg and Malmö, the more demanding scenarios result in a significant modal shift from car transport to cycling.



**Figure 3.** Per capita GHG emissions in scenarios S1–S4. Bars indicate the 5th and 95th percentile.

### 3.2. GHG emissions

Figure 3 displays the per capita GHG emissions in the four cities in 2040 for the four scenarios. Technological development and the pull policy package achieves close to 1 tCO<sub>2</sub>/cap in each city, around 40% compared to 2010 values. A reduction to 0.5–0.7 tCO<sub>2</sub>/cap requires additional push and land-use policies. Land-use policies (scenario 4) are most relevant in Malmö, where the highest population growth is expected.

### 3.3. Co-benefits

The change in social costs and associated benefits are summarized in table 4. Directly car-related costs, such as congestion, injuries and noise are likely to become worse in cities if car transport is not explicitly restricted via push measures as available in the third scenario, which also provide the largest marginal improvement among all scenarios. Air quality is likely to improve significantly or at least stay constant also in the less ambitious scenarios due to clean fuel standards.

Injuries, and the costs of injuries and fatalities, increase with more street activity of cars, cyclists and pedestrians. The first two scenarios, reflecting relative stable modal shares in trips but increasing overall activity, are likely to see an increase in the costs of injuries (table 4). With rapidly

declining modal shares of heavy motorized vehicles in the more demanding scenarios 3 and 4, the injuries from accidents will fall significantly (table 4).

Fuel spendings are likely to increase in the order of a billion € annually if urban transport remain on business-as-usual trajectories. Significant costs can be avoided in the more ambitious scenarios (the third and fourth scenarios). City inhabitants save around half of their fuel spending between the business-as-usual scenario and the most ambitious scenario. The range in table 4 represents a doubling and a six-fold increase in fuel prices, representing a conservative and a moderately challenging fuel price scenario.

Physical activity from more walking and cycling translates into statistical life savings. Statistical life savings are closely related to modal shift to non-motorized transport, including connecting to public transport. Savings are highest for walking in Barcelona and for cycling in Freiburg, Malmö and Sofia.

### 3.4. Transition dynamics

We also explicitly modeled the transitioning dynamics. Half of the dynamics are dominated by the turnover rate of cars. In our model, 40% of the overall 2040 GHG abatement effect is reached in 2020, but already 85% of the 2040 effect is reached in 2030. Pull measures depend on the timing of investments into public transit and NMT infrastructures. We assumed in each city a phase-in within the first 10 years of the scenarios, with instantaneous effects. The use of these infrastructures is however modified by push and land-use policies. Push policies are phased in between 2010 and 2025 in our models. They have a large instantaneous effect, but display an additional time lag due to hysteresis in car ownership and settlements patterns. Land-use policies act on the slowest time scales. Effects are realized in proportion to population growth and rate of relocation decisions and are mostly constant over the time period.

## 4. Discussion

This study introduces a multi-criteria sustainability assessment of transport policies tailored to achieve climate change mitigation, environmental and public health benefits. We deliberately choose not to monetize outcomes, as we think that the weighting of different dimensions is subject to a democratic, political process. We evaluate four increasingly ambitious policy packages for four European cities: Barcelona, Freiburg, Malmö and Sofia.

In simple terms, we find that a combination of policy packages, in addition to EU fuel standards, can reduce GHG emission by around 75% per capita from 2010 to 2040. This can be achieved by a policy packages incentivizing modal shift and moderately reduced transport demand. Notably, smaller cities like Freiburg and Malmö may rely on the bicycle as their dominant transport mode. In fact, total modal share of non-motorized transport may exceed 50%. In contrast, larger cities such as Barcelona and Sofia rely to higher degree on public transport, covering around 50% of all trips.

**Table 4.** Co-benefits listed as variable change from 2010 to 2040 for each of the four scenarios S1–S4.

	Air pollution (% change)	Accidents (% change)	Noise (% change)	Congestion (change in mill. EUR/yr)	GHG (change in tCO <sub>2</sub> /yr/cap)	Fuel spendings (change in mill. EUR/yr)	Life savings walking (statistical lifes/yr)	Life savings biking (statistical lifes/yr)
BCN								
S1	–34	24	7	1165	–0.8	[1200 14600]	230	16
S2	–46	1	0	73	–0.9	[500 12 500]	194	21
S3	–64	–32	–16	–1523	–1.2	[–800 7900]	465	58
S4	–73	–48	–29	–2352	–1.2	[–1400 6200]	708	162
Freiburg								
S1	–33	25	7	216	–0.9	[200 2500]	2.5	20
S2	–40	11	4	95	–1.0	[100 2200]	2.2	15
S3	–56	–19	–8	–161	–1.3	[–100 1500]	8.6	69
S4	–58	–21	–10	–184	–1.3	[–100 1200]	11.8	234
Malmö								
S1	30	99	24	828	–0.6	[200 1700]	27	51
S2	9	66	20	563	–0.7	[100 1400]	32	61
S3	–31	5	8	75	–1.1	[0 800]	52	99
S4	–67	–50	–20	–363	–1.3	[–100 400]	74	140
Sofia								
S1	–28	33	9	989	–0.8	[400 4600]	–93	20
S2	–46	1	0	23	–1.1	[0 3400]	–80	66
S3	–60	–25	–11	–738	–1.3	[–200 2400]	–54	86
S4	–71	–46	–26	–1354	–1.5	[–500 1700]	–15	117

This result partially reflects the assumption of policy makers in Barcelona and Sofia that large-scale investments into bicycle infrastructures are not feasible. The Copenhagen case however demonstrates that also larger cities can achieve modal shares of cycling beyond 40% (McGrane 2012).

In addition to pricing and infrastructure provision, we also explicitly included land-use policies in our model. Higher density settlements have lower GHG dimensions than sprawled areas in most cases (Glaeser and Kahn 2010, Weisz and Steinberger 2010) but not in all cases (Heinonen and Junnila 2011). In particular, higher density correlates with lower transport energy demand (Newman and Kenworthy 1989). The idea of using land-use planning for climate change mitigation in the transport sector remains contested. As a recent detailed modeling study suggests, the effects of land-use planning on reducing climate change mitigation might only be moderate, reporting a potential 5% reduction in vehicle km travelled in the UK by compact development patterns compared to a sprawled scenario (Echenique *et al* 2012). In the US, compactification is expected to reduce vehicle km travelled by 7–10% compared to baseline (Ewing *et al* 2008). Our results are not directly comparable, as we combined land-use policies with a congestion charge in the most ambitious scenario. We obtain values of 10–20% reduction in vehicle km travelled in these scenarios, and in the case of Malmö around 40%. This latter effect results from the expected high population growth that allows for huge effects of compact settlement policies compared to a low-density baseline.

This study, of course, is not a complete assessment. We do not report expected financial flows, e.g. of investment into infrastructures and of revenues and costs from pricing schemes. We also incompletely cover the change in utility for residents. For example, an increase in population density reduces floor area available for residents and increases costs of land, economic disadvantages not factoring into our evaluation. Softer dimensions, such as the increase of livability from increased street life, are also ignored. Methodologically, this study relies on demand elasticities but refrains from explicitly causally modeling economic relationships between agents, the economic systems, transport and land use. Our model results crucially depend on the values of elasticities, and hence, must be interpreted with caution. More advanced models (e.g., Wegener 2004, Echenique *et al* 2012) have high spatial resolution, explicitly represent the consumption and production side of the economy and detail the interaction between different economic sectors with input–output tables, all of which is beyond the scope of this paper. But even these detailed causal model, such as still rely on a to some degree arbitrary choice of parameters (e.g. substitution parameters in Cobb–Douglas functions). These models, however, would be very useful to study how region-specific economic development patterns impact land use, transport and its environmental and public health co-benefits and vice versa.

Our evaluation highlights two issues. First, it tries to firmly embed climate change mitigation within a multi-criteria assessment, emphasizing local ambience and benefits.

In this regard, the study builds among others on Creutzig and He (2009), calculating the economic costs of congestion, air pollution, noise, injuries from accidents and climate change of urban car traffic in Beijing; on Woodcock *et al* (2009) calculating the public health co-benefits of climate change mitigation of urban transport policies in London and Delhi; and on Rojas-Rueda *et al* (2011) detailing various public health outcomes from a modal shift towards cycling in Barcelona. Similarly, the co-benefit concepts has also entered urban climate adaptation studies (Bambrick *et al* 2011). The medical community suggests that a strong case can be build to embed climate change mitigation efforts into public health concerns (Haines and Dora 2012). But we think that a more general case should be made. Climate change mitigation efforts are usually accounted for and benchmarked in economic costs. In emphasizing co-occurring environmental and public health dimensions, our evaluation is complementary to the common evaluation of climate change mitigation efforts in terms of economic costs. This work demonstrates that the co-occurring social benefits and savings need to be fully integrated into any comprehensive assessment. At least in the case of urban transport, evaluating climate change mitigation efforts solely in terms of economic costs could be misleading.

Second, this evaluation suggests that there is not a single optimal policy but rather a mixture of policy packages, which act synergistically. This conclusion builds on a growing set of literature. Providing a more technical argument Creutzig and He (2009), systematically explored how increased public transit deployment increases the effectiveness of a congestion charge by modulating the demand elasticity. Similarly Mashayekh *et al* (2011), demonstrate the need for a combination of policies to decarbonize road transport. In our study, we indicate that urban transport is an arena where policy packages are better suited than single policies to achieve climate change mitigation. Rather than pricing the climate externality (a tax on the carbon content of fuel), a mixture of pricing instruments, such as parking charges, and supply instruments, such as bicycle networks, and land-use instruments, enabling the use of less-motorized modes, achieves significant reduction of GHG emissions. The pricing component limits rebound effects, and hence, is necessary to unfold the whole potential of non-motorized and public transport, and better vehicle technology. But only complementary action on infrastructures and land use reduces opportunity costs for city inhabitants and properly accounts for the path dependences inherent in human settlements and its transport infrastructures.

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