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ScienceDirect

Transportation Research Procedia 37 (2019) 163–170

Transportation Research Procedia

www.elsevier.com/locate/procedia

21st EURO Working Group on Transportation Meeting, EWGT 2018, 17th – 19th September 2018, Braunschweig, Germany

Investigating the impact of e-bikes on modal share and greenhouse emissions: a system dynamic approach

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Abstract

This study employs the ASTRA strategic system dynamics model to investigate the impact of electric bikes (e-bikes) on modal split in Europe at urban level. The resulting reduction of kilometers travelled by conventional internal combustion means of transports will consequently affect the amount of greenhouse emissions (GHG). This paper contributes in quantifying this impact employing an updated ASTRA model version testing the impact of the e-bike in both the baseline scenario (until 2050) and in a policy scenario where car vehicles entering in urban areas are charged. Both scenarios' results show a relevant growth of electric bikes' share until 2050, highlighting a considerable difference between the leading countries (The Netherlands, Denmark, Germany, Norway, Sweden, Finland) with respect to the rest of Europe. Interestingly, the advent of the e-bike reduces the trips performed with the other modes but also induces new trips. Urban areas greenhouse gas emissions, that already decline in the baseline scenario, are affected by a further reduction in the policy scenario.

Keywords: greenhouse gas emissions; electric bike; active modes

1. Introduction

The transport sector accounts for nearly one quarter of global energy-related CO2 emissions, mainly due to cars and trucks travelling on roads. In 2015, greenhouse gas emissions decreased by 22% in Europe compared to 1990 levels, putting EU on track to match its 2020 target, which is to reduce GHG emissions by 20% by 2020 and by 40%

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10.1016/j.trpro.2018.12.179

by 2030 compared with 1990. Last official available statistics (Eurostat) are from 2017 and are included in Figure 1. This shows a general descending trend between 1990 and 1999 while from 1999 to 2006 the trend remained relatively unchanged. In the following years an up and down motion has been registered. In the last reported year (2015), GHG emissions increased by 0.6% compared to 2014.

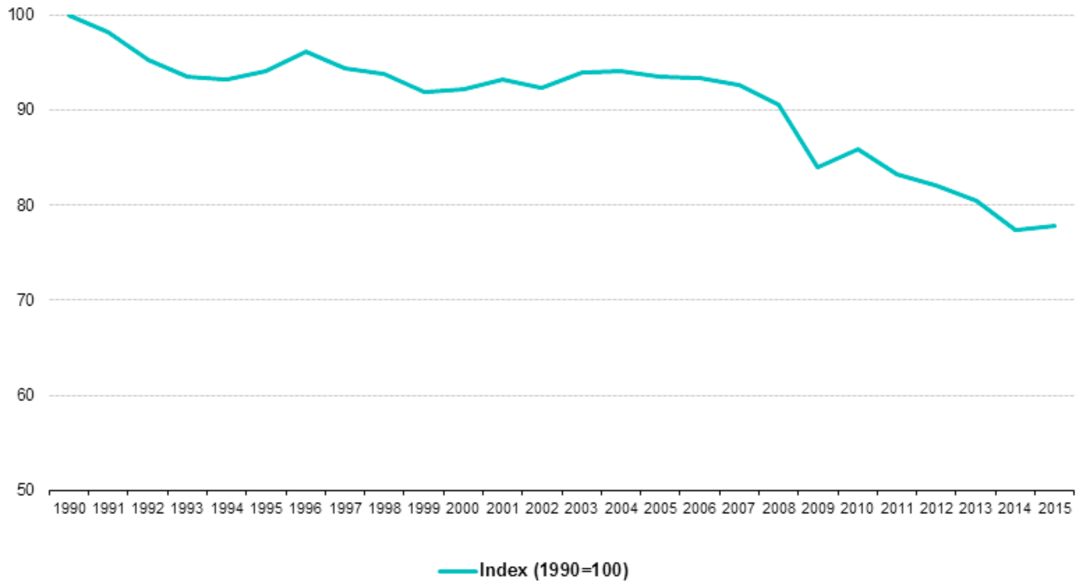


Fig. 1 Source Eurostat: trend of greenhouse gas emissions in Europe

The aim of this paper is to investigate the impact of active modes (walking, cycling and e-cycling) on greenhouse gas emissions in urban context. An increase of the use of these active modes directly reflects on the modal share which consequently affects the emissions caused by traditional modes (e.g. car, public transport), as bicycle's GHG emissions are ten times lower than those stemming from individual motorized transport (Blondel, 2011). E- bikes, despite their electric assistance, are also found to have greenhouse gas emissions in the same range as ordinary bikes. Thus, policies aimed at increasing the use of ordinary bikes, e-bikes and bike-sharing schemes, on their own and/or in combination with public transport, have the potential to substantially contribute to a much-needed modal shift.

This study is part of the REFLEX research project (Reflex, 2016) which aims at analyzing the development towards a low-carbon EU energy system with focus on the flexibility options linked to the use of renewable energy sources. The project employs the ASTRA (AsTrA model., 2011) model in combination with several different models dealing with energy production and consumption. The ASTRA strategic system dynamics model provides a comprehensive approach for simulating the impact of different strategies on transport energy consumption and carbon emissions as it considers both causal relation and structure decision behavior.

Different studies (Abbas, 1994) (Haghani, 2003) (Shepherd, 2014) demonstrated the capability of system dynamics approaches to model the transport sector, which indeed is a complex system characterized by the interaction of multiple variables coming from different sectors (environmental, economic, social, etc.) and by non-linear feedback loops. However, the lack of studies that adopt system dynamics modeling to investigate the role of active modes in the transport sector is evident and this paper contributes in filling this gap by examining the role of active modes in reducing kilometers travelled with motorized modes, and consequently greenhouse emissions. The calculation of changes in final energy consumption and GHG emissions for the transport sector across the years represents the main purpose of this paper in the REFLEX project context.

In summary the study illustrated in this paper aimed at:

- Improve the representation of active modes in the range of transport modes available in the model;
- Investigating their impact on km travelled by existing modes (e.g. car, public transport);

- Calculating the consequent impact on greenhouse gas emissions reduction.

2. Literature review

Several scientific studies focus on simulating the impact of different strategies on urban transport energy consumption and carbon emissions. In (Creutzig, 2012) the authors assess the state of urban mobility in four European cities (Barcelona, Malmo, Sofia and Freiburg) based on stakeholder interviews and data analysis. They also provide different ambitious scenarios to reduce greenhouse gas emissions from urban transport by up to 80% from 2010 to 2040. Among others, they found that non-motorized transport, especially bicycles, can achieve high modal shares, particularly in cities with less than 0.5 million inhabitants. The study of Woodcock et al. used instead Comparative Risk Assessment methods to estimate the health effects of alternative urban land transport scenarios in London and Delhi (Woodcock, 2009). They compared a 2030 projection without policies for reduction of the greenhouse gases with alternative scenarios: (i) lower carbon emissions motor vehicles; (ii) increased active travel; (iii) a combination of the two. In the increased active travel scenario, they envisaged large increases in the distances walked and cycled, accompanied by a 37% reduction in car use in London. They motivated these findings with the results of a travel survey that showed how almost 22% of the distance travelled by car accounted trips shorter than 8 km, including 11% of trips actually shorter than 2 km, thus within cycling and walking distance respectively. Finally, the study of Wen and Bai (Wen, 2017) constructs a system dynamics model for simulating the impact of different strategies on urban traffic's energy consumption and carbon emissions in Beijing. They proposed three applicable policies: (i) driving restriction on vehicle registration number; (ii) vehicle registration via a lottery system; (iii) development of public transportation infrastructures. The main result showed how private cars have the most significant impact on urban traffic's energy consumption and carbon emissions.

3. Methodology

3.1. System dynamic approach

The modelling of the use of e-bike as part of active modes in urban areas has been done using the ASTRA system dynamics model. ASTRA, whose geographical coverage is at European scale (EU28 countries, Switzerland and Norway), consists of different sub-modules: (i) the transport sub-model, simulating generation, distribution and modal split of passenger and freight movements; (ii) the vehicle fleet sub-model, simulating the development through the years of vehicles characteristics and technologies; (iii) the demographic sub-model, simulating the evolution of population socio-economic groups; (iv) the economy sub-model, which is based on countries I/O matrices and simulates the linkages of the transport sector with the whole economic system; (v) the environmental sub-model which, in addition to pollutant emissions, includes the calculation of all external costs related to transport (such as GHG emissions, accidents and air pollution). These sub-models are linked together and therefore a change in one sub-model is transmitted to the others and can create either positive or negative feedback effects. Thanks to its multidimensional structure, ASTRA is capable to simulate a wide range of impacts stemming from the application of a transport policy measure: in other words the model can address direct impacts as well as second-level and third-level impacts of transport policy measures. Passenger transport demand is generated at NUTS II level and further split by distance bands for intra-zonal movements. Urban mobility is modelled by segmenting trips by type of zone (based on the EUROSTAT 'Urban-rural typology' classification) and by distance bands (i.e. less than 3km; from 3 km to 50 km; etc.), where transport modes availability is different according to the characteristic of the zone (i.e. metro is available in metropolitan areas only) and the distance band (i.e. active modes are available only up to a given trip length).

In this study, the e-bike has been added to the range of transport modes for urban/suburban mobility and more precisely for the following two distance classes (Assist-project, 2011):

- In the "local" distance band (< 3km): E-bike is in competition with Car, Bus, Tram/Metro, Car-Sharing, Bike, Walk
- In the "very short" distance band (between 3 and 50 km): E-bike is in competition with Car, Bus, Tram/Metro, Rail, Car-Sharing, Bike.

E-bikes have been simulated considering the key characteristics of their service (cost, technical features, etc.) as well as the drivers of their diffusion (e.g. user profiles, mobility patterns, etc.).

Modal split in ASTRA is calculated separately for each spatial domain, e.g. for urban mobility at intra-NUTS II level and for each distance band ("local" and "very short"). Direct and cross elasticities to cost variation and time variation (implemented separately) are used. Additional elasticity parameters can be implemented to reflect the contribution of other significant determinants of modal split. In the end, mode split depends on the following elements: (i) Initial mode shares at the base year (and then mode shares at previous time period), (ii) Elasticity to cost variation over time, (iii) Elasticity to time variation over time, (iv) Elasticity to car ownership variation over time (for selected cases, only when a significant increase is observed starting from a low value at the base year), (v) Cross elasticity to re-distribute the shares from one mode to the others (which depend directly on mode split at previous time period). The following figure gives an overview of the mode split process for passenger demand.

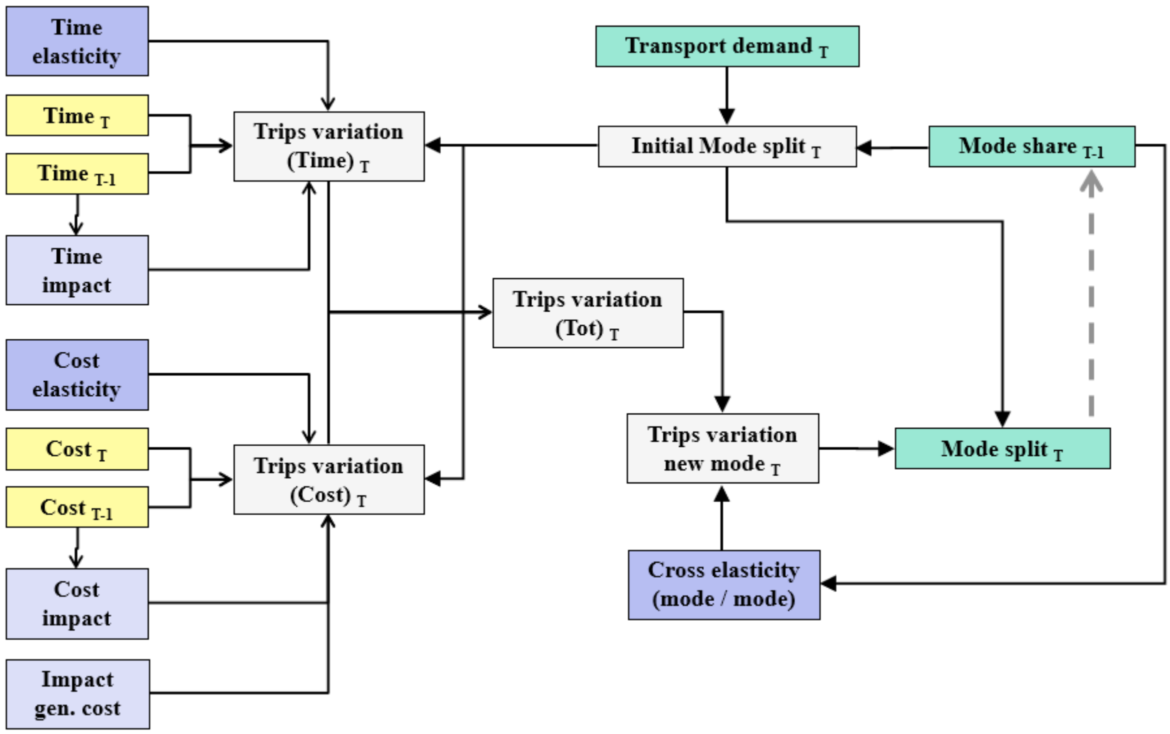


Fig. 2 Modal Split process for passenger demand in ASTRA

3.2. Data Collection

Data collection focused on two main sets of information: current modal share of the active modes, including e-bikes, in the different European countries and greenhouse gas emissions for e-bikes. As expected, official statistics on modal share that include e-bikes are hardly available. While data on e-bike sales worldwide and potential future market share are quite detailed (Engelmoer, 2012) (Navigant research, 2016), the statistics on modal share usually mention cycling as a generic mode of transport and do not distinguish between the different types of bikes.

In addition, the European picture varies substantially among the different countries (ECF, 2015): out of the 907,000 e-bikes sold on the EU market in 2013, the Netherlands and Germany accounted for 2/3 of these sales. More recent partial statistics indicate that the market continued to grow with double digit rates in 2014:as an example, in Germany the market grew by 17 % from 410,000 units in 2013 to 480,000 units in 2014, reaching a total volume of 2.1m e-bikes. Still in 2014 in Belgium, one in four bikes sold came with electric support (about 100,000 units out of 400,000) and in general, Netherlands and Denmark continue to be remarkably ahead compared to the other European countries (Mason, 2015). The latter study provided useful insights deriving e-bike modal share from market sales statistics. The authors used the European Cyclists' Federation (ECF) sales data through 2015 in various regions around the world as well as average vehicle-kilometers of travel (VKT) on e-bikes per year and average trip length to derive person-kilometers of travel (PKT) and trips/capita estimates. This was converted into mode share data by comparing these trip estimates to trips by other modes.

While official statistics are quite scarce for e-bikes mode share, several studies are instead focusing on understanding for which travel purpose this mode might be in competition with car or public transport; indeed due to its higher speed compared to traditional bike, e-bike has become a promising mode mainly for commuting trips, independently from the age of the rider (Lopez, 2017) (Gorenflo, 2017). In the authors' expectation the use of e-bikes for commuting could further affect car usage in two ways: (i) in a trip chain where the e-bike is the initial mode also other activities have higher chances of being performed by e-bike (ii) starting to use the e-bike for commuting could help in considering it as a competitive mode also for other purposes; and in addition, the increase in e-bike usage could also consequently reduce car ownership.

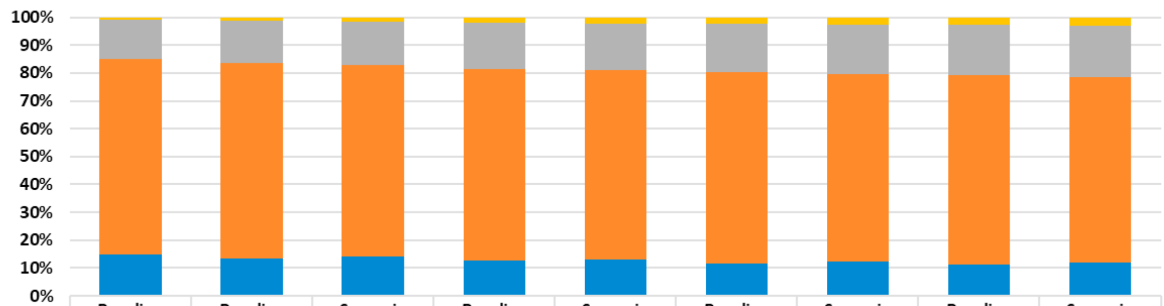
After the data collection phase, the ASTRA model has been used (i) to set a baseline scenario until 2050 and (ii) to investigate the effect of a road charging policy scenario.

3.3. Results of the baseline and policy scenarios

3.3.1. Modal Share

In the updated version of the ASTRA model the Active Modes include e-bike together with pedestrian and bike as three different transport modes, while originally there were only pedestrian and bike under the collective name of Slow Modes. The first step aimed at creating a baseline including the e-bike transport mode from the year 2015 until 2050. As mentioned in the Data Collection section, last official available statistics on e-bike modal share are from 2015; the latter is then used as base year in this study.

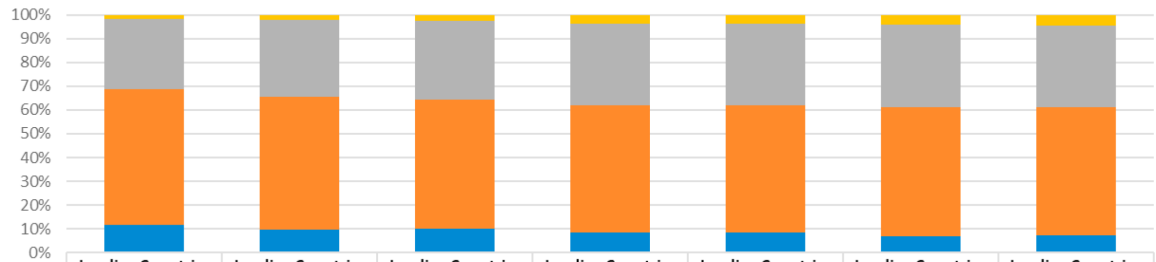
The following step has been the definition of a policy scenario where car usage is penalised by the introduction of a charge for all car vehicles entering in large urban areas since the year 2020; more precisely this is representative of a flat charge of 4.5 Euro/trip applied to private cars (buses and freight vehicles are not charged) on daily hours (e.g. from 8 a.m. till 8 p.m.) and only in the central part of the city, similarly to the urban charging scheme applied in the city of Milan (Italy).



	2015	2020		2030		2040		2050	
	Baseline	Baseline	Scenario	Baseline	Scenario	Baseline	Scenario	Baseline	Scenario
Ebike	1.0%	1.4%	1.5%	2.0%	2.2%	2.4%	2.5%	2.7%	2.9%
Bike	13.8%	15.1%	15.7%	16.5%	16.9%	17.4%	17.8%	18.0%	18.5%
Car	70.4%	70.2%	68.7%	69.0%	67.7%	68.6%	67.3%	67.9%	66.5%
PT	14.8%	13.4%	14.1%	12.5%	13.2%	11.6%	12.3%	11.3%	12.0%

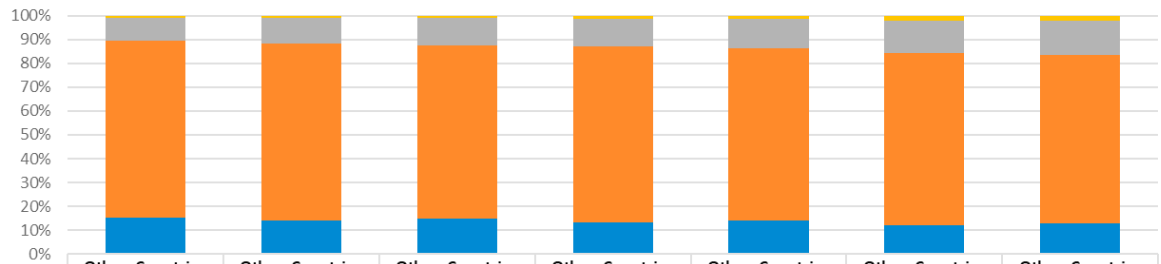
Fig. 3 Baseline and policy scenarios: Modal share for trips below 50km in EU28 countries

The two scenarios results are aggregated at European level and on yearly basis and make reference to trips below 50 km. The modes considered are Car (driver and passenger); Bike (traditional bike); PT (local bus, tram, metro, train); e-Bike (electric bike with max speed 25 km/h). Figure 3 includes the overall European modal share for both the baseline and the policy scenario, while Figure 4 and Figure 5 present the same results but differentiating per groups of countries: Leading countries (The Netherlands, Denmark, Germany, Norway, Sweden, Finland) and Other countries (the remaining 22 countries).



	Leading Countries Baseline 2015	Leading Countries Baseline 2020	Leading Countries Scenario 2020	Leading Countries Baseline 2030	Leading Countries Scenario 2030	Leading Countries Baseline 2050	Leading Countries Scenario 2050
Ebike	1.8%	2.4%	2.6%	3.6%	3.9%	4.1%	4.5%
Bike	29.6%	32.2%	33.1%	34.3%	34.2%	34.7%	34.5%
Car	57.1%	55.9%	54.3%	53.8%	53.2%	54.4%	53.9%
PT	11.5%	9.6%	10.1%	8.3%	8.7%	6.8%	7.2%

Fig 4 Baseline and policy scenarios: Modal share for trips below 50km in Leading countries



	Other Countries Baseline 2015	Other Countries Baseline 2020	Other Countries Scenario 2020	Other Countries Baseline 2030	Other Countries Scenario 2030	Other Countries Baseline 2050	Other Countries Scenario 2050
Ebike	0.8%	1.0%	1.1%	1.4%	1.5%	2.2%	2.3%
Bike	9.9%	10.8%	11.3%	11.7%	12.1%	13.4%	14.1%
Car	73.9%	74.1%	72.7%	73.8%	72.5%	72.1%	70.5%
PT	15.4%	14.1%	14.9%	13.1%	13.9%	12.2%	13.0%

Fig 5 Baseline and policy scenarios: Modal share for trips below 50km in Other countries

3.3.2. Emissions

In addition to the benefits related to energy consumption and congestion reduction, the increase in the use of active modes of transport in urban areas affects the amount of greenhouse gas and air pollutant emissions (CO, NOx, PM, VOC). The environmental impacts of e-bikes are dependent to a large degree on the mode they replace (Cherry & Cervero, 2007) and for those e-bikes replacing fully non-motorised modes (i.e. walking or bicycle) the result is a net negative impact on the environment. However, e-bikes are generally very energy efficient because of their light weight and electric drive technology, with most e-bikes consuming less than 2 kWh/100 km, about one-tenth the energy consumption of a small electric car (Ji, Cherry, Bechle, Wu, & Marshall, 2012) and around 40 less carbon dioxide (from power plants) than a standard car travelling the same distance.

Fuel consumption, greenhouse gas emissions, pollutant emissions, accidents and related externality values are calculated by the ASTRA environment module which in turn uses input from the transport module (in terms of vehicle-kilometres-travelled per mode and geographical context) and from the vehicle fleet module (in terms of the technical composition of vehicle fleets). For this study only hot emissions occurring during the driving activity have been considered and for the electric bikes they have been set to zero. In general terms, for each transport mode the following equation applies for the estimation of hot emissions:

$$hEM_{z,db}^{cc}(t) = hEF_{db}^{cc}(t) * shVft_{z}^{cc}(t) * Vkm_{z,db}(t) \quad \text{Eq. (1)}$$

Where $\mathrm{hEM}_{z,db}^{cc}$ represents the hot emissions for vehicle technology/emission standard cc and distance band db in zone z [t/year]; hEF_{db}^{cc} is the hot emission factor for vehicle technology/emission standard cc and distance band db [g/km]; shVft_{z}^{cc} is the vehicle fleet composition by vehicle technology/emission standard cc in zone z (the same in all zones of a country) [%]; $\mathrm{Vkm}_{z,db}$ are the vehicle-km travelled in zone z and distance band db [Mio*vkm/year]; z represents the NUTS I zone.

Table 1 shows the expected reduction (with respect to the baseline) in the amount of greenhouse gas and pollutant emissions related to urban transport due to the introduction of an urban road charge.

Table 1. GHG and pollutant emissions reduction in the policy scenario with respect to the baseline (trips are below 50 km)

	2020	2030	2040	2050
CO2	-0.7%	-0.4%	-0.2%	-0.2%
CO	-0.4%	-0.3%	-0.1%	-0.5%
NOx	-0.8%	-0.2%	-0.3%	-0.6%
VOC	-0.4%	-0.1%	-0.2%	-0.2%
PM	-0.7%	-0.1%	-0.3%	-0.4%

4. Discussion and Conclusions

The paper contributes to the research stream that investigates the impact of active modes on transport modal share and on greenhouse gas emissions at urban level. The study mainly focuses on understanding the role of the electric bike in this context. The model results show the impact generated by the diffusion of the electric bikes (Figure 3, Figure 4, Figure 5). On the one side, the e-bike reduces the car and public transport modal share, while on the other its inclusion has positive effects also on the other active modes (e.g. bike) due to feedback loops present in the model structure. This result is in line with the study of (Fyhri & Fearnley, 2015) which demonstrated how the advent of the e-bike has positive effect on the amount of cycling expressed as number of trips, cycled distance and cycling shares.

In the urban access charge policy scenario, the use of the car mode declines in favor of both active modes and public transport. While in the baseline the e-bike absorbs more demand from public transport than from car, in the policy scenario the impact on public transport and car is balanced. The disaggregation per groups of countries in Figure 4 and Figure 5 shows how the north European countries are remarkably ahead in terms of cycling infrastructures, cycling culture and safety measures, which clearly affects the test results with a larger impact (in terms of modal share) for the e-bike. Indeed, in the year 2015 the active mode share in these leading countries is already significant.

Finally, Table 1 shows the reduction of greenhouse gas and pollutant emissions in Europe at urban level due to the application of the urban access charge policy scenario from 2020. The highest reduction showed in 2020 coincides with the larger decrease of the car modal share presented in Figure 3. The presence of the e-bike, which already has a positive effect in reducing emissions over the years in the baseline scenario, amplifies the decline of car modal share.

In summary, the overall analysis included in this paper demonstrated the positive impact of e-bike in the reduction of motorized transport modes which is emphasized in the case of an urban access charge scenario. Future research directions aim at improving the presented analysis by testing the impact of the e-bike on modal share for different distance bands and in different policy contexts. In addition, investigating how the use of the e-bike might interact with car (and bike) sharing programs is of undoubted interest.

Acknowledgements

The research is funded by the EU Horizon 2020 innovation and research programme (Grant Agreement: 691685 — REFLEX project).

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