The implications of Mobility as a Service for urban emissions

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The implications of Mobility as a Service for urban emissions

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ABSTRACT

Mobility as a Service (MaaS), a user-centric framework for delivering a portfolio of multi-modal mobility services, promises to overcome negative externalities associated with the mobility sector by providing convenience to being multimodal and getting citizens away from using their private vehicles. The current work aims at providing pieces of evidence on the extent to which such a promise can be delivered. To this end, first, the adoption of MaaS and the use of various modes within MaaS bundles are examined using empirical data collected from portfolio and stated adaptation choice experiments. Next, an activity-based travel demand model (Albatross) is employed to simulate activity-travel patterns of travelers in the city of Amsterdam, the Netherlands. The results are linked to an emission model and the impacts on emission levels are compared for various scenarios with different MaaS bundles. It is found that the conservative, balanced, and optimistic scenarios decrease emission levels by 3–4%, 14–19%, and 43–54%, respectively.

1. Introduction

Transport offers a tremendous amount of benefits and opportunities to society such as increasing accessibility, inclusiveness, and quality of life (Wee et al., 2013). The car has even been claimed to be one of the biggest developments of the 20th century (Geels, 2012), and it has been steadily associated with freedom, wealth, and status ever since. As such, car ownership to a great extent drives other domains such as the housing market and economic activities (Docherty et al., 2018; Urry, 2004). Along with these benefits, nevertheless, come huge costs, such as air pollution and greenhouse gas emissions. In 2015, in 28 countries of the European Union, 852.3 million tons of CO$_2$ were emitted by road transport, constituting >70% of emissions from all modes of transport (European Commission, 2017). Transport is also a growing contributor to air pollution. It is estimated that road transport is responsible for up to 30% of small particulate matter (PM) emissions in European cities and is the main cause of air-pollution-related deaths and illnesses (World Health Organization, 2015).

MaaS is considered to be a service that can reduce emissions and even alleviate other negative externalities, such as congestion, air pollution, social exclusion, and the excess consumption of space (Hensher, 2018; Jittrapirom et al., 2017). Numerous definitions have been provided in the literature for MaaS. Hietanen (2014) posited that MaaS is “A mobility distribution model in which a customer’s major transportation needs are met over one interface and are offered by a service provider.”. Hietanen continued that MaaS is more than a mobility app and that it is a framework of offering multi-modal mobility services which put the user at the center of the offer. Ideally, these frameworks contribute to a more sustainable mobility system. The offerings furthermore are not limited to mobility, and may for example include non-transport related services such as parking. Heikkilä (2014) defined it as “A system in which a comprehensive range...
of mobility services are provided to customers by mobility operators.”. Recent years have witnessed a surge of diverse mobility innovations such as MaaS with the promise of providing enough convenience to convince citizens to give up using their private cars and adopt alternative transport modes available within their MaaS bundles. This surge in mobility innovations consequently leads to a surge in academic attention as well. Many of the present works on MaaS delved into the demand side to identify the potential target groups and the attractiveness of different offerings to those groups in terms of MaaS bundles. Many studies, which will be discussed to a greater extent in Section 2, suggest that the first MaaS users are likely to be young to middle-aged people (Zijlstra et al., 2020) and that MaaS may increase accessibility and reduce vehicle kilometers traveled (VKT) in a rural setting (Eckhardt et al., 2020). Despite the promises, little research or evidence currently exists to support the claims of the potential of MaaS in attenuating the environmental impact of mobility. There have been pilot projects in a handful of study areas, mainly in western Europe (e.g., Ubigo (Sochor et al., 2015a)) and Australia (e.g., Tripi (Hensher et al., 2021; Ho et al., 2021)). Data emanating from pilot studies are valuable in reflecting the real use behavior of citizens. They need, however, to reach a certain volume of subscribers and users to allow estimating forecasting models, useful for the service providers and city authorities. Moreover, to better capture the impact of MaaS on travel adaptations in general and mode switching behavior in particular, the best is to collect revealed data both before and after users subscribe to MaaS. This is often not straightforward to implement, especially during the present COVID-19 period, in which most MaaS pilots have encountered setbacks in attracting subscribers and users. Lastly, to evaluate the impact of different types of MaaS bundles on the market share, mode switching and consequently emission, sufficient variations in the MaaS characteristics are required. Stated preference and adaptation choice experiments facilitate such criteria. It is obvious that using revealed data with such properties is even more valuable.

In view of the above, using the results derived from stated adaptation choice experiments, this study intends to evaluate the potential impact of MaaS on the emission in general and the extent of changes in the emission levels under various MaaS service types in particular. To achieve the research objective, we employed state-of-the-art analytical methods and rich empirical data to answer a series of research questions. The research questions are formulated as follows:

(1) **Who will subscribe to MaaS, given the monthly fee, pricing scheme, and other service characteristics?**

To answer this question, data was collected via a portfolio choice experiment, upon which a mixed logit model was estimated. Once the potential demand for MaaS is known, knowledge needs to be created about the way people would switch from their current transport modes to available modes within their regular MaaS subscription. This is an important piece of information as MaaS can only deliver its promises regarding societal impacts if mode switching is in favor of less environmentally destructive modes for a large number of subscribers. Therefore, the second research question is:

(2) **Which transport mode within one’s MaaS bundle will be chosen, when, for which distance and activity purpose?**

An error component multinomial logit model was formulated and calibrated on a dataset collected through a stated adaptation choice experiment to answer this question. Finally, knowing the mode switching behavior for the population of interest, the third research question is:

(3) **To what extent the emission level is sensitive to the types of offered MaaS and the adoption rate?**

An activity-based travel demand model (Albatross) (Arentze and Timmermans, 2000; Timmermans and Arentze, 2011) was activated to simulate the daily activity-travel patterns. Choice models developed to answer the first two research questions were then utilized to determine the probability of adopting MaaS and switching mode for the simulated citizens. Albatross’s outcome was then coupled with the emission model, COPERT (Ntziahristos et al., 2009), to evaluate the impact of MaaS on emissions. The entire simulation framework was applied to the city of Amsterdam (Netherlands), one of the pioneers deploying mobility innovations. Various scenarios are defined in terms of future MaaS characteristics, and a comparison is made on their consequential impacts on the emissions. By answering the above research questions, the contribution of this research is twofold. First, combining Albatross with the estimated models of adoption and usage of MaaS contributes to the methodological research for offering empirically founded evidence on mobility behavior adaptation at a large scale. Second, the evaluation provides insights for stakeholders, such as policymakers, researchers, and MaaS providers on the impact of MaaS with different characteristics on the emissions in urban areas.

The remainder of the paper is organized as follows. Section 2 provides an overview of related works. Section 3 highlights the contributions of the current work and the simulation framework. The results of a case study are presented in Section 4. Section 5 concludes the paper with a discussion of the main contributions of this study and a reflection on its limitations.

2. Related work

This section reviews related research on the adoption and usage of MaaS and its consequences for the environment. Much of recent research on MaaS has focused on potential target groups, their interest in MaaS (Alonso-González et al., 2020; Caiati et al., 2020; Durand et al., 2018; Floreze et al., 2019; Zijlstra et al., 2019), and their preferred MaaS bundles (Caiati et al., 2020; Guidon et al., 2020; Ho et al., 2020, 2019; Jang et al., 2020; Matyas and Kamargianni, 2018; Reck et al., 2020; Reck and Axhausen, 2020; Vij et al., 2020). These studies have used literature reviews, stated preference experiments, and models such as latent class models and latent variable models to analyze the data. Stated preference experiments offer substantial control to the researchers over the choice environment. A disadvantage however is that people will not always do what they state they would do in the real world. Due to the novelty of the
concept of MaaS, a limited number of pilots are available at small scales, which limits the possibility of conducting revealed choice studies.

2.1. Adoption of MaaS

Concerning the adopters of MaaS, Durand et al. (2018) systematically reviewed the literature and reported that the first groups to adopt MaaS are likely to be young to middle-aged people living in urban areas. Conversely, Fioreze et al. (2019) argued that it is not necessarily the demographic characteristics such as age that drive the interest in the adoption of MaaS, but the travel behavior. Kim & Rasouli (2019) examined the association of (latent) lifestyle with the adoption of MaaS and provided evidence that such a relationship exists. Other researchers found a similar target group as Durand et al.; young to middle-aged individuals, living in urban areas, who are already multi-modal (Zijlstra et al., 2020, 2019). Besides multi-modality, the authors also suggested the ‘hyper-mobile lifestyles’ to have a positive association with an interest in MaaS. Other works refer to multimodal travel behavior as well (Alonso-González et al., 2020). They found that younger and higher educated people are more multimodal in their travel behavior, which – in congruence with the concept of MaaS – is often seen as an indicator of their adoption potential for MaaS. The authors used an exploratory factor analysis and a latent class cluster analysis and found five clusters of people regarding their attitudes towards MaaS. These clusters were formed according to the unobserved (latent) variables that explain the responses to four main indicators: mobility integration, shared mobility modes, mobile applications, and willingness to pay (WTP). Covariates such as socio-economic and mobility-related characteristics were later added to characterize the clusters.

Regarding adoption and bundle formation, studies with different designs exist examining the citizens’ preferences. Ho et al. (2018) conducted a stated choice experiment to understand potential MaaS uptake in Sydney, the WTP for a mobility plan, and the way MaaS would change the travel patterns. Almost half of the respondents indicated interest to take MaaS services. In their experiment, MaaS bundles included public transport (PT), car-sharing (CS), taxi, and UberPool. A limited number of transportation modes was included to limit the cognitive burden. The findings of this study also indicated that young to middle-aged people are potential target groups highly interested in MaaS. Matyas and Kamargianni (2018) estimated a bundle choice model to see which modes individuals are willing to include in their bundles. Interesting findings were that only 8.6% of the chosen MaaS plans did not include bike or car-sharing. Furthermore, 64% of the respondents indicated they would be willing to try new transport modes as part of their MaaS plans. Guidon et al. (2020) used discrete choice models to investigate the differences between the WTP for stand-alone and bundled services. They found that the WTP for PT, CS and ride services are higher in bundles, while the bike-sharing (BS) and taxi are valued lower in bundles. Stand-alone – or pay-as-you-go – schemes, were preferred over bundled schemes in an Australian-based experiment (Vij et al., 2020). The authors found that in Australia bike-sharing is the least popular mode within MaaS options. Due to the absence of advanced cycling infrastructure and culture, this observation does not come as a surprise. Overall, the authors found that 32% of Australians would adopt MaaS if such a service was available in the market today. While most previously discussed work either examine the adopters or the bundle choice, Caiati et al. (2020) addressed both the adopters as well as the bundle issue. The authors formulated two portfolio choice mixed logit models to predict whether a respondent would subscribe to MaaS, and if so, which bundle to form. They found that people within the age group 18–35 are most likely to be interested to adopt MaaS. The highest percentage of bundle choices involve public transport, taxi, car-sharing, and car rental. This does not mean that the respondents would obsessively use these modes, but it reflects the fact that these options had been among the maximum of the four transport modes they included in their bundles. They also found that respondents were keen to have a highly inclusive pricing scheme for public transport, bike-sharing, and ride-sharing.

2.2. Usage of MaaS

MaaS promises enhancing accessibility and equity (Jittrapirom et al., 2017) and reduction of congestion (Furtado et al., 2018, 2017a, 2017b; Santos, 2018). Much of the literature claims that MaaS may lead to a reduction in private car use and potentially a reduction in GHG emissions (Gould et al., 2015; Jittrapirom et al., 2017). However, due to the limited number of comprehensive MaaS pilots, limited evidence exists to support this claim. Sochor et al. (2015a, 2015b) found a decrease in private vehicle use during the Ubigo trial in Gothenburg, Sweden. A more recent trial from Sydney also supports the notion that multi-modal travelers are more interested in MaaS than uni-modal travelers. Moreover, the majority of people signing up for their experiment were frequent users of both public transport and private cars, contradicting the suggestion that MaaS may not appeal to frequent car users. The Tripi trial furthermore suggested that a significant reduction in VKT could be achieved (Hensher et al., 2021). The authors furthermore posited that if the probability of choosing a bundle increases by 1 percent, there is an expected reduction in VKT from 434 km to 367 km. However, as also being acknowledged by the authors, it is not yet clear how these outcomes are transferable to and scalable over a large population (Hensher et al., 2020). Ho et al. (2021) continued on this note, emphasizing that there is no guarantee that MaaS will have real potential to contribute to sustainability goals in a commercially viable way, or as Reck et al. (2021) put it, “MaaS may (currently) be more of a niche product than a ‘game changer’ in urban mobility”. Increasing the relative attractiveness of the services and the facilitation of the decline of private cars are said to be essential for the future development of MaaS (Smith and Hensher, 2020). One of the instruments to increase the relative attractiveness is bundles. Ho et al. (2021) developed a choice model based on revealed preference data to assess the interests in MaaS subscription bundles, and their findings suggested that subscription bundles can help MaaS obtain a sizeable uptake. Reck et al. (2021) also investigated MaaS bundles, and particularly the relation between MaaS bundles and car-sharing usage. The authors emphasized the boundary conditions of the amount of car-sharing included in MaaS bundles, under which MaaS can indeed contribute to sustainability goals or not.
While the aforementioned works suggested a mode shift away from private vehicles, Docherty et al. (2018) speculated that new travel demand induced by the increased accessibility may contribute to counterbalancing the positive impact of MaaS. Other unforeseen consequences, such as the mode shift from active modes (i.e. walking and cycling) to motorized MaaS modes and from the conventional high capacity transit services to demand-driven low capacity transit, are often discussed in the literature as well (Fioreze et al., 2019). These effects may offset the positive impact of the sharing concept underlying MaaS. Another study examining the impact of the MaaS concept was conducted based on a MaaS pilot in Ghent, Belgium (Storme et al., 2019). The study focused on the relationship between car ownership and MaaS use, for which 90 car-owners were recruited from Ghent university to take part in the study. They found that private car use did reduce considerably, but not completely. Especially for leisure trips, the car was still dominantly used. In cases when the car was replaced, (e-)bike was the main mode of transport to which people switched. The authors concluded that MaaS and private car usage are complementary systems. Reck & Axhausen (2020) also aimed their study at car trips and constructed a MaaS scenario in which observed car trips were replaced by the best alternative shared mode for a sample of Danish students. They found that PT season ticket is a core component of MaaS plans for the majority of their sample, while pay-per-ride is the preferred scheme for other modes such as bike and car-sharing. Mode switching behavior was also studied by Feneri et al. (2020), who investigated the switching behavior from current modes of transport to modes within hypothetically assigned MaaS bundles of a sample of citizens in the Netherlands. The results showed that respondents – particularly frequent bike users – tended to stick to their current transport mode. Besides, younger millennials were significantly more eager to switch compared to older respondents. In terms of preferences toward MaaS transport modes, PT, CS, and BS were chosen most often. Not having to transfer while using PT had a positive effect on the likelihood of sticking to PT. The BS option became less attractive with increasing trip duration and travel cost. Continuing on the cost aspect, Ho et al. (2020) assessed WTP in Sydney and the impact of different bundles and pricing schemes on potential MaaS uptakes. Their results suggested that a pay-as-you-go scheme would increase the MaaS uptake, but would lead to less sustainable travel behavior since those adopters tended to stick relatively close to their current travel patterns, while monthly subscribers did more often indicate switching to PT and active modes. Jang et al. (2020) elaborated this by positing that the extent of transition in mode choice behavior as a consequence of MaaS adoption would depend on how bundles are constructed. The results of their stated choice experiment suggested that MaaS contributes to improving sustainable transportation in a non-linear manner as a function of decreasing monthly subscription fees and/or increasing the length of the subscription.

2.3. The implication of MaaS for the environment

MaaS is claimed to be a disruptive low-carbon innovation, which ought to help with reaching the 2 degrees climate mitigation set out in the Paris agreement (Wilson et al., 2019). Wilson et al. (2019) even claimed MaaS to be the number one of the most disruptive innovations with one of the largest potentials to reduce emissions in the mobility sector. In most empirical studies, emissions were not discussed in terms of emitted tons of CO₂ equivalents, but in the reduction of car usage (Storme et al., 2019; Feneri et al., 2020). To the best of our knowledge, little to none empirical evidence or simulation studies exist on the extent of emission reduction due to the MaaS deployment, apart from the discussed trials. Therefore, we chose to provide a review of studies reporting the impact of modes that could potentially be part of MaaS on the emissions, starting with PT. PT is likely to function as the backbone of MaaS particularly in the European context, and many studies suggest that PT can alleviate the negative externalities of private car use.

Studies in developed European cities such as Barcelona have shown that transitions from car to PT and bike trips would substantially benefit the health of citizens as a result of being more physically active and would lead to a reduction in air pollution (Rojas-Rueda et al., 2012). Zheng and Kahn (2013) and Sun et al. (Sun et al., 2019) posited that an increase in PT capacity would likely lead to less private car use and thus less congestion and air pollution. Carroll et al. (2019) contributed to this position and suggested that a shift from private cars to PT results in decreases in CO₂, NOₓ and PM₂.₅ emissions. Tittos et al. (2015) evaluated the impacts of changes in the transportation system, such as renewing the PT fleet and dedicating a central road to PT in Grenada on the emissions, and concluded that a significant decrease in emissions would be expected. Kwan and Hashim (2016) systematically reviewed the literature on the role of mass public transportation in climate change mitigation and found differences in conclusion between developing and developed countries. They concluded that PT is a suitable first step to reduce motorized vehicles mainly in developing countries where urban sprawl is still an issue. Field data from Mexico City showed decreases in PM₁₀, NOₓ, and CO as short-term impacts of the introduction of Bus Rapid Transit (Bel and Holst, 2018). On the contrary, Ma et al. (Ma et al., 2021) argued that merely PT provision and its improvements will not be enough to reduce air pollution in the city of London.

Car- and ride-sharing are expected to play a major role in MaaS not only in terms of emission reduction but also recovery of urban spaces (Firnkorn and Müller, 2011), although evidence triggering such expectations is mainly based on stand-alone sharing services and needs to be confirmed within MaaS frameworks. Early experiments already mentioned a reduction in fuel consumption (Doherty et al., 1987). A study on ride-sharing in Ireland evaluated three possible scenarios, all resulting in reductions of both VKT and CO₂ emissions (Caulfield, 2009). Likewise, UberPool, the ride-sharing service of Uber, claimed to have saved 124 metric tons of CO₂. Labee et al. (2018) investigated the switching behavior from current modes of transport to modes within hypothetically assigned MaaS bundles of a sample of citizens in the Netherlands. The results showed that respondents – particularly frequent bike users – tended to stick to their current transport mode. Besides, younger millennials were significantly more eager to switch compared to older respondents. In terms of preferences toward MaaS transport modes, PT, CS, and BS were chosen most often. Not having to transfer while using PT had a positive effect on the likelihood of sticking to PT. The BS option became less attractive with increasing trip duration and travel cost. Continuing on the cost aspect, Ho et al. (2020) assessed WTP in Sydney and the impact of different bundles and pricing schemes on potential MaaS uptakes. Their results suggested that a pay-as-you-go scheme would increase the MaaS uptake, but would lead to less sustainable travel behavior since those adopters tended to stick relatively close to their current travel patterns, while monthly subscribers did more often indicate switching to PT and active modes. Jang et al. (2020) elaborated this by positing that the extent of transition in mode choice behavior as a consequence of MaaS adoption would depend on how bundles are constructed. The results of their stated choice experiment suggested that MaaS contributes to improving sustainable transportation in a non-linear manner as a function of decreasing monthly subscription fees and/or increasing the length of the subscription.

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Cycling is a zero-emissions transportation mode (considering the usage phase). An increase of the range, enabled by the emergence of E-bikes, is believed to result in a slight decrease in CO₂ emissions (Venturini et al., 2019). Since cycling is already embedded in the culture of many European countries, bigger gains are foreseen in the prevalence of e-bike sharing (Nieuwenhuijzen, 2020), especially due to their added value in the first and last mile (DeMaio, 2009). Optimal layouts for bike-sharing stations can contribute to higher emissions (Vento, 2019).
emission reductions (Zhang et al., 2018).

To summarize, an increasing amount of attention has been paid to MaaS in the academic world, much of which focused on the target groups suggesting that the biggest share of adopters is most likely among the people younger than 35 years old. Besides age, a higher income and education level are said to have a positive effect on the adoption potential. A few works also suggest lifestyle and current travel behavior are relevant predictors of adoption. Studies exploring bundle choice behavior of these potential target groups pose that PT, CS, and BS are likely to be among the transport modes to which users are most inclined to switch. While based on the studies above these transport modes are believed to reduce emissions, little to no comprehensive studies exist assessing the impacts of full MaaS implementation on emission levels, and we must critically note that previous works focused on the specific modes rather than on MaaS as a whole.

3. Simulation framework

From the literature review, it becomes clear that no research is available on the extent to which various types of MaaS can contribute to changes in the emission level. To explore the isolated impact of MaaS characteristics on emission, a large scale simulation model (supported by empirical data) is required. The current work intends to achieve this by coupling models of MaaS adoption and usage with an activity-based travel demand model (Albatross). In this section, we discuss the conceptual simulation framework and the MaaS adoption to study the impacts of MaaS usage on emissions.
3.1. Conceptual model

This study proposes an approach built around the state-of-the-art activity-based model (ABM) Albatross (A Learning-Based Transportation Oriented Simulation System) (Arentze and Timmermans, 2000, 2004; Timmermans and Arentze, 2011; Rasouli et al., 2018) to forecast travel demand for a synthetic population in the form of activity and travel schedules. Albatross is a computational process model, also known as a rule-based model, and is based on choice heuristics theories. At the heart of the model is the Chi-square Automatic Interaction Detection (CHAID) decision tree learning algorithm. This supervised learning technique extracts decision rules from empirical data provided by the travel diaries. Albatross predicts activity schedules for a synthesized population. These activity schedules contain the types of activities, their starting and ending time, their locations (at four-digit postal code level (PC4)), and transport modes. MaaS is currently not included in Albatross due to the lack of relevant data in the Dutch travel survey (upon which Albatross has been built), which is why it was modeled exogenously. The probability of MaaS adoption and chosen bundles for each household in the synthesized population is estimated by a mixed logit model (elaborated in Section 3.2.1). The activity-travel schedules of the citizens, created by Albatross, are adjusted based on the utility and probability functions for the mode switching behavior. More specifically, for each individual and each episode of travel simulated by Albatross, the probability of switching from the status quo mode to any of the MaaS modes is calculated. That is possible because the error component model estimated for the mode switching has all necessary information such as the type of mode in the status quo, travel time, travel cost, waiting time, access and egress time, parking cost, and activity purpose. The mode choice is then simulated using the calculated probabilities. The models to estimate these functions are elaborated upon in Section 3.2.2. For sharing rides, the following principles

| Characteristic | C – Conservative | B- Balanced | O – Optimistic |
|---------------|-----------------|-------------|----------------|
| Monthly fee   | €240            | €210        | €150           |

Table 1

MaaS scenarios.

| Pricing scheme | FT | (E)-BS | (E)-CS | Taxi | (E)-CR | RS | ODB |
|----------------|----|--------|--------|------|--------|----|-----|
| Monthly fee    | €240| €210   | €150   |      |        |    |     |
| Pricing scheme | Pay per ride | Unlimited rides in one zone | One hour free per day | Unlimited rides | 300 min included | Unlimited rides | Unlimited rides in one zone |

Fig. 2. Location of Amsterdam and the main road network.

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This study proposes an approach built around the state-of-the-art activity-based model (ABM) Albatross (A Learning-Based Transportation Oriented Simulation System) (Arentze and Timmermans, 2000, 2004; Timmermans and Arentze, 2011; Rasouli et al., 2018) to forecast travel demand for a synthetic population in the form of activity and travel schedules. Albatross is a computational process model, also known as a rule-based model, and is based on choice heuristics theories. At the heart of the model is the Chi-square Automatic Interaction Detection (CHAID) decision tree learning algorithm. This supervised learning technique extracts decision rules from empirical data provided by the travel diaries. Albatross predicts activity schedules for a synthesized population. These activity schedules contain the types of activities, their starting and ending time, their locations (at four-digit postal code level (PC4)), and transport modes. MaaS is currently not included in Albatross due to the lack of relevant data in the Dutch travel survey (upon which Albatross has been built), which is why it was modeled exogenously. The probability of MaaS adoption and chosen bundles for each household in the synthesized population is estimated by a mixed logit model (elaborated in Section 3.2.1). The activity-travel schedules of the citizens, created by Albatross, are adjusted based on the utility and probability functions for the mode switching behavior. More specifically, for each individual and each episode of travel simulated by Albatross, the probability of switching from the status quo mode to any of the MaaS modes is calculated. That is possible because the error component model estimated for the mode switching has all necessary information such as the type of mode in the status quo, travel time, travel cost, waiting time, access and egress time, parking cost, and activity purpose. The mode choice is then simulated using the calculated probabilities. The models to estimate these functions are elaborated upon in Section 3.2.2. For sharing rides, the following principles
Transportation Research Part D 102 (2022) 103128

were applied: it is assumed that people are matched based on the same origin and destination (at PC4 level) and the same departure time interval (15 min per interval), and a ride is shared with at most one person. To calculate the emissions, the simulated activity-travel schedules are aggregated to create an Origin-Destination (OD) matrix per fuel and age type of the car, resulting in a multi-class OD matrix at PC4 level on a 30-minute interval. The OD matrices are subsequently assigned to the road network using a user equilibrium algorithm, after which COPERT (Version 5) is used to calculate the emissions for different pollutants (elaborated in Section

| Variable                   | Attribute level | Synthesized |
|----------------------------|-----------------|-------------|
| Age                        | <35             | 54.8%       |
|                            | 35–55           | 23.2%       |
|                            | 55–65           | 7.6%        |
|                            | 65–75           | 7.0%        |
|                            | >75             | 7.4%        |
| Gender                     | Female          | 42.8%       |
|                            | Male            | 57.2%       |
| Monthly income             | <€625           | 13.7%       |
|                            | €625–€1250      | 16.2%       |
|                            | €1250–€1875     | 14.5%       |
|                            | €1875–€2500     | 42.3%       |
|                            | >€2500          | 13.2%       |
| Highest level of education | BO/LO           | 8.7%        |
|                            | LBO/VGLO/LAVO/MAVO | 20.2%    |
|                            | MBO/HAVO        | 34.9%       |
|                            | HBO/University/Ph.D. | 23.1% |
|                            | Other           | 13.1%       |
| Household composition      | Single person with no work | 31.8% |
|                            | Single person with work | 24.7% |
|                            | Two-person household with one worker | 10.2% |
|                            | Two-person household with two workers | 17.6% |
|                            | Two-person household with no workers | 15.6% |
| Number of cars             | 0               | 19.6%       |
|                            | 1               | 49.3%       |
|                            | >1              | 31.2%       |
| Fuel type                  | Petrol          | 76.5%       |
|                            | Diesel          | 15.1%       |
|                            | Electric        | 6.6%        |
|                            | LPG             | 1.8%        |

Table 2

Socio-demographic characteristics.

Fig. 3. Trip distribution.
3.3) based on the traffic flows, generated by the traffic assignment. In COPERT, emission factors are functions of average speeds and coefficients which are vehicle type and fuel types specific. The conceptual framework is shown in Fig. 1. The teal part (left-hand side) of the figure constitutes the core of the framework and corresponds to the status quo, in which no MaaS is incorporated. The MaaS scenario framework is shown in lilac (right-hand side). The rectangular steps represent computational steps, and the other shapes are explained in the legend.

Fig. 4. Differences in CO emissions per scenario per PC4 area for a typical day.

Table 3
Predicted average trips per day per person.

| Mode                  | Age  | 18–35 | 35–55 | 55–65 | 65–75 | 75+ |
|-----------------------|------|-------|-------|-------|-------|-----|
| Car as driver         | 1.2  | 1.3   | 1.1   | 0.9   | 0.6   |
| Car as passenger      | 0.3  | 0.2   | 0.3   | 0.3   | 0.3   |
| PT                    | 0.2  | 0.2   | 0.2   | 0.2   | 0.2   |
| Walking or biking     | 1    | 1     | 0.9   | 0.9   | 0.9   |
| Total predicted       | 2.8  | 2.7   | 2.5   | 2.3   | 2.3   |
3.2. Forecasting MaaS adoption and usage

The forecasting of MaaS adoption and usage consists of two simulations: the adoption of MaaS and the mode switching behavior after subscribing to MaaS. The first step is to simulate the adopting population, which refers to research question 1. Once the degree of MaaS adoption is known the second step is to determine the switching behavior of the adopters, referring to research question 2.

3.2.1. Adoption of MaaS

The degree of MaaS adoption is likely to be influenced by the attractiveness of the MaaS service moderated by socio-demographics. To simulate the subscription to the MaaS service, estimated parameters of a mixed logit model – which was built upon a sequential portfolio choice experiment – were adopted from Caiati et al. (2020). In the experiment, respondents were asked if they were willing to subscribe to the service given service characteristics (e.g., monthly fee, transport modes’ pricing schemes, time commitment, and social influence). The lists of attributes, their levels, and estimated parameters are provided in the appendix (Tables A.1–A.4). The respondents who showed interest in subscribing were then requested to configure their MaaS bundles. In the portfolio choice experiment, the respondents could pick a maximum of four transport modes out of seven options: PT, E-bike sharing (E-BS), E-car-sharing (E-CS), taxi, Car Rental (CR), ridesharing (RS), and On-Demand Bus (ODB).

A table showing the average trips per day by mode per person in 2010 in the Netherlands (CBS, 2018) is also presented.

A table illustrating the share of MaaS adoption for three scenarios is also included.

Another table presenting the mode share of MaaS adoption for different scenarios.

A table showing the simulated emissions in kilograms per day is also included.

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After having simulated the MaaS adopters and their chosen bundles, the mode switching was simulated, explained in the next
Table 8
Mann-Whitney U test results – CO emissions.

| Scenario   | Median (grams) | Scenario   | Median (grams) | n (Number of zones) | U   | P-value (exact sig. 2-tailed) |
|------------|----------------|------------|----------------|---------------------|-----|-----------------------------|
| Day        |                |            |                |                     |     |                             |
| Base scenario | 74389.8        | Scenario C | 72157.0        | N1 = N2 = 65        | 2042.5 | 0.744                      |
| Base scenario | 74389.8        | Scenario B | 65274.6        | N1 = N2 = 65        | 1909.5 | 0.344                      |
| Base scenario | 74389.8        | Scenario O | 46190.3        | N1 = N2 = 65        | 1457.5 | 0.002                      |
| Scenario C | 72157.0        | Scenario B | 65274.6        | N1 = N2 = 65        | 1946.5 | 0.439                      |
| Scenario C | 72157.0        | Scenario O | 46190.3        | N1 = N2 = 65        | 1496.5 | 0.004                      |
| Scenario B | 65274.6        | Scenario O | 46190.3        | N1 = N2 = 65        | 1631.5 | 0.025                      |
| 08:00      |                |            |                |                     |     |                             |
| Base scenario | 2821.3         | Scenario C | 2727.0         | N1, N2 = 65         | 2035.5 | 0.722                      |
| Base scenario | 2821.3         | Scenario B | 2449.2         | N1, N2 = 65         | 1880.5 | 0.281                      |
| Base scenario | 2821.3         | Scenario O | 1714.1         | N1, N2 = 65         | 1379.5 | 0.001                      |
| Scenario C | 2727.0         | Scenario B | 2449.2         | N1, N2 = 65         | 1925.5 | 0.386                      |
| Scenario C | 2727.0         | Scenario O | 1714.1         | N1, N2 = 65         | 1422.5 | 0.001                      |
| Scenario B | 2449.2         | Scenario O | 1714.1         | N1, N2 = 65         | 1573.5 | 0.012                      |
| 12:00      |                |            |                |                     |     |                             |
| Base scenario | 1852.0         | Scenario C | 1809.6         | N1, N2 = 65         | 2015.5 | 0.657                      |
| Base scenario | 1852.0         | Scenario B | 1584.9         | N1, N2 = 65         | 1901.5 | 0.327                      |
| Base scenario | 1852.0         | Scenario O | 1179.3         | N1, N2 = 65         | 1466.5 | 0.002                      |
| Scenario C | 1809.6         | Scenario B | 1584.9         | N1, N2 = 65         | 1953.5 | 0.461                      |
| Scenario C | 1809.6         | Scenario O | 1179.3         | N1, N2 = 65         | 1512.5 | 0.005                      |
| Scenario B | 1584.9         | Scenario O | 1179.3         | N1, N2 = 65         | 1649.5 | 0.031                      |
| 17:00      |                |            |                |                     |     |                             |
| Base scenario | 4222.5         | Scenario C | 4056.1         | N1, N2 = 65         | 2051.0 | 0.778                      |
| Base scenario | 4222.5         | Scenario B | 3747.8         | N1, N2 = 65         | 1916.5 | 0.363                      |
| Base scenario | 4222.5         | Scenario O | 2757.0         | N1, N2 = 65         | 1476.5 | 0.003                      |
| Scenario C | 4056.1         | Scenario B | 3747.8         | N1, N2 = 65         | 1957.5 | 0.472                      |
| Scenario C | 4056.1         | Scenario O | 2757.0         | N1, N2 = 65         | 1509.5 | 0.005                      |
| Scenario B | 3747.8         | Scenario O | 2757.0         | N1, N2 = 65         | 1621.5 | 0.022                      |

section.

3.2.2. Mode switching

Since no large-scale comprehensive MaaS empirical data is available in the Netherlands, a stated adaptation experiment was adopted from Feneri et al., (2020) to assess how the MaaS population is going to use MaaS once subscribed. The parameters of the error component logit model estimated by Feneri et al. have been used in the current study. The stated adaptation experiment was conducted with a total of 2,143 respondents in the Netherlands. In their experiment, respondents were asked to report their travel patterns and, assuming they had subscribed to a hypothetical bundle (with certain characteristics in terms of monthly fee and pricing scheme for each transport mode within the bundle), to state whether or not they would change their transport modes, and if so, to which alternative modes. The four bundles are presented in the appendix (Table A.5). Attributes related to each mode within MaaS were shown to the respondents. Many attributes of status quo (SQ), such as type of mode, travel time, travel cost, waiting time, access and egress time, parking time, cost, time pressure, day of the week, and activity purpose, have been included in the utility function of SQ. The utility of each mode within a MaaS bundle was then defined by the experimental variables. The full list of variables and the estimated parameters are presented in the appendix (Tables A6 and A.7). More elaborate information on how the data was collected in order to estimate the model can be found in the referenced work. An estimated model then was used to calculate the utility derived from using the current transport mode (status quo) versus the utility derived from switching to an alternative transport mode within MaaS.

3.3. Emissions forecast

Activity-travel schedules of citizens were simulated using Albatross, which formed the base scenario. A multiclass OD matrix (at PC4 level) was created and used as input in a user equilibrium model of traffic assignment. The traffic assignment was set up for and conducted at a 30-minute interval. To more realistically represent the service level of the network, morning peak, evening peak, and off-peak travel time were differentiated. This yields required input – such as loaded network speeds – for the emissions forecast. The emission factors from COPERT (version 5) were used to calculate the emissions, including CO, NOx, CH4, and PM and CO2.

For the MaaS scenarios, it is assumed that all vehicles operated in the MaaS bundles are electric, i.e. not producing any tailpipe emissions. This assumption holds for instance for the Amaze consortium, which currently provides services in Amsterdam (‘Amaze,’ 2019). Amaze is a MaaS app that enables users to use e-bikes (provided by Urbee), shared electric scooters (provided by Felyx), or shared electric cars (provided by Amber). For ride-sharing, it is assumed that people are matched based on the same OD pair (at PC4 level) within 15 min departure time window, and a ride is shared with a maximum of one other person. The simulated activity-travel schedules of citizens were updated for the three different MaaS scenarios; after which OD trip matrices were created, with which traffic assignments were conducted; finally, emissions forecasts were made for each scenario.
### Table A1
MaaS subscription decision – estimated random parameters.

| Attribute in utility function                  | Attribute level                              | Coefficient | Scenario | Std. Error | p-value |
|-----------------------------------------------|----------------------------------------------|-------------|----------|------------|---------|
| Constant (joining MaaS)                       |                                              | −3.38       |          | 0.40       | 0.00    |
| Monthly subscription price                    | 150 €/month                                  | 1.10        | O        | 0.07       | 0.00    |
|                                              | 180 €/month                                  | 0.24        |          | 0.07       | 0.00    |
|                                              | 210 €/month                                  | −0.43       | B        | 0.08       | 0.00    |
|                                              | 240 €/month                                  | −0.91       | C        |            |         |

### Transportation modes attributes

| Public Transportation                        |                                              |             |          |            |         |
|---------------------------------------------|----------------------------------------------|-------------|----------|------------|---------|
| Unlimited rides                             |                                              | 0.33        | O        | 0.07       | 0.00    |
| Unlimited rides in one zone and for the others pay per ride | 0.03       | B        | 0.07       | 0.67    |
| Pay per ride with 20% of discount on standard fare | −0.12       |          | 0.07       | 0.09    |
| Pay per ride                               |                                              | −0.23       | C        |            |         |
| E-bike sharing                             |                                              |             |          |            |         |
| Unlimited rides                             |                                              | 0.00        |          | 0.07       | 0.98    |
| 1 free hour per day and then pay per ride  | −0.02                                          | B        | 0.07       | 0.81    |
| Pay per ride with 50% of discount on standard fare | 0.13                                          | O        | 0.07       | 0.06    |
| Pay per ride                               |                                              | −0.11       | C        |            |         |
| E-car sharing                              |                                              |             |          |            |         |
| 300 min included and then pay per use      | 0.03                                           | B        | 0.07       | 0.67    |
| 120 min included and then pay per use      | 0.17                                           | O        | 0.07       | 0.02    |
| Pay per use with 20% of discount on standard fare | −0.10                                           | C        | 0.07       | 0.16    |
| Pay per ride                               |                                              | −0.09       |          |            |         |
| Taxi                                       |                                              |             |          |            |         |
| 50 km included and then pay per ride       | −0.13                                          | C        | 0.08       | 0.09    |
| 30 km included and then pay per ride       | 0.12                                           |          | 0.07       | 0.12    |
| Pay per use with 40% of discount on standard fare | 0.02                                          | B        | 0.08       | 0.75    |
| Pay per ride                               |                                              | −0.01       |          |            |         |
| Car rental                                 |                                              |             |          |            |         |
| 4 days included and then pay per use       | 0.09                                           | O        | 0.07       | 0.21    |
| 2 days included and then pay per use       | −0.04                                          | C        | 0.08       | 0.60    |
| Pay per use with 20% of discount on standard fare | −0.03                                           |          | 0.08       | 0.71    |
| Pay per ride                               |                                              | −0.02       | B        |            |         |
| Ride sharing                               |                                              |             |          |            |         |
| Unlimited rides                             |                                              | 0.26        | O        | 0.07       | 0.00    |
| 100 km included and then pay per ride      | −0.01                                          | B        | 0.07       | 0.87    |
| Pay per use with 20% of discount on standard fare | −0.12                                           |          | 0.08       | 0.13    |
| Pay per ride                               |                                              | −0.13       | C        |            |         |
| On demand bus                              |                                              |             |          |            |         |
| Unlimited rides                             |                                              | 0.11        |          | 0.07       | 0.14    |
| Unlimited rides in one zone and for the others pay per ride | −0.17                                           | C        | 0.08       | 0.03    |
| Pay per use with 20% of discount on standard fare | −0.08                                           | B        | 0.07       | 0.28    |
| Pay per ride                               |                                              | 0.14        | O        |            |         |

### Scale parameters of random parameters

|                                | Coefficient | Scenario | Std. Error | p-value |
|--------------------------------|-------------|----------|------------|---------|
| Price                         | 150 €/month | 1.70     | 0.10       | 0.00    |
| 180 €/month                   | 0.53        |          | 0.09       | 0.00    |
| 210 €/month                   | 0.43        |          | 0.09       | 0.00    |
| Public Transportation         |             | 1.16     | 0.09       | 0.00    |
| Unlimited rides               |             | 0.70     | 0.08       | 0.00    |
| Pay per ride with 20% of discount on standard fare | 0.06                                           |          | 0.09       | 0.47    |
| E-bike sharing                |             | 0.79     | 0.09       | 0.00    |
| Unlimited rides               |             | 0.25     | 0.09       | 0.00    |
| Pay per ride with 50% of discount on standard fare | 0.41                                           |          | 0.08       | 0.00    |
| E-car sharing                 |             | 0.32     | 0.08       | 0.00    |
| 120 min included and then pay per use | 0.17                                          |          | 0.08       | 0.04    |
| Pay per use with 20% of discount on standard fare | 0.86                                           |          | 0.08       | 0.00    |
| Taxi                          |             | 0.25     | 0.09       | 0.00    |
| 50 km included and then pay per use | 0.54                                           |          | 0.08       | 0.00    |
| Pay per ride with 40% of discount on standard fare | 0.49                                           |          | 0.09       | 0.00    |
| Car rental                    |             | 0.12     | 0.08       | 0.14    |
| 4 days included and then pay per use | 0.16                                          |          | 0.09       | 0.07    |
| Pay per use with 20% of discount on standard fare | 0.15                                           |          | 0.08       | 0.06    |
| Ride sharing                  |             | 0.04     | 0.08       | 0.60    |
| Unlimited rides               |             | 0.20     | 0.08       | 0.02    |
| Pay per ride with 20% of discount on standard fare | 0.26                                           |          | 0.09       | 0.00    |
| On demand bus                 |             | 0.62     | 0.09       | 0.00    |
| Unlimited rides               |             | 0.56     | 0.09       | 0.00    |
| Pay per ride with 20% of discount on standard fare | 0.29                                           |          | 0.09       | 0.00    |
Table A2  
MaaS subscription decision – estimated non-random parameters.

| Non-random parameters                                      | Coefficient | Scenario | Std. error | p-Value |
|------------------------------------------------------------|-------------|----------|------------|---------|
| **Subscription Attributes**                                |             |          |            |         |
| **Time commitment**                                        |             |          |            |         |
| 1 month                                                    | –0.10       | C, B, O  | 0.07       | 0.19    |
| 3 months                                                   | –0.17       |          | 0.07       | 0.03    |
| 6 months                                                   | 0.14        |          | 0.07       | 0.06    |
| 12 months                                                  | 0.12        |          |            |         |
| **Data required**                                          |             |          |            |         |
| Full name, email address and phone number                  | –0.30       |          | 0.08       | 0.00    |
| Full name, email address, phone number and payment information | 0.01   |          | 0.07       | 0.90    |
| Full name, email address, phone number and permission to use GPS | 0.15   |          | 0.07       | 0.04    |
| Full name, email address, phone number, payment information and permission to use GPS | 0.15 | C, B, O  | 0.07       | 0.04    |
| **Social influence attributes**                            |             |          |            |         |
| **General public reviews of the service**                  |             |          |            |         |
| Only positive                                              | 0.22        |          | 0.07       | 0.00    |
| Mainly positive                                            | 0.08        |          | 0.07       | 0.27    |
| Mainly negative                                            | –0.19       | C, B, O  | 0.07       | 0.01    |
| Only negative                                              | –0.12       |          |            |         |
| **Share among Relatives**                                 |             |          |            |         |
| 0%                                                        | –0.31       | C, B, O  | 0.07       | 0.00    |
| 25%                                                       | –0.07       |          | 0.07       | 0.31    |
| 50%                                                       | 0.17        |          | 0.07       | 0.01    |
| 75%                                                       | 0.22        |          |            |         |
| **Share among Friends**                                   |             |          |            |         |
| 0%                                                        | –0.17       | C, B, O  | 0.07       | 0.02    |
| 25%                                                       | 0.01        |          | 0.07       | 0.86    |
| 50%                                                       | 0.11        |          | 0.07       | 0.13    |
| 75%                                                       | 0.05        |          |            |         |
| **Share among Colleagues**                                |             |          |            |         |
| 0%                                                        | –0.19       | C, B, O  | 0.08       | 0.01    |
| 25%                                                       | 0.05        |          | 0.07       | 0.45    |
| 50%                                                       | 0.14        |          | 0.07       | 0.05    |
| 75%                                                       | 0.00        |          |            |         |
| **Gender**                                                 |             |          |            |         |
| Female                                                     | 0.10        |          | 0.05       | 0.05    |
| Male                                                       | –0.10       |          |            |         |
| **Age**                                                    |             |          |            |         |
| 18-25                                                      | 1.13        |          | 0.15       | 0.00    |
| 25-35                                                      | 0.46        |          | 0.11       | 0.00    |
| 36-50                                                      | 0.17        |          | 0.11       | 0.13    |
| 51-65                                                      | –1.04       |          | 0.11       | 0.00    |
| >65                                                        | –0.71       |          |            |         |
| **Household situation**                                   |             |          |            |         |
| Single or couple without (resident) children               | –0.99       |          | 0.10       | 0.00    |
| Single or couple with resident(s) child(s)                | 0.18        |          | 0.10       | 0.08    |
| Living at (large) parent (s)/family                       | 1.18        |          | 0.14       | 0.00    |
| Others                                                     | –0.57       |          |            |         |
| **Education**                                              |             |          |            |         |
| High                                                       | –0.23       |          | 0.08       | 0.00    |
| Middle                                                     | 0.18        |          | 0.08       | 0.02    |
| Low                                                        | 0.05        |          |            |         |
| **Work status**                                            |             |          |            |         |
| Student                                                    | 0.43        |          | 0.16       | 0.01    |
| Employed                                                   | 0.07        |          | 0.11       | 0.53    |
| Unemployed/Job Seeker                                     | –0.48       |          | 0.15       | 0.00    |
| Retired                                                    | 0.54        |          | 0.25       | 0.03    |
| Others                                                     | –0.57       |          |            |         |
| **Monthly income**                                         |             |          |            |         |
| < €625                                                     | –0.11       |          | 0.15       | 0.46    |
| €626-€1250                                                 | –0.01       |          | 0.10       | 0.96    |
| €1251-€1875                                               | 0.95        |          | 0.09       | 0.00    |
| €1876-€2500                                               | –0.71       |          | 0.10       | 0.00    |
| €2501-€3125                                               | –0.57       |          | 0.12       | 0.00    |
| > €3125                                                    | 0.44        |          |            |         |
| **Nr of cars in the household**                            |             |          |            |         |
| One                                                       | 0.57        |          | 0.06       | 0.00    |
| More than one                                             | –0.45       |          | 0.10       | 0.00    |
| None                                                      | –0.12       |          |            |         |
| **Driving license**                                        |             |          |            |         |
| Yes                                                       | 0.47        |          | 0.06       | 0.00    |
| **Car sharing membership**                                |             |          |            |         |
| Yes                                                       | 1.84        |          | 0.10       | 0.00    |
| **Smartphone ownership**                                  |             |          |            |         |
| Yes                                                       | 0.75        |          | 0.13       | 0.00    |
| **Modal share**                                            |             |          |            |         |
| Walk                                                      | –1.23       |          | 0.39       | 0.00    |
| Biking                                                    | –0.65       |          | 0.38       | 0.08    |
| Car as driver                                             | –2.19       |          | 0.38       | 0.00    |
| Car as passenger                                          | 5.26        |          | 0.53       | 0.00    |
| Public Transport                                          | 0.98        |          | 0.39       | 0.01    |
| Train                                                     | 4.86        |          | 0.51       | 0.08    |
4. Case study

To assess the impact of MaaS on emissions, we applied the above simulation framework for Amsterdam (Netherlands) (see Fig. 2). In the base scenario as well as three MaaS scenarios, a synthetic population of the city was generated. Iterative proportional fitting (IPF) was used to create the synthetic population consistent with the known distribution of the census data for Amsterdam.

The Dutch national travel survey data MON (Mobiliteit Onderzoek Nederland) contains the required socio-demographic information of the household heads and their travel diaries. This dataset serves as the multidimensional table within which the consistencies between various sociodemographic variables are preserved and are fitted to the marginal values provided by the census data. The IPF method proportionally fits cell values corresponding to both the marginal row and the marginal column totals.

The synthetic population resulted in 405,790 households. Since the ultimate goal of the study is to evaluate emissions, fuel types of vehicles owned by the households and vehicle sizes were among variables to be synthesized. Socio-demographic characteristics of the synthetic population, as well as the share of vehicles’ fuel types, are shown in Table 2.

To employ a user equilibrium model for the traffic assignment, lengths and directions of the road network, capacity, free-flow time, and maximum allowed speed are also required. This information was extracted from the strategic transportation model the Landelijk Model Systeem (LMS) (National Modeling System).

4.1. Base scenario

The Base scenario embodies activity-travel patterns without any MaaS service. Trip distribution per transport mode for various departure times for the base scenario is illustrated in Fig. 3. The areas shaded in lilac highlight the morning and evening rush hours. In total, 44.1% of the trips are made using private cars. The second-largest share of trips – 36.4% – is made by walking or biking, while 11.3% of the trips are made being a car as a passenger. The remaining 8.2% are made using public transport. In total, 13.2 million kilometers are driven on average per day.

The predicted and measured average numbers of trips per day per person for the base scenario are shown in Tables 3 and 4, respectively. A Chi-Square test is used to compare the values from both tables. The results of the Chi-Square test suggest no significant differences: $\chi^2 (3, N = 25) = 0.034, p = 0.998$; indicating that the predicted modal split is an adequate representation of the measured values.

4.2. MaaS scenarios and their comparisons

The scenarios defined in Section 3.2 result in the adoption rates as shown in Table 5 according to the discussed functions in the same aforementioned section. The table highlights substantial differences in the market share of MaaS service depending on the service characteristics.

In scenario C, 63.7% of the adopters fall in the age category of ‘younger than 35 years old’. A majority of younger people was already expected in line with previous research (Alonso-González et al., 2020; Zijlstra et al., 2020). A similar share of 61.6% ‘younger than 35’ is found in scenario B. Only in scenario O, this share is slightly smaller, 57.3%. That can be explained by the fact that the number of adopters is significantly larger in this scenario, which lowers the share of this specific group of young age. Besides age, education is a characteristic worth highlighting. In scenario C, >58% of MaaS adopters are medium to highly educated, compared to 60% in both scenario B and scenario O. For all three scenarios, nearly 50% of the adopters have one car in the household. In scenario C, only 16.5% of the adopters’ households have no car, which compares to 16.2% for scenario B and 18.0% for scenario O. In scenario C, 37.0% of the adopters have two or more cars, compared to 36.6% in scenario B and 33.2% in scenario O. The base and three MaaS...
scenarios are compared on two key mobility indicators: share of various modes (presented in Table 6) and emissions (reported in Table 7).

Table 6 shows the modal share for different scenarios. In the conservative scenario, using car as a driver and walking or biking are the dominant transport modes with 42.7% and 33.7% respectively, which are still lower than their corresponding shares in the base scenario. In total, 13.2 million kilometers are driven by CaD, CS, RS and CR in the conservative scenario. In the balanced scenario, driving car decreases by 5.4% but is still the most dominant mode of transport. The share of all transport modes increases in this

Table A4
Bundle configuration decision – estimated non-random parameters for transportation modes attributes and cross effects between transportation modes.

| Attribute                  | Attribute levels                                          | Coefficient | Scenario | Std. Error | |z| > Z* |
|----------------------------|-----------------------------------------------------------|-------------|----------|------------|-------|
| **Non-random parameters in utility function** |                            |             |          |            |       |
| Public Transportation      | Unlimited rides                                           | 0.49        | O        | 0.14       | 0.00  |
|                           | Unlimited rides in one zone and for the others pay per ride| -0.08       | B        | 0.14       | 0.55  |
|                           | Pay per ride with 20% of discount on standard fare         | -0.12       | B        | 0.14       | 0.36  |
|                           | Pay per ride                                              | -0.28       | C        |            |       |
| E-bike sharing             | Unlimited rides                                           | 0.22        | B        | 0.12       | 0.06  |
|                           | 1 free hour per day and then pay per ride                 | -0.02       | B        | 0.12       | 0.85  |
|                           | Pay per ride with 50% of discount on standard fare         | 0.24        | O        | 0.12       | 0.04  |
|                           | Pay per ride                                              | -0.44       | C        |            |       |
| E-car sharing              | 300 min included and then pay per use                     | 0.07        | B        | 0.12       | 0.55  |
|                           | 120 min included and then pay per use                     | 0.08        | O        | 0.12       | 0.50  |
|                           | Pay per use with 20% of discount on standard fare          | -0.03       | C        | 0.12       | 0.83  |
|                           | Pay per ride                                              | -0.13       |          |            |       |
| Taxi                       | 50 km included and then pay per ride                       | 0.04        | C        | 0.12       | 0.75  |
|                           | 30 km included and then pay per ride                       | 0.18        | O        | 0.12       | 0.12  |
|                           | Pay per ride with 40% of discount on standard fare         | 0.10        | B        | 0.12       | 0.39  |
|                           | Pay per ride                                              | -0.32       |          |            |       |
| Car rental                 | 4 days included and then pay per use                      | 0.25        | O        | 0.12       | 0.03  |
|                           | 2 days included and then pay per use                      | 0.04        | C        | 0.12       | 0.75  |
|                           | Pay per ride with 20% of discount on standard fare         | -0.07       |          | 0.12       | 0.53  |
|                           | Pay per ride                                              | -0.21       | B        |            |       |
| Ride sharing               | Unlimited rides                                           | 0.24        | O        | 0.11       | 0.02  |
|                           | 100 km included and then pay per ride                     | 0.08        | B        | 0.11       | 0.49  |
|                           | Pay per ride with 20% of discount on standard fare         | -0.12       |          | 0.11       | 0.28  |
|                           | Pay per ride                                              | -0.20       | C        |            |       |
| On demand bus              | Unlimited rides                                           | 0.28        |          | 0.13       | 0.03  |
|                           | Unlimited rides in one zone and for the others pay per ride| -0.12       | C        | 0.14       | 0.38  |
|                           | Pay per ride with 20% of discount on standard fare         | 0.03        | B        | 0.14       | 0.82  |
|                           | Pay per ride                                              | -0.19       | O        |            |       |
| **Cross effects between transportation modes** |                                            |             |          |            |       |
| Public transportation      | E-bike sharing                                            | 0.37        |          | 0.16       | 0.02  |
|                           | E-car sharing                                             | 0.74        |          | 0.16       | 0.00  |
|                           | Taxi                                                      | 0.34        |          | 0.15       | 0.03  |
|                           | Car rental                                                | 0.23        |          | 0.15       | 0.13  |
|                           | Ride sharing                                              | 0.31        |          | 0.15       | 0.04  |
|                           | On demand bus                                             | 0.45        |          | 0.18       | 0.01  |
| E-bike sharing             | E-car sharing                                             | 0.91        |          | 0.14       | 0.00  |
|                           | Taxi                                                      | 1.00        |          | 0.15       | 0.00  |
|                           | Car rental                                                | 0.36        |          | 0.15       | 0.01  |
|                           | Ride sharing                                              | 0.28        |          | 0.14       | 0.05  |
|                           | On demand bus                                             | -0.14       |          | 0.17       | 0.41  |
| E-car sharing              | Taxi                                                      | 0.58        |          | 0.15       | 0.00  |
|                           | Car rental                                                | 1.09        |          | 0.15       | 0.00  |
|                           | Ride sharing                                              | 0.70        |          | 0.14       | 0.00  |
|                           | On demand bus                                             | 0.16        |          | 0.17       | 0.35  |
| Taxi                       | Car rental                                                | 1.11        |          | 0.15       | 0.00  |
|                           | Ride sharing                                              | 0.59        |          | 0.14       | 0.00  |
|                           | On demand bus                                             | 1.02        |          | 0.16       | 0.00  |
| Car rental                 | Ride sharing                                              | 0.87        |          | 0.14       | 0.00  |
|                           | On demand bus                                             | -0.05       |          | 0.17       | 0.79  |
| Ride sharing               | On demand bus                                             | 1.05        |          | 0.15       | 0.00  |
scenario (compared to the conservative scenario) which is compensated by a cut in the share of driving car, walking, and biking. In the balanced scenario, the VKT of CaD, CS, RS and CR accumulate to 11.9 million km.

The share of driving car further decreases in the optimistic scenario to the extent that driving car loses its dominant position. This decrease also results in a lower summed VKT of CaD, CS, RS and CR: 8.2 million km. In this scenario, PT is the most used mobility option. The noticeable insight from Table 6 is the substantial drop in active mobility in the optimistic scenario, a phenomenon that had already been observed in some pilot studies (Fioreze et al., 2019). To find out if the differences among modal share between the four scenarios are significant, a Chi-Square test was conducted for the share of modes for the whole day and breaking down by morning peak, evening peak, and off-peak hours. Half hourly mode shares are used in these analyses. The degrees of freedom are calculated by 

\[ \chi^2 = \frac{(O - E)^2}{E} \]

where \(O\) is the observed frequency and \(E\) is the expected frequency. The results of the Chi-Square test suggest significant differences for all the above comparisons: for 08:00, \(\chi^2 (27, N = 286293) = 59569.609, p = 0.000\); for 12:00, \(\chi^2 (27, N = 218715) = 37106.981, p = 0.000\); for 17:00 \(\chi^2 (27, N = 477225) = 48657.484, p = 0.000\). For the whole day significant differences were also found, \(\chi^2 (27, N = 6147644) = 936104.144, p = 0.000\). While significant differences in mode share could be expected for the comparison between the three MaaS scenarios and the base scenario, significant differences were also found comparing the three MaaS scenarios: \(\chi^2 (18, N = 4610733) = 589178.309, p = 0.000\). For the latter test, the degree of freedom is 18 due to the exclusion of the base scenario.

Table 7 shows the simulated emissions per pollutant for all four scenarios. Figs. B1–B4 in Appendix B illustrate the number of trips per purpose per transport mode in each scenario. From these figures, it becomes clear that in the MaaS scenarios PT will be used more. Furthermore, the share of CS particularly increases for work-related trips.

The predicted total daily amount of CO\(_2\) emissions for the base scenario is 2200 tons for a typical day. To validate the result, we compared it with the annual CO\(_2\) reported by Rijkswaterstaat (2020) for Amsterdam. It is reported to be 504,377 tons per year. When workdays, holidays, and weekends, traffic intensity ratio (weekday/weekend as 2.5:1) are taken into account, the daily CO\(_2\) emissions of 2100 tons are obtained, which is rather close to the predicted value. In conservative scenario (C), reductions are found in all five emissions: 3.3% in CO, 3.5% in NO\(_x\), 4.2% in PM, 3.1% in CH\(_4\) and 3.4% in CO\(_2\). In scenario B, larger reductions in emissions are observed: 16.2% in CO, 17.3% in NO\(_x\), 18.5% in PM, 14.0% in CH\(_4\) and 16.1% in CO\(_2\). In optimistic scenario (O), a substantial drop in emissions can be seen in Table 7: 50.9% in CO, 51.9% in NO\(_x\), 54.6% in PM, 43.1% in CH\(_4\) and 50.2% in CO\(_2\). A spatial comparison at the PC4 level of four scenarios for CO\(^1\) is illustrated in Fig. 4. The subgraphs illustrate the varying impacts of MaaS on the CO emissions on the city scale of Amsterdam. The maps show the differences per scenario compared to the base scenario, for the complete day, and the labels show the differences in percentages, where a minus sign indicates a decrease. It becomes clear that with increasing attractiveness of MaaS and therefore higher MaaS adoption rates, more substantial decreases in emissions happen. This is demonstrated most noticeably by comparing subgraph O with subgraph C. These spatial graphs furthermore show that the areas generating the most emissions are either near the city’s ring road or in the city center. To compare the daily urban CO emissions per PC4 area in Amsterdam a Mann-Whitney \textit{U} test is conducted to see where the differences occur. In addition, the CO emissions for the specific times 08:00, 12:00, and 17:00 are compared as well, to highlight the differences during the morning peak, evening peak, and off-peak times. The results from these tests are shown in Table 8. The table suggests that significantly less CO is emitted per zone in the optimistic scenario, compared to any of the other scenarios, at all different times.

5. Conclusion, discussion, and limitations

Insights generated before the full employment of MaaS are valuable in knowing how certain MaaS promises regarding emissions will be delivered before using a scattergun approach. Having these insights may help govern the service towards a more desirable environmental impact. The present work has generated such insights for the city of Amsterdam, The Netherlands. Such understanding will help policymakers to be aware of various possible futures regarding the societal impacts of MaaS. The work also emphasizes the endless possibilities of using an ABM framework. To this end, three different scenarios were developed: a conservative, balanced, and optimistic scenario, which are associated with a low, medium, and high interest in using MaaS, respectively. The results suggest that the share of citizens adopting MaaS is expected to be 20.3 percent for the conservative scenario, while this value ramps up and reaches 84.8 percent in the optimistic scenario. Although three MaaS scenarios have commonly a lower rate of using private car and a higher rate of public transport, the optimistic scenario is the one leading to the largest decrease in the use of private cars and results in PT

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1 CO is the most dangerous for climate change as well as human health, which is why it is regulated in many parts of the world (Shindell et al., 2006). Due to the twofold risks CO imposes, this pollutant is selected for more detailed illustration in this work.
Table A6

Parameters stated adaptation experiment.

| Error components          | Coefficient | Std. Error | p-value |
|---------------------------|-------------|------------|---------|
| MaaS.PT-MaaS.CS           | 1.287       | 0.073      | 0.000   |
| MaaS.PT-MaaS.BS           | 0.981       | 0.073      | 0.000   |
| MaaS.PT-MaaS.Taxi         | 0.456       | 0.141      | 0.001   |
| MaaS.CS-MaaS.BS           | 1916        | 0.097      | 0.000   |
| MaaS.CS-MaaS.Taxi         | 1132        | 0.145      | 0.000   |
| MaaS.BS-MaaS.Taxi         | 0.984       | 0.131      | 0.000   |

Parameters in utility functions

Utility for SQ (No MaaS)

| ASC_SQ                    | 5.446       | 0.537      | 0.000   |

Individual characteristics

| Age 18–35                 | –0.975      | 0.547      | 0.074   |
| Age 35–55                 | –0.608      | 0.528      | 0.249   |
| Age 55–65                 | 0.730       | 0.748      | 0.329   |
| Older than 65             | 0.854       | 0.499      | 0.083   |
| Female                    | 0.117       | 0.281      | 0.678   |
| Education middle          | 0.585       | 0.549      | 0.287   |
| Education high            | 0.538       | 0.565      | 0.341   |
| education basic           | –1.123      | 0.499      | 0.083   |
| Unemployed                | –0.867      | 0.763      | 0.449   |
| Employed (full/part time) | 0.894       | 0.589      | 0.129   |
| Retired                   | –0.604      | 1.341      | 0.652   |
| Working from home (yes)   | –0.002      | 0.458      | 0.884   |
| Income €0–1250            | 0.067       | 0.374      | 0.479   |
| Income €1250–2500/mo      | –0.265      | 0.492      | 0.153   |
| Income >2500/mo           | –0.703      | 0.901      | 0.736   |
| “I don’t want to say”     | 0.270       |            |         |

Trip related & decision context

| High interest in MaaS (yes) | –0.166 | 0.255 | 0.516 |
| Work-related purpose (yes) | –0.162 | 0.284 | 0.570 |
| Weekday (yes)               | 0.196  | 0.259 | 0.449 |
| Time pressure (Yes)         | 0.030  | 0.287 | 0.917 |
| Travel time                 | –0.047 | 0.005 | 0.000 |
| Travel cost                 | –1.525 | 0.042 | 0.000 |
| Waiting time 0 min          | 0.003  | C, B, O | 0.347 | 0.993 |
| Waiting time 5 min          | 0.181  | 0.316 | 0.567 |
| Waiting time 10 min         | –0.294 | 0.351 | 0.403 |
| Waiting time > 10 min       | 0.109  | 0.088 | 0.662 |
| Parking time 0-5 min        | 0.038  | 0.099 | 0.974 |
| Parking time 5-10 min       | –0.003 | C, B, O | 0.100 | 0.182 |
| Parking time > 15 min       | 0.099  |        |       |
| Parking cost €0             | 0.299  | 0.094 | 0.001 |
| Parking cost €1.10/hour     | 0.037  | 0.004 | 0.694 |
| Parking cost €2.20/hour     | –0.171 | 0.092 | 0.062 |
| Parking cost €3.30/hour     | –0.164 | C, B, O | 0.093 | 0.161 |
| Access time 0-3 min         | –0.130 | 0.099 | 0.195 |
| Access time 3–6 min         | 0.128  | 0.096 | 0.591 |
| Access time 6–9 min         | –0.052 | 0.054 | 0.872 |
| Access time 9-12 min        | 0.054  |        |       |
| Egress time 0-3 min         | –0.052 | 0.090 | 0.565 |
| Egress time 3–6 min         | –0.009 | C, B, O | 0.095 | 0.924 |
| Egress time 6–9 min         | 0.029  | 0.090 | 0.750 |
| Egress time 9-12 min        | 0.032  | 0.149 | 0.000 |
| SQ_DA                      | –1.315 | 0.227 | 0.000 |
| SQ_Passenger               | –1.383 | 0.174 | 0.982 |
| SQ_Walk                    | –0.004 | 0.172 | 0.002 |
| SQ_Bike                    | 0.526  | 2.177 |       |
| SQ_EBike                   | 0.075  |        |       |

Interactions

| Female × Travel time       | –0.001 | 0.003 | 0.872 |
| Female × SQ_Walk           | 0.159  | 0.099 | 0.110 |
| x SQ_Bike                  | 0.279  | 0.093 | 0.003 |
| x SQ_DA                    | 0.169  | 0.075 | 0.024 |
| x SQ_Passenger             | 0.324  | 0.125 | 0.009 |
| Interest × SQ_Walk         | –0.345 | 0.124 | 0.005 |

(continued on next page)
Table A6 (continued)

| Coefficient | Std. Error | p-value |
|-------------|------------|---------|
| x SQ_Bike   | -0.529     | 0.117   | 0.000 |
| x SQ_DA     | -0.640     | 0.087   | 0.000 |
| x SQ_Passenger | -0.382   | 0.162   | 0.018 |
| Work purpose × SQ Walk | -0.642 | 0.133 | 0.000 |
| x SQ_Bike   | 0.001      | 0.102   | 0.989 |
| x SQ_DA     | 0.135      | 0.083   | 0.107 |
| x SQ_Passenger | -0.269   | 0.124   | 0.031 |
| Travel time × SQ Walk | 0.013 | 0.006 | 0.039 |
| x SQ_Bike   | -0.002     | 0.006   | 0.700 |
| x SQ_DA     | 0.045      | 0.005   | 0.000 |
| x SQ_Passenger | 0.031   | 0.007   | 0.000 |
| Travel cost × SQ DA | 1.489     | 0.042   | 0.000 |
| x SQ_Passenger | 1.517   | 0.043   | 0.0000 |

Utility for MaaS-PT

| Coefficient | Std. Error | p-value |
|-------------|------------|---------|
| ASC_MaaSPT  | 3.719      | 0.550   | 0.000 |

Individual characteristics

| Coefficient | Std. Error | p-value |
|-------------|------------|---------|
| Age 18–35   | -0.221     | 0.580   | 0.703 |
| Age 35–55   | -0.344     | 0.555   | 0.535 |
| Age 55–65   | 0.511      | 0.751   | 0.496 |
| Older than 65 | 0.054   | 0.288   | 0.934 |
| Female      | 0.024      | 0.566   | 0.402 |
| Education middle | 0.474 | 0.578   | 0.697 |
| Education high | 0.225   | 1.341   | 0.944 |
| “I don’t want to say” | 0.788 | 0.280   | 0.993 |

Trip related & decision context

| Coefficient | Std. Error | p-value |
|-------------|------------|---------|
| High interest in MaaS (yes) | -0.371 | 0.267   | 0.166 |
| Work-related purpose (yes) | -0.091 | 0.276   | 0.742 |
| Weekday (yes) | 0.269 | 0.258   | 0.297 |
| Time pressure (Yes) | 0.048 | 0.287   | 0.868 |
| Travel time | -0.004 | 0.004   | 0.227 |
| Travel cost | -0.013 | 0.011   | 0.255 |
| Waiting time 0 min | -0.034 | 0.061   | 0.576 |
| Waiting time 5 min | 0.028 | C, B, O 0.059 | 0.631 |
| Waiting time 10 min | 0.001 | 0.059   | 0.983 |
| Waiting time >10 min | 0.004 | 0.032   | 0.000 |
| No transfers | 0.162 | 0.059   | 0.545 |
| Access time 0–3 min | -0.036 | 0.036   | 0.561 |
| Access time 3–6 min | 0.016 | 0.059   | 0.785 |
| Access time 6–9 min | -0.016 | 0.059   | 0.785 |
| Access time 9–12 min | 0.053 | 0.061   | 0.388 |
| Egress time 0–3 min | -0.010 | 0.059   | 0.868 |
| Egress time 3–6 min | -0.085 | 0.061   | 0.166 |
| Egress time 6–9 min | 0.042 | 0.121   | 0.066 |
| Egress time 9–12 min | -0.229 | 0.121   | 0.400 |
| MaaS bundle A | 0.261 | 0.117   | 0.025 |
| MaaS bundle B | 0.064 | 0.117   | 0.025 |
| MaaS bundle C | 0.064 | 0.117   | 0.025 |
| MaaS bundle D | 0.064 | 0.117   | 0.025 |

Interactions

| Coefficient | Std. Error | p-value |
|-------------|------------|---------|
| Female × MaaS A | 0.049 | 0.119   | 0.678 |
| x MaaS B | -0.072 | 0.121   | 0.551 |
| x MaaS C | -0.008 | 0.117   | 0.945 |
| x Travel time | 0.006 | 0.003   | 0.095 |

Utility for MaaS-CS

| Coefficient | Std. Error | p-value |
|-------------|------------|---------|
| ASC_MaaS-CS | 1.621     | 0.652   | 0.013 |

Individual characteristics

| Coefficient | Std. Error | p-value |
|-------------|------------|---------|
| Age 18–35   | -0.021     | 0.664   | 0.975 |
| Age 35–55   | -0.365     | 0.640   | 0.568 |

(continued on next page)
|                      | Coefficient | Std. Error | p-value |
|----------------------|-------------|------------|---------|
| Age 55–65            | 0.617       | 0.803      | 0.443   |
| Older than 65        | –0.231      |            |         |
| Female               | 0.038       | 0.298      | 0.899   |
| Education middle     | 0.901       | 0.584      | 0.123   |
| Education high       | 0.680       | 0.601      | 0.258   |
| education basic      | –1.581      |            |         |
| Unemployed           | –0.514      | 0.592      | 0.385   |
| Student              | 0.303       | 0.843      | 0.720   |
| Employed (full/part time) | 0.535     | 0.646      | 0.408   |
| Retired              | 0.175       | 1.483      | 0.906   |
| Working from home (yes) | –0.499     |            |         |
| Income 0–1250        | 0.225       | 0.520      | 0.666   |
| Income €1250–€2500/mo| –0.008      | 0.407      | 0.985   |
| Income >€2500/mo     | –0.818      | 0.568      | 0.150   |
| “I don’t want to say”| 0.601       |            |         |
| Flexible working hours (yes) | 0.099     | 0.291      | 0.734   |

**Trip related & decision context**

|                      | Coefficient | Std. Error | p-value |
|----------------------|-------------|------------|---------|
| High interest in MaaS (yes) | –0.054     | 0.296      | 0.855   |
| Work-related purpose (yes) | –0.188     | 0.279      | 0.500   |
| Weekday (yes)         | 0.208       | 0.264      | 0.432   |
| Time pressure (Yes)   | 0.183       | 0.289      | 0.528   |
| Travel time           | –0.004      | 0.005      | 0.391   |
| Travel cost           | –0.024      | 0.011      | 0.029   |
| Waiting time 0 min    | 0.053       | 0.084      | 0.528   |
| Waiting time 5 min    | –0.100      | C, B, O    | 0.082   |
| Waiting time 10 min   | 0.152       | 0.083      | 0.068   |
| Waiting time > 10 min | –0.105      |            |         |
| Parking time 0–5 min  | 0.121       | 0.081      | 0.134   |
| Parking time 5–10 min | 0.006       | C, B, O    | 0.079   |
| Parking time 10–15 min| –0.062      | 0.084      | 0.458   |
| Parking time > 15 min | –0.065      |            |         |
| Access time 0–3 min   | –0.037      | 0.082      | 0.651   |
| Access time 3–6 min   | –0.017      | 0.088      | 0.848   |
| Access time 6–9 min   | 0.066       | 0.086      | 0.444   |
| Access time 9–12 min  | –0.012      |            |         |
| Egress time 0–3 min   | 0.010       | 0.082      | 0.899   |
| Egress time 3–6 min   | 0.000       | C, B, O    | 0.083   |
| Egress time 6–9 min   | –0.003      | 0.087      | 0.975   |
| Egress time 9–12 min  | –0.007      |            |         |
| MaaS bundle A         | –0.231      | 0.174      | 0.185   |
| MaaS bundle B         | 0.129       | 0.175      | 0.459   |
| MaaS bundle C         | 0.357       | 0.173      | 0.039   |
| MaaS bundle D         | –0.255      |            |         |

**Interactions**

|                      | Coefficient | Std. Error | p-value |
|----------------------|-------------|------------|---------|
| Female × MaaS A      | 0.263       | 0.168      | 0.117   |
| x MaaS B             | –0.041      | 0.164      | 0.800   |
| x MaaS C             | –0.274      | 0.179      | 0.125   |
| x Travel time        | 0.005       | 0.004      | 0.163   |

**Utility for MaaS-BS**

|                      | Coefficient | Std. Error | p-value |
|----------------------|-------------|------------|---------|
| ASC_MaaSBS            | 2.978       | 0.582      | 0.000   |

**Individual characteristics**

|                      | Coefficient | Std. Error | p-value |
|----------------------|-------------|------------|---------|
| Age 18–35            | –0.193      | 0.623      | 0.757   |
| Age 35–55            | –0.151      | 0.611      | 0.805   |
| Age 55–65            | 1.154       | 0.784      | 0.141   |
| Older than 65        | –0.810      |            |         |
| Female               | 0.076       | 0.293      | 0.795   |
| Education middle     | 0.773       | 0.604      | 0.200   |
| Education high       | 0.696       | 0.628      | 0.268   |
| education basic      | –1.469      |            |         |
| Unemployed           | –0.729      | 0.560      | 0.193   |
| Student              | 0.505       | 0.817      | 0.536   |
| Employed (full/part time) | 0.210     | 0.621      | 0.736   |
| Retired              | 0.298       | 1.370      | 0.828   |
| Working from home (yes) | –0.284     |            |         |
| Income 0–1250        | 0.036       | 0.521      | 0.946   |
| Income €1250–€2500/mo| –0.282      | 0.398      | 0.479   |
| Income >€2500/mo     | –0.668      | 0.551      | 0.225   |
| “I don’t want to say” | 0.915       | 0.675      | 0.977   |
| Flexible working hours (yes) | 0.019     | 0.292      | 0.949   |

(continued on next page)
becoming the leading transport mode in terms of modal share. For this scenario, however, the share of active mode trips decreased substantially. The impacts of MaaS were then assessed for the emissions. The resulting emissions were calculated every half an hour for each PC4 area. In the conservative scenario, the total emissions decreased around 3\%–4\%, while in the balanced scenario the decrease amounts to 14\%–17\%. The most substantial decline in emissions (as expected) is associated with the optimistic scenario in which the total emissions dropped 43\% to 54\% for various pollutants. The statistical test demonstrated that the amount of emissions in the optimistic scenario for all PC4 areas is significantly lower than those in other scenarios while such significant differences do not exist for the conservative and balanced scenario compared to the base scenario. As stated earlier, and important to keep in mind, is that the emission calculation is based on the assumption that car sharing, ride sharing and car rental within MaaS will have zero tailpipe emission, which is in line with the situation in Amsterdam.

The results of this study emphasize the importance of managing expectations about the benefits that MaaS service can bring for a city. Promoting MaaS, a priori, as a panacea for the urban environment should be scrutinized. This study proved that a MaaS service that is highly attractive to citizens can lead to a meaningful decrease in emissions at the postcode level. It is imperative to note that a lower adoption rate could decrease emissions significantly only in some postcode areas. Once the city authorities set up goals (in terms

| Table A6 (continued) | Coefficient | Std. Error | p-value |
|----------------------|-------------|------------|---------|

\textbf{Trip related & decision context}  
High interest in MaaS (yes) \(-0.277\) 0.291 0.436  
Work-related purpose (yes) \(-0.133\) 0.283 0.639  
Weekday (yes) \(0.220\) 0.264 0.405  
Time pressure (Yes) \(-0.027\) 0.287 0.925  
Travel time \(-0.034\) 0.002 0.000  
Travel cost \(-0.300\) 0.129 0.020  
Access time 0–3 min \(0.108\) 0.083 0.195  
Access time 3–6 min \(0.103\) 0.084 0.222  
Access time 6–9 min \(-0.065\) 0.082 0.429  
Access time 9–12 min \(-0.146\) 0.002 0.000  
MaaS bundle A \(-0.423\) 0.250 0.091  
MaaS bundle B \(0.358\) 0.165 0.030  
MaaS bundle C \(0.665\) 0.166 0.000  
MaaS bundle D \(-0.599\)  

\textbf{Interactions}  
Female \(\times\) MaaS A \(0.040\) 0.164 0.806  
MaaS B \(0.286\) 0.156 0.066  
MaaS C \(-0.301\) 0.148 0.043  
Travel time \(-0.005\) 0.002 0.024  

\textbf{Utility for MaaS-Taxi}  
\textbf{Trip related & decision context}  
Travel time \(-0.023\) 0.020 0.248  
Travel cost \(-0.005\) 0.008 0.534  
MaaS bundle A \(-0.147\) 0.411 0.721  
MaaS bundle B \(0.155\) 0.459 0.735  
MaaS bundle C \(0.227\) 0.509 0.656  
MaaS bundle D \(-0.235\)  

log likelihood (estimated) \(-7320.143\)  
log likelihood (base) \(-10391.366\)  
McFadden adjusted rho-squared \(0.434\)  
AIC \(14998.285\)  
AIC/N \(1.856\)  
BIC \(15339.712\) 

| Table A7 | Coefficient | Std. Error | p-Value |
|---------|-------------|------------|---------|

\textbf{Marginal effect travel cost}  
MaaS-PT \(-0.006\) 0.9760 \(\times 10^{-04}\) 0.000  
MaaS-CS \(-0.016\) 0.00021 0.000  
MaaS-BS \(-0.006\) 0.00018 0.000  
MaaS-TAXI \(-0.003\) 0.4923 \(\times 10^{-04}\) 0.000  

\textbf{Marginal effect travel time}  
MaaS-PT \(-0.018\) 0.00015 0.000  
MaaS-CS \(-0.008\) 0.8710 \(\times 10^{-04}\) 0.000  
MaaS-BS \(-0.077\) 0.00067 0.000  
MaaS-TAXI \(-0.007\) 0.8631 \(\times 10^{-04}\) 0.000  

The results of this study emphasize the importance of managing expectations about the benefits that MaaS service can bring for a city. Promoting MaaS, a priori, as a panacea for the urban environment should be scrutinized. This study proved that a MaaS service that is highly attractive to citizens can lead to a meaningful decrease in emissions at the postcode level. It is imperative to note that a lower adoption rate could decrease emissions significantly only in some postcode areas. Once the city authorities set up goals (in terms
of identifying areas where they seek a reduction in congestion/emissions), they can purposefully monitor and evaluate large-scale MaaS pilots against those goals. Although the optimistic scenario in our study appeared to lessen emissions in the city of Amsterdam, a concerning side effect emerged in the form of less active mobility. This conclusion should be flagged and checked once data regarding large-scale MaaS Pilot becomes available in Amsterdam.

Nevertheless, this research comes with some limitations. Since a comprehensive MaaS pilot (wide range of modes and users) is not available in the Netherlands, the adoption rate and mode switching have been built upon stated choice experiment data. While this

![Fig. B1. Cross table transport mode × activity type – Base scenario.](image)

![Fig. B2. Cross table transport mode × activity type – MaaS conservative scenario.](image)
| Transport mode | Car | 22,729 | 51,652 | 38,917 | 8,315 | 8,774 | 20,819 | 40,914 | 15,850 | 114,777 |
|----------------|-----|--------|--------|--------|------|------|--------|--------|-------|--------|
| Car as Passenger | 9,368 | 4,932 | 16,324 | 10,850 | 2,608 | 2,369 | 5,276 | 10,501 | 3,564 | 4,711 |
| MaaS-BS | 2,172 | 713 | 1,027 | 815 | 189 | 270 | 395 | 792 | 503 | 2,951 |
| MaaS-CR | 817 | 414 | 649 | 523 | 105 | 158 | 205 | 464 | 224 | 1,995 |
| MaaS-CS | 3,894 | 2,188 | 3,264 | 2,664 | 521 | 832 | 1,264 | 2,708 | 1,208 | 10,559 |
| MaaS-ODB | 349 | 111 | 357 | 235 | 63 | 53 | 104 | 245 | 135 | 361 |
| MaaS-P | 17,104 | 9,099 | 21,903 | 15,773 | 3,826 | 3,706 | 8,242 | 15,604 | 7,467 | 34,467 |
| MaaS-RS | 603 | 205 | 523 | 390 | 98 | 98 | 191 | 373 | 149 | 976 |
| MaaS-Taxi | 976 | 472 | 865 | 698 | 163 | 186 | 302 | 676 | 294 | 2,070 |
| Public Transport | 4,061 | 3,273 | 6,517 | 5,177 | 1,164 | 1,442 | 2,417 | 5,364 | 2,308 | 15,214 |
| Walking or Biking | 26,996 | 16,192 | 39,848 | 27,392 | 7,231 | 7,051 | 14,527 | 26,996 | 16,176 | 57,999 |

**Fig. B3.** Cross table transport mode × activity type – MaaS balanced scenario.

| Transport mode | Car | 18,474 | 38,173 | 28,525 | 6,184 | 6,344 | 15,234 | 29,882 | 11,354 | 77,364 |
|----------------|-----|--------|--------|--------|------|------|--------|--------|-------|--------|
| Car as Passenger | 8,514 | 4,605 | 14,958 | 10,628 | 2,509 | 2,273 | 5,186 | 10,624 | 3,897 | 4,660 |
| MaaS-BS | 3,837 | 1,575 | 2,662 | 2,115 | 455 | 629 | 1,037 | 2,124 | 1,228 | 7,488 |
| MaaS-CR | 983 | 859 | 1,353 | 1,968 | 227 | 364 | 566 | 1,166 | 552 | 3,484 |
| MaaS-CS | 6,495 | 5,457 | 5,648 | 5,451 | 1,292 | 1,548 | 2,617 | 5,471 | 2,374 | 22,032 |
| MaaS-ODB | 472 | 218 | 695 | 429 | 146 | 154 | 235 | 459 | 222 | 607 |
| MaaS-P | 36,414 | 20,890 | 50,476 | 36,414 | 8,796 | 8,944 | 19,216 | 36,414 | 18,042 | 87,551 |
| MaaS-RS | 1,065 | 389 | 961 | 715 | 175 | 175 | 335 | 750 | 375 | 2,003 |
| MaaS-Taxi | 1,820 | 807 | 1,743 | 1,336 | 363 | 324 | 710 | 1,416 | 680 | 4,201 |
| Public Transport | 4,228 | 3,644 | 4,850 | 5,292 | 1,242 | 1,479 | 2,538 | 5,457 | 2,431 | 15,312 |
| Walking or Biking | 10,949 | 6,451 | 17,210 | 11,382 | 3,113 | 2,877 | 6,082 | 11,094 | 6,370 | 20,760 |

**Fig. B4.** Cross table transport mode × activity type – MaaS optimistic scenario.
data collection method has value in providing sufficient data points in the whole value ranges of variables, there is a historical debate about the degree to which respondents abide by the choice they state they would make in the real world. Although we validated a major part of our findings by the aggregate data available, it is still worthwhile to keep an eye on real large-scale MaaS pilots in the region and update the modeling attempts with the real data. Lastly, it is worthwhile in future work to look at the emissions from the life cycle perspective and examine to what extent the conclusions made in this study still hold.

**CRediT authorship contribution statement**

**Pim Labee:** Conceptualization, Methodology, Investigation, Formal analysis, Software, Writing – original draft, Visualization.

**Soora Rasouli:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Resources, Supervision.

**Feixiong Liao:** Writing – review & editing, Resources, Supervision.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Appendix A**

See Tables A.1–A.7.

**Appendix B**

See Figs. B1–B4.

**References**

Alonso-González, M.J., Hoogendoorn-Lanser, S., van Oort, N., Cats, O., Hoogendoorn, S., 2020. Drivers and barriers in adopting Mobility as a Service (MaaS) – A latent class cluster analysis of attitudes. Transp. Res. Part A: Policy Pract. 132, 378–401. https://doi.org/10.1016/j.jtra.2019.11.022.

Amaze [WWW Document], 2019. URL https://amazemobility.nl/nl/article/nieuwsartikel-2 (accessed 3.15.21).

Arentze, T.A., Timmermans, H.J.P., 2004. A learning-based transportation oriented simulation system. Transp. Res. Part B: Methodol. 38 (7), 613–633. https://doi.org/10.1016/j.trb.2002.10.001.

Arentze, T.A., Timmermans, H.J.P., 2008. ALBATROSS: a learning based transportation oriented simulation system. ERIASS.

Carroll, P., Caulfield, B., Ahern, A., 2019. Measuring the potential emission reductions from a shift towards public transport. Transp. Res. Part D: Transp. Environ. 73, 338–351. https://doi.org/10.1016/j.trd.2019.07.010.

Caiati, V., Rasouli, S., Timmermans, H., 2020. Bundling, pricing schemes and extra features preferences for mobility as a service: Sequential portfolio choice experiment. Transp. Res. Part A: Policy Pract. 131, 123–148. https://doi.org/10.1016/j.jtra.2019.09.029.

DeMaio, P., 2009. Bike-sharing: History, Impacts, Models of Provision, and Future. J. Public Transp. 12 (4), 41–56. https://doi.org/10.5038/2375-090110.5038/2375-090112.410.5038/2375-090112.4.3.

Docherty, I., Marsden, G., Anable, J., 2018. The governance of smart mobility. Transp. Res. Part A: Policy Pract. 115, 114–125. https://doi.org/10.1016/j.jtra.2017.09.012.

Doherty, M.J., Sparrow, P.T., Sinha, K.C., 1987. Public Use of Autos: Mobility Enterprise Project. J. Transp. Eng. 113 (1), 84–94. https://doi.org/10.1061/(ASCE)0733-947X(1987)113:1(84).

Durand, A., Harms, L., Hoogendoorn-Lanser, S., Zijlstra, T., 2018. KiM Netherlands Institute for Transport Policy Analysis Mobility-as-a-Service and changes in travel preferences and travel behaviour: a literature review.

Eckhardt, J., Caulfield, B., 2009. Estimating the environmental benefits of ride-sharing: A case study of Dublin. Transp. Res. Part D: Transp. Environ. 14 (7), 527–531. https://doi.org/10.1016/j.jtrd.2009.07.008.

European Commission, Directorate-General for Mobility and Transport, European Union, Eurostat, 2017. EU transport in figures. Publication Office of the European Union, Luxembourg.

Fereti, C., Debicki, J., Timmermans, H.J.P., 2020. Modeling the effect of Mobility-as-a-Service on mode choice decisions. Transp. Lett. 1–8. https://doi.org/10.1007/s13242-020-00307-z.

Fiume, E., De Groot, M., Geurs, K., 2019. On the likelihood of using Mobility-as-a-Service: a case study on innovative mobility services among residents in the Netherlands. Case Stud. Transp. Policy 7 (4), 790–801. https://doi.org/10.1016/j.cstp.2019.08.002.

Furtado, F., Luís, M., Petrik, O., 2018. Shared Mobility Simulations for Dublin, OECD Case-Specific Policy Analysis. Int. Transp. Forum. https://doi.org/10.1787/5423af87-en.

Furtado, F., Luís, M., Petrik, O., 2017a. Shared Mobility Simulations for Auckland. Int. Transp. Forum. https://doi.org/10.1787/5423af87-en.

Furtado, F., Luís, M., Petrik, O., 2017b. Shared Mobility Simulations for Helsinki, OECD Case-Specific Policy Analysis. Int. Transp. Forum. https://doi.org/10.1787/5423af87-en.

Gould, E., Wehrmeyer, W., Leach, M., 2015. Transition pathways of e-mobility services. Sustainable City X 1, 349–359. https://doi.org/10.2495/sc150311.
World Health Organization, 2015. WHO | Database on source apportionment studies for particulate matter in the air (PM10 and PM2.5) [WWW Document]. WHO. URL http://www.who.int/quantifying_ehimpacts/global/source_apport/en/ (accessed 2.2.21).

Zhang, H., Song, X., Xia, T., Zheng, J., Haung, D., Shibessiki, R., Yun, Y., Liang, Y., 2018. MaaS in Bike-Sharing: Smart Phone GPS Data Based Layout Optimization and Emission Reduction Potential Analysis. Energy Procedia, Clean. Energy Clean. Cities 152, 649–654. https://doi.org/10.1016/j.egypro.2018.09.225.

Zheng, S., Kahn, M.E., 2013. Understanding China’s Urban Pollution Dynamics. J. Econ. Literat. 51 (3), 731–772. https://doi.org/10.1257/jol.51.3.731.

Zijlstra, T., Durand, A., Hoogendoorn-Lanser, S., Harms, L., 2020. Early adopters of Mobility-as-a-Service in the Netherlands. Transp. Policy 97, 197–209. https://doi.org/10.1016/j.tranpol.2020.07.019.

Zijlstra, T., Durand, A., Hoogendoorn-Lanser, S., Harms, L., 2019. Promising Groups for Mobility-as-a-Service in the Netherlands 56. 10.13140/RG.2.2.28796.69766.