Managing urban traffic emissions with focus on people and atmospheric impacts

Mira Hulkkonen and Nønne L. Prisle

Abstract With a growing majority of the world's population residing in cities, it is vital to advance a shift to low-emission urban mobility in order to mitigate climate change. Despite the fundamental role played by infrastructure, daily decisions and routines of individuals ultimately generate traffic. When people choose a conventionally fuelled private car, it causes externalities detrimental for both individuals and the urban system as a whole: congestion, noise, greenhouse gas emissions, air pollution. Empirical studies show that the awareness of and exposure to those do not provide enough motivation for people to shift to more sustainable travel modes. Convenience overpowers environmental values. To break the habits and manage emissions, authorities must deploy incentives or sanctions – structural, regulative, economic, persuasive – that can increase the comparative advantage of low-carbon traffic modes. The potential of different initiatives to reduce traffic emissions is invaluable information for decision makers. Our contribution investigates the variety of possible ways to advance the desired shift, and highlights the importance, challenges and key factors of high quality impact evaluations. A functional approach to test and evaluate traffic initiatives is multidisciplinary, with ways to quantify people's behavior and preferences, traffic emerging from them, and the resulting atmospheric emissions. By shedding light on reliable approaches to reveal the real impacts of traffic initiatives, the efforts for climate change management may be reinforced.

Keywords: Climate change, Air pollution, Traffic, Emissions, Behavior change, Modal shift, Initiatives, Incentives, Sanctions, Impact evaluation

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1 Introduction

People in an urban environment leave their footprints, figuratively, in the air. The city with its infrastructure, policies, rules and climate form a setting for individuals to perform their daily activities and transitions between them. Multiple decisions are made by each individual in the course of a day, and it is those decisions that eventually determine how big their atmospheric footprints are. These footprints consist of climate emissions, like CO_2 and other combustion related greenhouse gasses, and also particulate matter.

A power plant stands still on a point, generating heat or electricity and emitting fuel-dependent amounts of carbon dioxide in the air. Traffic as an emission source, however, is very different by nature. It is mobile, highly dynamic, and responsive to mundane decisions of individual human beings. On a sunny Tuesday morning, one car owner decides to hop on a bicycle on a whim and take the scenic cycleway to work instead of habitually driving through congested highway, and the overall emissions of that morning commute are already different – by a tiny fraction, but still.

Urban traffic is usually more than the sum of its parts, because the interactions between individuals produce combined effects. There are thousands of individual people scheduling their everyday activities and deciding between available traffic modes based on their preferences. Time, cost, convenience, comfort of routine – it is the perspective of each individual that governs the mode selection, but being part of a complex system implies that the outcome of a reasoned choice may not be optimal after all. The traffic mode choices of people may be called irrational, if their combined effects lead to a situation that is not optimal for either the individual or the urban environment as a whole. Such a non-optimal situation may include congestion, extended travel times, noise, greenhouse gas emissions and other air pollution, exposure to which has consequences to public health and mortality. They can be referred to as traffic externalities, and most of them emerge from the popularity of choosing conventionally fuelled private car.

Traffic produces greenhouse gas (GHG) emissions that are the key driver of current climate change. The transport sector, including passenger and freight transport, accounts for 14% of global carbon dioxide emissions (IPCC, 2014), and 40% of the CO_2 emissions from road transport are from urban mobility. Looking at the carbon footprint of an individual person, mobility is often the sector that contributes the most. In addition, traffic is a significant source of other gaseous pollutants and fine particles that affect atmospheric processes, climate (through direct and indirect impacts) and human health. Within a city, the traffic-originated fraction of measured fine particle concentrations may range from less than 10% to close to 100% (Karagulian et al, 2015). In addition, wearing down of tyres leaves behind microplastics that may be harmful to us and our environment in unforeseen ways (Kole et al, 2017).

The majority, 55%, of the world's population resides in urban areas, and rapid urbanization is projected for many countries by 2050 (United Nations, Department of Economic and Social Affairs, Population Division, 2018). The OECD International

Transport Forum (2017) has predicted that the global passenger demand would more than double between 2015 and 2050. From the perspective of the atmosphere's composition, climate and human health, it is critical how that growing demand is addressed: what traffic modes are available to people, and what kind of habits people develop. Managing the footprints in urban air comes down to advancing a shift from conventionally fuelled vehicles and private cars to more sustainable (low-emission) modes of traffic: different forms of public transport, active mobility (cycling and walking), and vehicles powered by electricity, hydrogen or biogas (with a low-carbon "well-to-wheels chain", i.e. life cycle from vehicle component and energy production to the emissions from usage).

People's frequently repeated travel mode choices are highly habitual, and when the surrounding environment and circumstances remain the same, decision-making is on "auto pilot" (e.g. Gärling and Axhausen (2003)). Being exposed to congestion, noise and air pollution, and the awareness about climate emissions produced by traffic do not seem to provide enough motivation for people to change their habits towards moving more sustainably. The behavior change that is necessary for reducing traffic emissions requires 'nudging' and interventions. Leaning on behavioral psychology, two avenues are possible: making the sustainable traffic modes more desirable, beneficial, easy and barrier free, and/or making the unsustainable modes less attractive, more difficult or costly.

From developing public transport systems to providing city bikes, from congestion charges to subsidies for electric car purchase, from driving bans to games rewarding cycling and walking – a variety of measures have the potential to induce change in people's traffic habits and could be considered for advancing the shift towards a carbon neutral urban environment. The attempt to rank their effectiveness leads us to think of the key questions that determine the scale of impacts:

- What is the direction of the shift: from which mode(s) to which?
- How many people adopt new behavior, how quickly and for how long?
- Could the shift lead to indirect emissions or leakage to another sector?

Transfer of good practices and diffusion of successful policies have been identified to happen in the field of sustainable transport (Matsumoto et al, 2007). An often highlighted example of lesson-drawing is related to the development of bus rapid transit systems: the development in e.g. Jakarta, Seoul and Beijing clearly refer to the pioneering development in Curitiba, Brazil, where transit-oriented urban planning was successfully deployed. Another example is the transfer of *Bella Mossa*, the modern incentive-driven program encouraging more active mobility in Italian cities with the help of gamification. Demonstrated ability to reduce emissions and to bring about other synergies is pivotal for the diffusion of these measures.

It is easier to estimate the emission reduction potential in some sectors than others. If an old power plant is to be replaced by geothermal heat pumps, the expected change in emissions is straightforward to calculate. If an extensive cycleway network is considered to be built to promote active mobility and to advance a shift from driving to cycling, the attempt to estimate the achievable emission reductions quickly faces the question of how to predict individual-level decisions that are constrained by the schedules and challenges of everyday life, and the power of habit. Answering the three key questions required for quantifying the atmospheric impact of a measure targeting traffic, and especially the second question about people's response, is far from straightforward. Think about the person who decided to bike to work on a sunny Tuesday, despite being a frequent car user. Was it all about the nice weather, or did the improved bike lane affect the decision? What would it take to make the same decision again, and how many weeks of cycling would be required for it to become the new routine?

In this chapter we discuss about ways to manage traffic emissions, ”the footprints in urban air”, by advancing a shift away from conventionally fuelled vehicles and towards low-emission mobility. We highlight the importance and challenges of quantifying the achievable impacts, and accentuate approaches that manage to capture the essential and even address the often overlooked part, irrational human behavior. For climate change mitigation, only tangible emission reductions matter. We conclude that tools enabling a realistic assessment of effectiveness may prove to be the key for knowing where the focus should be directed.

2 Understanding people and traffic

In order to know how to target traffic emissions, we need to understand the factors governing people's traffic mode choices. By building on theoretical knowledge and empirical studies, we can identify the key variables affecting behavior change that results in changes in the shares of different traffic modes, i.e. in modal shifts.

A meta-analysis of the psychological and behavioral determinants of travel mode choices (Lanzini and Khan, 2017) concludes that habits and past use are the most accurate predictors of future choices. Breaking the habits and providing new alternatives is thus the most relevant avenue for achieving changes in behavior and mode choices.

The physical infrastructure, and how people have grown to use it, is an important influence on people's choice of traffic modes. For example, cycling and walking culture cannot prosper, if the whole environment is designed on the terms of private vehicles. Mateo-Babiano (2016) talks about pedestrian hierarchy of needs that includes factors such as safety, ease, barrier-free movement and equitable access, and how the poor pedestrian facilities in Manila force people to choose other modes than walking. This is an example of how the conditions can ”dis-incentivize” choosing sustainable traffic modes. The observations of de Souza et al (2014) are from Brazil, and they point to the same direction: the lack of adequate cycling infrastructure, slopes and the lack of safety are the main deterrents against cycling. Interestingly, the individuals with a positive attitude towards cycling perceive weaker barriers, whereas a very negative attitude is associated with the perception of stronger barriers. Also a report about cycling in Australia (Butterworth and Pojani, 2018) highlights the importance of different barriers when it comes to the low prevalence of soft mobility. According to the study, these barriers include - among others - cognitive aversion to cycling, resource limitations, inertia and competing interests.

As important as prior conditions, such as existing infrastructure, history, culture, topography and climate, are perceived to be, they do not necessarily determine how successful a modal shift is. Infrastructure changes may be necessary, but they are not sufficient as such for achieving modal shifts (Song et al, 2017). Regarding the adoption of cycling, Pucher et al (2010) state that new policies are at least as important. Different policies and measures are required to enhance opportunities, to improve people's perception and to increase people's motivation to consider more sustainable traffic modes.

In order to grasp the variety of determinants that affect traffic mode choice, we can take a closer look at factors that have been identified to be important for how easily bike-sharing is adopted as a preferred travel mode. According to Shaheen et al (2011), the key factors include psychographics, perception of bike sharing and travel behavior before the scheme. For the use of bike sharing in Montreal, Bachand-Marleau et al (2012) state convenience and the possibility to avoid private bike theft and bike maintenance to be the key facilitators. Li and Kamargianni (2018) add to these with the results from a mode choice study for Tiyuan, China, exploring the impact of air pollution on mode choice behavior: there was a significant negative impact of ambient air pollution on bike-sharing choice. (They then investigated if improving air quality would advance bike-sharing ridership, but found that overall improvements in the actual bike-sharing service would be more effective.)

Related to personal attributes, gender has been identified to have an effect on traffic mode choices, especially on how cycling is perceived and on the intention to reduce car use (Steinbach et al (2011), Matthies et al (2002)). Based on a survey among inhabitants of a German city, Matthies et al (2002) conclude that women's stronger ecological norms are reflected in the *intention* to reduce car use travel, while actual travel behavior is more strongly influenced by habits. Also Steinbach et al (2011) discuss gendered differences in traffic mode choices, but they add social class and ethnic identity as factors that significantly affect one's propensity to choose active mobility. According to them, cyclists can act as an example to other people, but the role model is only effective for the same type of people. Reversely, if one observes that there are no people from the same social group cycling, it reduces the opportunity to see cycling as a candidate mode of transport. Several other studies suggest that social forces may indeed be a significant factor in travel decisions (e.g. Riggs (2017)). When it comes to, for example, using public transport, the expectation of what "important others" do (referring to *social norms*) is an important factor stimulating both the intention to choose public transport and actual usage (Zhang et al, 2016). In addition, the awareness of a social problem such as greenhouse gas emissions and poor air quality, may activate personal norms and an internal sense of responsibility to choose more sustainable traffic modes.

The overall emotional experience of using a certain traffic mode has a profound impact on mode choice. For that, having the sense of acting according to one's social and subjective norms is important, but so is e.g weather, the subjective sensitivity to it and its impacts on mood (Böcker et al, 2016). Also people's perception of how e.g. public transport functions, how reliable it is and what kind of service they get, belongs to the list of attributes that affect the emotional experience.

Mode choices for commuting to work form a special case. In addition to the physical environment and psychological factors that govern mode choices in ”normal” conditions, social settings and obligations play a role when it comes to commuting. The spatio-temporal flexibility in work arrangements is especially important for an individual’s mode choice for commuting. Guell et al (2012) describes commuting as a complex social phenomenon and practice. Aittasalo et al (2019) present a study regarding a real-life setting that included infrastructure improvements and workplace-specific social and behavioral strategies, awareness raising and encouragement, and conclude that only the *motivation* to active commuting was facilitated, but the measures resulted in no impact on actual behavior during a 6-month follow up period. Meanwhile, the general use of the improved walking and cycling paths did increase. Referring to Spotswood et al (2015) and Heinen et al (2010), perceptions on commuting to work are different from those on recreational mobility, which indicates that behavior change may be even harder to achieve, even with a combination of actions.

How people value different aspects (e.g. time, cost, convenience, comfort, distance, sense of autonomy) related to mobility determines their mode choices. People aim to maximize their utility, which is more sensitive to some things than other (Mei et al, 2017). For example, some people are not willing to take up suggestions for alternative routes, which makes them very sensitive to factor ’route’, whereas others want to stick with their preferred mode no matter what, making their utility sensitive to ’mode’. In a hypothetical simulation, Leblanc and Walker (2013) demonstrate that the valuation is flexible: it depends on the offered incentive how people value their travel time. If the incentive is tempting enough, most people are ready to compromise their travel time, despite it having been important to their overall utility before the incentives were offered.

An overview of the discussed factors that influence the traffic mode choices of an individual is presented in Figure 1. Psychological, social and environmental factors are mapped, with ’environmental’ referring to both the natural and built environment.

The Theory of Planned Behavior can be applied as a conceptual framework for the analysis of factors that influence people’s traffic mode choices, and also for understanding the possibilities to affect them. With that framework, Hunecke et al (2010) demonstrate that it is important and useful to account for combinations of people’s attitudes, norms, and values, when explaining their traffic mode choices. They conclude that the attitude-based approach is better than segmenting people based on sociodemographic and geographic factors. Bamberg et al (2003) use the same theoretical framework, but focus more on investigating habits and the impacts of an intervention (providing a prepaid bus ticket). They conclude that people’s decisions about traffic mode choices can indeed be affected by interventions that produce changes in attitudes, subjective norms, and perceptions of behavioral control. According to their results, past travel choice contributes to the prediction of later behavior only if circumstances remain relatively stable.

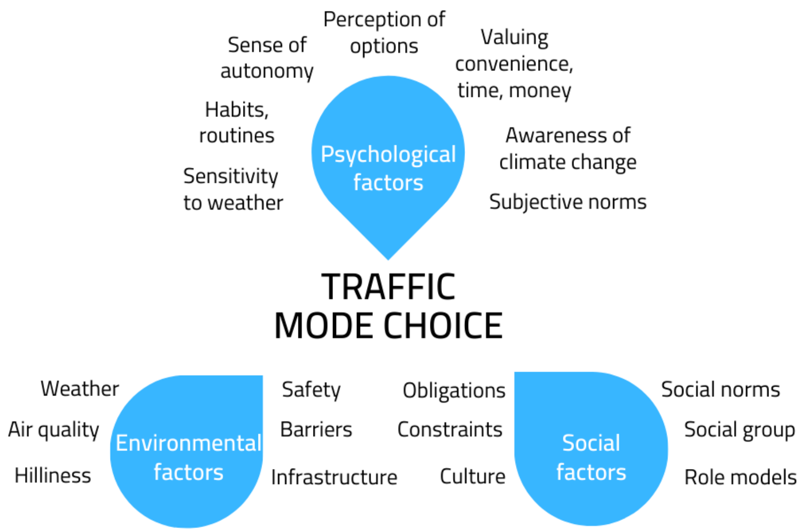

Fig. 1 A map of factors that may influence the traffic mode choice of an individual.

3 The variety and effectiveness of approaches to advance low-emission mobility

To break the habits that lead to unsustainable urban mobility, authorities must deploy actions that increase the comparative advantage of low-emission traffic modes. Measures may be designed to remove barriers and to incentivize the use of sustainable traffic modes, or to restrict the use of the unsustainable ones. For effectiveness, it is important to take into account the actual factors (Figure 1) that govern people's choices, and address them.

A tool for characterising and designing behavior change interventions, a ”behavior change wheel”, is presented by Michie et al (2011). At the centre of their proposed framework is a 'behavior system' involving three essential conditions: capability, opportunity, and motivation. They are surrounded by different interventions that aim to address deficits in one or more of the conditions, and around them, there are different policy categories that could enable those interventions to occur. This conceptual framework can be used for identifying possible approaches and for analysing behavior change interventions – also in the context of traffic.

A variety of initiatives to address people's capability, opportunity, and motivation to choose low-emission mobility have been deployed around the world. Reviews of the variety have been conducted, with different perspectives, by e.g. Hulkkonen et al

(2020) focusing on the atmospheric impacts of initiatives that advance modal shifts, Graham-Rowe et al (2011) focusing on ways to reduce car use, and Pucher et al (2010) focusing on ways to increase cycling.

Traffic initiatives can be categorised to structural, regulative, economic and persuasive actions. Structural measures typically refer to city planning, to the provision of a better public transport system and to improving the conditions and infrastructure that enable active mobility, cycling and walking. Urban development is sometimes viewed as either ”car-friendly” or ”people-friendly”, and land use planning is in the core of this progression. Also improving the refuelling infrastructure for low-emission fuels such as hydrogen is a structural measure. Policy instruments are usually about regulatory or economic measures: fees (e.g. congestion charges), tolls, subsidies (for e.g. electric vehicles or for the conversion of a conventionally fuelled car to operate on bio-gas), restrictions, low-emission zones, driving bans. Persuasive instruments form the fourth category and their purpose is to increase people's motivation and to reward desired choices: they can be awareness and concern raising campaigns, events (e.g. car-free days), competitions (e.g. collecting biking kilometres and competing in teams), decision support tools (e.g. applications to assist traffic mode choice) and gamified approaches (e.g. rewarding biking with points that can be redeemed as discounts).

The history of and economic development in different countries affect the types of measures that are deployed for addressing traffic emissions. In western countries with established infrastructure, the focus is often on either restricting car use or incentivizing biking and the use of public transport with soft, persuasive measures. In Asia, especially in big cities with severe air pollution problems, restrictions based on e.g. license plate numbers (the so-called *odd/even* scheme) and vehicle labelling are common. In many South-American countries, the development of a functional public transport system is often the central measure for advancing more sustainable traffic. Measures to increase biking form a cross-cutting theme for cities around the world, but, for example in some Italian cities it is advanced via gamification and rewards provided by local companies, while in Brazilian cities the key for getting more people to bike is to improve safety (Tucker and Manaugh, 2018). Different forms of bike sharing schemes have spread to over 800 cities (Fishman, 2016).

Implementing ”carrot or stick” for urban mobility is a complicated and partly unpredictable process. This is mostly due to the multitude and variability of factors governing urban development, policies, initiatives and people's reactions to them. For example, urban development policies may respond to city extension, urban sprawl, sub-urbanization or fluctuating fuel and energy cost; initiatives may target congestion, public health, air quality issues or climate change; and people's reactions may stem from car ownership, car dependency, convenience or peer influence.

Considering cultural, climatic and development stage related differences, it is evident that there is no one-size-fits-all approach to a successful shift towards more sustainable transport. We can, however, learn from initiatives that were successful in reducing emissions by facilitating a desired shift in traffic modal shares. In addition to identifying success factors, it is also worthwhile to notice the pitfalls and to learn from cases, where a good effort to advance a shift towards low-emission mobility failed to produce emission reductions.

Let us look at some examples of initiatives from different categories and discuss their success and failure factors when it comes to achieving emission reductions as a result of modal shifts. For more examples and references, the reader is guided to the scoping review by Hulkkonen et al (2020).

3.1 Structural measures: Examples and lessons

Looking at national or city level action plans, modifying the infrastructure is often considered in them as the most central measure for promoting public transport and active mobility. The goal is to improve people's opportunity and capability to move around flexibly by public transport and bike. The preconditions for structural measures to be successful include that people perceive the new infrastructure as a genuine alternative to the private car, that their travel times remain reasonable and that the shift to a new mode is 'cognitively effortless' for them. The mere existence of new infrastructure may not be enough to entice people to use it, but efforts on increasing people's motivation may be required. For example a walking and cycling infrastructure programme *Connect2* deployed in many towns in the U.K. has been evaluated to not have produced any statistically significant changes in CO_2 emissions (Brand et al, 2014), likely because there was no comprehensive approach for promoting active mobility so that the people who usually drive would have been motivated to shift to using the new cycling infrastructure.

So called social marketing in combination with structural improvements has been identified as a potential and increasingly popular means to address both the motivation deficit and the conversion of motivation to behavior (Thøgersen, 2014). Referring to Section 2 about the factors that affect an individual's mode choice, social marketing relies on understanding people's preferences, needs and perceived barriers. The understanding can be achieved with data collection similar to market research. With different marketing techniques, public transport and cycling can then be promoted to appear desirable and gratifying, whereas the use of car can be de-marketed and made appear less attractive. The aspect of motivation deficit also makes it rather difficult to realistically predict people's response, modal shifts and the emission reductions that can be achieved with a structural measure such as new infrastructure. Cases related to the development of Bus Rapid Transit systems in different cities demonstrate this: In Jakarta, the expected emission reductions were not achieved because people's negative attitudes towards the new bus service were not addressed, whereas in Bogotá they managed to brand the bus service so that it won over the local people, has produced tangible emission reductions and was even approved by the United Nations to sell carbon credits under the Kyoto Protocol mechanisms.

Nieuwenhuijsen et al (2019) evaluate the barriers and facilitators for realizing fully car free cities. How to change existing infrastructure that was designed for cars to infrastructure for active and public transport is a challenge, but achievable, especially for compact cities. They describe 9 prerequisites to facilitate the transition to a car free city, and conclude that equally important to changing the infrastructure is to address people's perceptions and attitudes.

Flexibility and convenience are important factors for many people. As a large scale structural measure, urban planning directing the relative location of public transport network, homes, jobs and services is the key to enabling flexible yet sustainable mobility in cities. Infrastructure includes also parking facilities, which have been shown to significantly influence people's propensity to choose the private car. For example, Weinberger (2012) has studied commuting to Manhattan, and found that private residential parking, especially the minimum parking requirements, encourage and increase car use. Logically, cases with a reverse setup indicate that eliminating parking spots or removing the right to park reduces car use.

The importance of effortlessness applies also to shared mobility: according to reported experiences of ride-sharing services, enough flexibility for e.g. driving range, capacity and docking is essential for people to commit to using it. Shared mobility has been shown to decrease emissions from urban mobility, but it is important to be aware that it can also do the opposite: if most users of a ride-sharing service are people who did not use a car before, the result is a net increase in vehicle kilometres travelled, and an increase of emissions. Mobility-as-a-Service (MaaS) is another potential avenue for advancing a shift away from personally owned vehicles and towards flexible mobility based on people's needs. Both public and private transportation providers can contribute to the service, and the user can choose a suitable combination of transportation modes and pay with one account. MaaS initiatives have been deployed in many European cities, but their popularity and effectiveness for reducing traffic emissions are not yet evident.

3.2 Regulative measures: Examples and lessons

Driving bans, low emission zones and other restrictions have been widely deployed to address acute air quality issues, but not so often for mitigating climate emissions, although the potential for decreasing CO_2 and particle emissions often go hand in hand. The goal of restrictive measures is to reduce car traffic and related air pollution in a specified area. When it comes to evaluating the effectiveness of restrictions for air quality improvement, two potential pitfalls arise. Firstly, it is not a straightforward task to analyse how large a fraction of the potentially observed change in ambient concentrations of air pollution is attributable to the deployed restriction. Secondly, restrictions may lead to ripple effects or leakage of traffic from e.g. city centre to the outskirts of a city, which means that air pollution is simply displaced, not reduced. For climate change management, it is relevant to understand the potential reductions in CO_2 emissions: for regulations and restrictions targeting air quality, CO_2 is often not reported at all.

The case of managing traffic volumes and related emissions during the Beijing Olympic Games is an example of a regulative policy mix that managed to reduce emissions and ambient air pollution concentrations, albeit not permanently. 4 million people were reported to have switched from private car to public transport during the restriction period, while 47.8% of the regulated car owners did not follow the rules at all (Wang et al, 2014). Other famous cases of restrictive policies include *Hoy No Circula* in Mexico City and the *odd/even* scheme in Delhi, and the effectiveness of both has been questioned. Based on reported experiences from these policies, car drivers may be associated with a tendency to seek ways to circumvent driving restrictions.

An identified success factor for restrictive policies is to couple them with the provision of incentives or rewards. For example, a voluntary weekly no-driving-day in Seoul has achieved a relatively high participation rate, because they have combined it with rewards that increase people's motivation to participate.

3.3 Economic measures: Examples and lessons

Road pricing and congestion charges have been deployed in many cities in order to control traffic volumes, congestion and air pollution levels. It is a rather controllable measure in the sense that access to the specified area (such as city centre) is typically monitored by cameras, data is automatically collected and there is no possibility to circumvent paying the fee if you want to access with a car. Exemptions or reduced charges may be granted for low-emission vehicles. Croci (2016) has analysed the cases of Stockholm, Milan and London. The review brings up that despite the polls that showed citizens not being in favour of the policy when the charge was announced, the majority of them turned to be in favour of it after implementation in all cities. This type of a policy leaves the choice to the people. The availability of transit options that genuinely substitute for private travel are also important for the success of road pricing and congestion charge schemes. In Stockholm, Milan and London, a substantial part of congestion charge revenues have been invested for "sustainable mobility" such as developing public transport. All those cities demonstrate very coherent CO_2 emission reductions (14-16%) achieved with the congestion charge scheme.

In Norway, for example, the market penetration of electric vehicles has been successfully advanced with economic incentives. Purchase subsidies and fee exemptions are traditional economic measures to increase the comparative advantage of certain choices. An interesting policy type falling under this category is fare-free public transport. It has been considered as a potential avenue to persuade people away from using the private car. However, an analysis based on real-life examples from e.g. Rome and Tallinn shows that fare-free public transport actually mostly entices people who would otherwise walk, not those who would drive (Fearnley, 2013). The shift is thus from walking or cycling to public transport, while vehicle traffic volumes and emissions are left with marginal changes. In this case, if the impact evaluation of the policy focused solely on how much the public transport patronage has increased, the achieved emission reductions would be overestimated.

There is a wealth of studies on the elasticity of people to different economic measures, fees, tolls, subsidies, price increase and decrease. As discussed in Section 2, however, cost is just one factor affecting people's traffic mode choices. Convenience, time, sensitivity to weather and the love of old habits may dominate over cost.

3.4 Persuasive measures: Examples and lessons

Individualised incentives represent the most recent frontier in the efforts for managing traffic emissions. This is related to technological development, especially digitalization and the possibilities offered by wide-spread smart phone usage. Applications can both collect data and provide information, goal setting, feedback and prompts for the user. Mobile sensors can track journeys, and sustainable travel can produce points or credits that can be redeemed as tangible rewards. Gamification approaches, use of rewards and social force are supported by behavioral psychology. For example the *Bella Mossa* project in Bologna, Italy, has managed to engage thousands of people, and mitigate over 700 tons of CO_2 emissions during the 6-month programme period.

The uncertainty related to the longevity of an incentivized shift in traffic mode choices is a common issue that tends to hamper both the actual impacts and the ability to predict possible emission reductions. Many reward schemes, programmes and competitions have proven to be effective temporarily, but failed at producing a sustained long-term change in people's habitual traffic mode choices. People's driving habits and mode choices may change significantly, for example during the period of reward provision for congestion avoidance (such as *Spitsmijden* in the Netherlands) or a competition for biking kilometres (such as *Kilometrikisa* in Finland), but they tend to revert to their previous behavior astonishingly quickly after the conditions have ”normalized”. This has been demonstrated by multiple cases that, at first glance, seemed very promising. A more than 50% drop in traffic-related carbon dioxide emissions of the participants of a commuter challenge is very impressive, but if it is temporary (or if the evaluation does not extend to post-program situation), the result can be grossly misleading. Neither practice nor literature in this domain seem to have the answer to the question of how long an incentive program or a restrictive measure would have to be sustained so that the new desired behavior would actually stick and the impacts would be permanent after the measure has ended.

Real atmospheric impacts mean a permanent drop in CO_2 emissions, which requires a behavior change that sticks after e.g. the use of an application with novelty has ended. The new behavior has to become a routine. The ability to perceive synergies, such as positive health and monetary impacts of the new behavior, is invaluable. Persuasive measures such as incentives serve the purpose of capturing interest in a new activity, e.g. commuting by bike, but the activity itself must turn out to be genuinely rewarding for people in order for the behavior to continue after incentive provision ends.

3.5 Traffic initiatives and their overall effectiveness for emission reductions

Bike sharing schemes and city bikes have become a popular measure deployed in numerous cities. The utilization rate of shared bikes can be measured in different ways, which provides data for the impact evaluation. However, information about what the usage of a city bike substitutes is usually missing. The assumption that all increased biking replaces driving is often coarsely misleading, and, like in the case of fare-free public transport, will lead to overestimated emission reductions. Furthermore, the emission impact of the scheme is not limited to how much the bikes are used and in lieu of which mode. There are also indirect impacts, which may change the overall picture to either direction. An example of a positive indirect impact is that bike sharing has been reported to increase the use of public transport by providing a solution to the ”first/last-mile” dilemma, i.e. the (unwalkable) gap between origin and transportation network and/or from public transit stop to destination. Negative indirect impacts are related to increasing emissions: the emissions that are ”saved” through an actively used bike sharing system may be partly cancelled out by emissions from the vehicles that are used for redistributing the bicycles back to docking stations (Winslow et al, 2019). There is even evidence from e.g. London that the required motor vehicle support actually overcompensates the achieved car travel reduction, which leads to a situation where the net effect of the bike sharing scheme is actually an increase in vehicle kilometres travelled (Fishman et al, 2014).

Similarly, when a technological shift such as from conventionally fuelled vehicles to electric cars, is evaluated, an analysis of emissions covering the full life cycle is necessary for revealing the total impacts. If just vehicle use is considered, it is straightforward to calculate that the relative decrease in carbon dioxide emissions is almost one-to-one with the increased fraction of electric vehicles. However, the overall picture does not take shape before the emissions of both battery and energy production are accounted for. For example, an analysis of the emission impacts of traffic electrification in China produces vastly different results for different regions, when the regionally varying energy mix is considered (Wu et al, 2012).

The above described cases highlight some core issues related to evaluating the overall effectiveness of transport modal shifts. The evaluation of changes in emissions requires data about mode-specific emissions, about the modal shift (its direction and scale), and about possible indirect impacts. Whether measured, estimated or simulated, those pieces of information are critical – if approached wrong, the results of the impact evaluation will be misleading and potentially hampering the mitigation of climate change and air pollution. Unreliable assessments of the emission reduction potential of different traffic management actions may lead to directing investments to initiatives that are not that effective after all.

Data may be deliberately collected as a part of the scheme, which forms a rather solid starting point for a high quality evaluation. For example, gamification-based applications designed to reward sustainable mobility may include journey tracking with sensors (Poslad et al, 2015), congestion price schemes include monitoring the traffic volumes, and the deployment of a travel plan at an organization often involves collecting data about people's traffic mode choices with a survey. Schemes set up for research purposes, such as testing the efficacy of freeway closure or fare-free public transport for changing the perceptions of habitual drivers (Fujii et al (2001), Thøgersen and Møller (2008)), naturally produce useful data. In contrast, the starting point for evaluating the impacts of infrastructure improvements is weaker in the sense that there is typically no unambiguous data at hand. When people's motivation and choices (affected by multiple motives) are the key factor for the success of an initiative, predicting and analysing the outcomes becomes clearly more difficult.

Reliable evaluations of deployed actions for managing traffic emissions are critical for the diffusion of effective practices. Coarse assumptions and the absence of data may lead to misleadingly large numbers for achievable emission reductions. As concluded in the review by Hulkkonen et al, a proper evaluation of the impacts and overall emission reductions of different types of initiatives should reliably cover the following key points:

1. Direction of the modal shift: from which traffic mode(s) to which
2. How many people adopt the shift and for how long
3. The possible indirect impacts: e.g. increase of emissions or traffic volumes elsewhere
4. Excluding other factors that possibly have contributed to the shift and/or to the observed emission reduction.

3.6 An optimal mix

Above, we have mostly discussed about individual initiatives from different categories. But as highlighted by e.g. Matsumoto et al (2007) and demonstrated by some of the case examples that were elaborated in the previous sections, initiatives that rely on combinations of success factors are more likely to be adopted. Optimal policy mixes may be more effective than using good but single policy instruments. Simultaneous use of structural, regulative, economic and persuasive measures as a policy package may result in the best outcomes. For example, a study of transport policies in Latin American cities found that increasing the share of trips by bicycle from 1% to 10% could reduce the amount of GHG emissions in the city by 8.4%, whereas an action package consisting of developments of a bus rapid transit system, awareness raising and improvements in the safety of walkways and cycleways would result in a 25.1% reduction of GHG emissions (Wright and Fulton, 2005).

This is also highlighted in the fifth Assessment Report (AR5) by the IPCC: With *high confidence*, it is stated that

> [...] avoided journeys and modal shifts due to behavioral change, uptake of improved vehicle and engine performance technologies, low-carbon fuels, investments in related infrastructure, and changes in the built environment, **together** offer high mitigation potential.

4 Bottom-up models for a realistic identification of emission reduction potential

After the need for addressing traffic emissions has been recognized, cost-effective ways to actually produce desired shifts and emission reductions still remain to be identified. Policy makers can adopt various approaches, for example simply try and find out, rely on experiences from other cities and their evaluated impacts, or carry out simulations using models for traffic, emissions and costs. The human component in the effectiveness of any measure is complicated. Individual-level traffic mode choices with multiple motives make actions, evaluations and simulations alike challenging. We, unique individuals with our rather irrational decision making and fondness for routine, are not easy to quantify. Nevertheless, the effectiveness of any policy or measure is dependent on how the people adopt it. Therefore, we stress the importance of placing the focus on individuals and their actions with a bottom-up perspective to evaluating and modelling potential modal shifts and related emission reductions.

For some deployed initiatives that address people's traffic mode choices, the effectiveness on behavior change has been evaluated with real life data. Also some mode choice simulations have been conducted, with the aim to estimate how people's decisions about traffic modes can be affected. Those evaluations and simulations demonstrate that there are different approaches to take the response of individuals into account in models. The potential behavior change induced by different interventions or incentives can be simulated. For managing the atmospheric emissions that result from people's actions, the ability to evaluate versatile measures targeting individual-level behavior is crucial for finding the most effective way.

Incentivized behavior change may occur, if the provided incentive, reward or facilitation is substantial enough to overcome the inconvenience of changing habits. People value different aspects of their decisions differently, and aim to maximize the overall utility. Building on data, the decision process and the possible effectiveness of e.g. incentives on it may be represented mathematically and quantified. That quantification can then form the basis for both impact analysis and simulation of future actions. An example of suitable data includes surveyed information about people's stated preferences (ranking of preferred traffic modes and ranking of factors such as time, cost, distance, convenience) in combination with revealed preferences (i.e. their historically selected traffic modes). To support observed, measured or surveyed behavior change data, and to strengthen the analysis of effectiveness, knowledge about human psychology can be applied. It helps to interpret the observed changes and to anticipate outcomes. For example, in behavioral science, asymmetry has been observed in how elastic people are to price increase versus decrease, rewards versus fees. Such responses are worthwhile considering in relation to economic incentives or sanctions.

One way to combine available data and knowledge is to form a so-called *nested logit model* that is built upon specifications about possible choices and information about how people value different attributes relative to each other. This type of a model can produce the probability with which an individual person chooses certain alternatives, and how sensitive they are to trade-offs. Another approach to study poeple's mode choices utilizes *artificial neural networks* that enable a variety of human perceptions to be represented simultaneously (Hensher and Ton, 2000). Examples of mode choice models are presented by Wardman et al (2007) and Zahabi et al (2016). Their goal is to predict the impacts of different measures to encourage cycling. Zahabi et al (2016) conducted a model study of the effect of new cycling infrastructure on modal shares and transport-related GHG emissions in Montreal, Canada. A statistically significant link was found between the cycling infrastructure accessibility and bike mode choice. A reduction of close to 2% in GHG emissions was observed for an increase of 7% in the length of the bicycle network. Wardman et al (2007) used a model built upon an extensive survey data for revealed and stated preferences. The conclusion that they drew from their model output was that even an unfeasible scenario of a universally provided and completely segregated cycleway would increase cycling to work by only 55%, and, importantly, result in just a slight reduction in driving. Some real-life cases of cycling-supportive infrastructure investments with community-wide promotion and awareness campaigns are in line with that simulation by demonstrating only a slight increase in commuting by bike and hardly any change in vehicle kilometres travelled. On the other hand, payments for cycling were found to be highly effective for getting people to cycle more in the simulation by Wardman et al (2007), but no deployed examples of this could be found.

Also Hackl et al (2019) introduce a computational way to investigate walking and cycling modal shares and the reasons for their observed variation in Austria. To explain the observations, they use multivariate regression models with a rather extensive set of variables that potentially influence the choice of active mobility. Examples of factors that they consider in the analysis include snow cover, hilliness, number of bike racks, share of green and pleasant roadside views, deployed climate protection initiatives that advance biking, and even proxy variables reflecting political and administrative commitment to promote cycling at the municipal level. They conclude that their model is able to explain a ”considerable proportion” of the observed modal shares. Their approach seems applicable for the planning of measures to encourage active mobility and for simulating the incremental effects of individual initiatives. This kind of a multivariate approach for analysing why people (don't) walk and cycle shows potential for the identified need to be able to analyse individual-level traffic mode choices: the model manages to capture the observed reality and is methodologically feasible.

The traffic mode selection process represents one part of the bottom-up perspective on traffic. The bottom-up approach can be adopted also when analysing the big picture of people's mobility, traffic and emissions. Hatzopoulou et al (2011) have done pioneering work with a so-called *agent based model* (ABM) framework. It simulates people's activity schedules and daily chains of trips, which are then linked to a model that produces the resulting travel demand and traffic flow in an urban environment. Traffic emissions from the whole network get calculated without losing linkage to each individual person and their socio-demographic and personal attributes. With this approach, Hatzopoulou et al have simulated the development of traffic-originated CO_2 and nitrogen oxide emissions in the Greater Toronto Area in five scenarios (considering varying development of population, employment, emission standards, vehicle technology and public transport). They have also coupled the bottom-up simulation of people and traffic with an atmospheric dispersion model to get a view of the impacts on air quality in different scenarios. The results of their simulations indicate that it will be very challenging to achieve reductions in GHGs and air pollution in a region where both population and employment are expected to increase by approximately 50% in 30 years (2001-2031).

For managing the climate emissions of traffic, the ability to evaluate and test the effectiveness of different actions and initiatives is critical in order to be able to direct the investments towards more effective measures and to have an idea of what may and may not be expected in terms of emission reductions. The potential of policy initiatives and other measures to affect people's traffic mode choices is challenging to predict, but a few scientific attempts have been conducted, demonstrating rather plausible results.

Li and Kamargianni (2018) use a combination of stated preference and revealed preference data with nested and mixed logit models to simulate the traffic mode choices of individual people. The mixed logit model allows the parameters to vary from one individual to another, thus capturing the heterogeneity of the population better. In addition to studying the impacts of different features (such as environmental conditions, people's preferences for travel, and trip and mode attributes) on mode choices, they extend the analysis to cover potential impacts of different policies on changes in traffic modal split. An example of their simulation outcomes is that policies targeting the access time to the parking spots of city bikes and bus stops (thus providing people with time savings) were found to be more effective for promoting a modal shift than policies addressing travel costs.

Mei et al (2017) approach the challenge of predicting how incentives can affect people's traffic mode choices by constructing a Rule-based Incentive Framework utilizing decision trees and evolutionary game theory. They simulate the effectiveness of personalized incentives on individuals' traffic mode choices while processing measured travel information. The application of game theory is a step closer to a reliable simulation of real life, where no individual is in isolation, but the choices of others may affect e.g. the travel strategy of an individual. Mei et al use measured data about how sensitive people are to different factors (such as using a specific traffic mode, being exposed to high traffic volumes, and travelling a specific route) together with data about people's historical traffic mode decisions. The sensitivity ranking data shows that there is substantial variation in how sensitive people are to different criteria: one individual is very sensitive to a specific route, but not at all sensitive to changing mode or experiencing congestion, while the ranking can be opposite for someone else, and a third individual is moderately sensitive to all considered factors. Mei et al tested what kind of incentives would be effective for these different travellers. Based on their work and other literature, it is evident that the same incentives can not work to affect the traffic mode choices of very different individuals, but personalised rewards enabled by e.g. smart applications may. Some experiences of using personalised incentives exist and show effectiveness in getting people to choose low-emission traffic modes instead of the private car. However, the need exists for further research and more sophisticated models that would help to understand how to achieve a *permanent* behavior change and modal shifts that last after e.g. incentive provision has ended.

For a realistic simulation of behavior change induced by e.g. a traffic initiative, it is important to capture also the cultural evolution of sustainable behaviors: how interactions between people and changes in their environment can lead to a collective behavior change. An agent-based model is promising for this purpose. Kaaronen and Strelkovskii (2020) have built an ABM to study the collective adoption of pro-environmental behaviors and validated the model against cycling behavior in Copenhagen. They conclude that changes in our everyday environment can increase people's opportunity to adopt a pro-environmental behavior such as cycling, which, through habituation and social learning, can trigger a self-reinforcing feedback loop that leads to collective adoption. So from changes in the urban environment (whether e.g. structural or persuasive) and the behavior change of some individual people, a collective behavior change can emerge as we interact with each other. The ability to model this is a step closer to simulating the outcomes of e.g. efforts to manage traffic emissions in a very realistic way.

5 Recommendations and concluding remarks

The potential to significantly reduce greenhouse gas emissions from urban traffic exists, but the task is not easy, since we are dealing with the habits, attitudes and preferences of individual people. There is a multitude of factors influencing people's choices of traffic modes, and they need to be understood in order to understand traffic and the possible ways to change it to be more sustainable from a climate perspective.

A variety of initiatives targeted to affect individual-level traffic mode choices have been deployed around the world. Their impact evaluations vary in quality – especially when it comes to analysing the direction, extent, and permanence of change in people's behavior, which ultimately determines the level of emission reductions. The quality and reliability of evaluations should be acknowledged when looking for effective practices and examples. For example, ”saved emissions” are often reported in the context of initiatives advancing cycling, but it is recommended to critically analyse if it is a realistic assumption that all observed increase in cycling has replaced car driving. Importantly, one should always aim to exclude other factors that may have affected or even caused the observed change, and to perceive the overall emission reductions achieved with a policy, i.e. including possible (negative and positive) indirect impacts.

Some success factors can be identified based on the analysis of deployed traffic initiatives and their outcomes. Infrastructure improvements are more likely to be effective in advancing modal shifts, if they are combined with actions such as social marketing to address people's motivation deficits. A positive perception of the desired low-emission mode, whether public transport or bike, is critical. People need to perceive other tangible synergies (such as positive impact on health, money savings, improved mood etc.) than "just" emission savings that come with choosing low-emission mobility, if they are to sustain the new behavior. Restrictive policies such as no-driving-days may win people over if they are accompanied with reward provision. Congestion charge may induce a significant drop in traffic volumes and related emissions, if there is a functional transit system that people can easily turn to. In general, a shift towards more climate-friendly mobility seems to require an optimal combination of policies targeting people's opportunity, capability *and* motivation to choose low-emission traffic modes.

Reliably quantified evidence of emission reductions helps the diffusion of successful measures to other cities. However, action-specific evidence and realistic evaluations of the impacts of deployed initiatives are not always available. In that case, tested and validated simulations that capture people's behavior and response to different initiatives can significantly alleviate the work of policy makers who try to find the most effective ways to manage traffic-originated climate emissions. Simulations lean on data: it is highly recommended to collect data about the local people – their sensitivity to different factors, their stated and revealed preferences regarding traffic modes and mobility – before conducting a simulation of a policy or other measure and its potential atmospheric outcomes.

An urban system, a city, is complex. It comprises individual people with different preferences and motivations, social structures, infrastructure, dynamic traffic, and emissions, in a dynamic exchange with the boundary layer of the atmosphere. If we want to predict the outcomes of an action that addresses one part of the system, such as infrastructure or people's awareness, the selected analysis approach should be able to capture the complexity. For example simulations that enable testing how people might respond to different policies and how the shares of different traffic modes would shift, and models for predicting what the aggregate impacts on traffic and the achievable emission reductions could be, can support real-life action by setting expectations in proportion. When it comes to planning new measures to manage traffic-originated climate emissions, one should be able to evaluate the real emission reduction potential of different policies without overlooking the most important part that is critical for success: the people.

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