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Complementarity and substitution between public transport and bicycles

Moez Kilani (corresponding author)
University of the Littoral Opal Coast
moez.kilani@univ-littoral.fr

Souhir Bennaya
University of the Littoral Opal Coast
souhir.bennaya@univ-littoral.fr

Seghir Zerguini
University of Bordeaux
seghir.zerguini@u-bordeaux.fr

Abstract: We analyze the impacts of several improvements to urban transport and find that the bus can be made much more attractive by the simultaneous provision of dedicated lanes and higher service frequencies. At the same time, fare reforms, including free public transport, have limited impacts and do not seem to play an important role in reducing the use of the private car. In addition, our analysis considers active modes, bicycles in particular, and shows how they substitute for, or complement, public transport. We find that substitution prevails when public transport is rather accessible by walking (small spacing between the stations), but complementarity arises when the number of stations is small (large spacing between the stations). Our analysis is based on a micro-simulation approach, allowing us to develop a realistic and flexible framework where features like traffic lights, location of the stations, and road crossings for pedestrians are explicitly described.

Keywords: Public and active transport, intermodal transport, bus stations, dedicated bus lanes and cycle-paths, microsimulation with Sumo

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1 Introduction

Urban transport plays a central role in economic activities (Small, 2013). Urban economic theory has contributed to identify the role of transport in the development of urban form and the growth of the city (Fujita, 1989). In a more general context, (Aschauer, 1989) highlighted the importance of investment in infrastructure on national economic growth. During the last two decades, several authors have used advanced econometric techniques to identify and evaluate the magnitude of agglomeration economies and found that efficient transport systems can explain up to 2% of higher productivity in metropolitan areas (Duranton & Puga, 2004).

At the same time, transport activities are the source of negative externalities (Arampatzis et al., 2004), including road congestion (delays in travel times) and pollution (emissions of greenhouse gases and fine particulates). The excessive use of the private car is generally the main problem in urban transport, and since the early 2000s several

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cities in Europe and North America put in place reforms to restrict its daily usage. The worsening of the environmental situation, and related global warming, is pushing towards solutions targeting the reduction of the emissions of local pollutants and greenhouse gases.

Since the pandemic, we observe more users of the soft modes, like the bicycle and electric scooters, and local authorities try to build on this new trend to stimulate transition to a greener transport system. It is now clear that this objective requires both an upgrade in the infrastructure, to accommodate new users of the bicycles, and an improvement of public transport services. The combination of several modes can, indeed, make public transport more flexible by enlarging its accessibility to lower density areas. (Manout, et al., 2018) highlight the importance of accessibility to transit and how it can be evaluated. The improvement of public transport services can be achieved through higher service frequencies, the locations of the stations, the development of service lines or lower fares. A more attractive public transport system can also be obtained when there is a better complementarity with other modes, in particular the bicycle (or other active modes) that can efficiently feed a mass transit system.

To address this multidimensional problem, we develop a detailed simulation framework based on a monocentric city that extends along a main axis where workers commute to work. The axis is crossed by a set of secondary roads and the intersections are managed by traffic lights. Each user chooses a transport mode (private car, public transport, bicycle or walk) and switches to an alternative one when the travel time (including wait time) is too large. The specific point about our framework is the high level of details. Indeed, and since our approach is based on microsimulation, we are able to account for exact position, speed and acceleration of each vehicle and agent; we provide a realistic representation of pedestrians as well as of bikers. To run the simulations we use the simulation engine Sumo (version 1.16), but we manage all the related processes ourselves (network construction, mode choice, calibration). A set of comprehensive scripts has been written for this purpose.[1]

We use this framework to study several scenarios related to the (i) development of a more efficient public transport system and to the (ii) provision of cycle-paths, ensuring safer use of the bicycle. The examination of this simplified city yields a number of interesting results. We show how traffic flows, and the benefits from some reforms, can be highly dependent on some small technical details. For example, the benefits from a dedicated bus lane are much more important when there is a full segregation between the buses and the cars. If both modes share some road sections, in particular where the bus makes the turn-around maneuver, the corresponding congestion cancels a significant part of the benefit brought by the dedicated lane. Moreover, dedicated bus lanes are found to be particularly efficient when accompanied with high frequency services, while fare reforms, like free public transport, are found to have limited impacts when the supply of public transportation remains unchanged. With respect to the bicycle, we find that dedicated lanes induce a clear benefit and produce an important modal switch. These results are consistent with the findings in (Kilani & Bennaya, 2023) and in (Bennaya & Kilani, 2024).

The development of a simulation framework involves several steps, ranging from the development of the network and demand generation to the examination of policy scenarios. The main difficulty is to deal with the number of technical steps involved in

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[1] The scripts are available from the corresponding author upon request. An opensource version will be made publicly available after some cleaning and once a short documentation is completed.

this process. For example, the usage of the bus needs a preliminary trip where the agent walks from the home location to the departure station, and another walk from the arrival station to the final destination. Walkers should be routed to the nearest stations [2] and this may need crossings at some road sections. We allow road crossings for pedestrians only at the intersections.

The development of cycle-paths induces, in general, a positive impact on traffic conditions, in particular for bikers. But, at the same time, it increases the complexity of the intersections and may locally have negative impacts. (Kilani & Bennaya, 2023) showed that when the number of bikers is below (15%) the negative impact can dominate, but for higher modal shares of the bicycle the overall impact of dedicated cycle-paths is positive.

The benefits of public transport have been highlighted in earlier studies (e.g., Parry & Small, 2009). The main fact, that is our contribution, is that these studies generally rely on aggregate models and do not consider technical details that we show to be of first importance when it comes to operating transport services.

The base-case in our study involves a large share of the private car (above 70%) and minor shares for the alternative modes (public transport and bicycle). This induces large external costs (congestion and pollution). The alternative scenarios examine the modal switch that equilibrates this distribution and mitigates the attractiveness of the private car. We show that combining the improvement of public transport services with the upgrade of the infrastructure to provide bikers with safer lanes is the most efficient alternative. While each of these instruments has positive impacts when implemented alone, we show how the benefits can be smaller (or even cancel out) when the reform involves a set of uncoordinated actions, or when some specific implementation details are not considered.

In many cases, we find that several users switch between public transport and the bicycle, suggesting that the two modes are rather substitutes. In additional scenarios, examined in a second step, we reduce the accessibility to public transport and allow users to combine the bicycle and the bus in the same trip. In this case, several users of the bus replace the walk to the stations, which is now at a longer distance by comparison to the base-case, with the bicycle trip to the station. We obtain a significant complementarity between the two modes maintaining a good ridership of public transport with a limited (or no) switch to the private car.

The paper is organized as follows. Section 2 briefly reviews the literature related to public transport and active modes. The workflow of the simulation and the case study are described in Section 3. The improvement of public transport (service frequencies and stations spacing) is discussed in Section 4, and the development of active modes, the bicycle in particular, is discussed in Section 5. Section 6 concludes.

2 Related literature

Transportation plays an essential role in shaping social life and influencing the location choices of the main activities (Dong et al., 2020). While the demand for transport is increasing, issues related to sustainable development have gained importance and are currently calling into question the use of the private car (Pietri 2023; Tortosa 2023). The problems linked to the car stem from its heavy environmental footprint. In addition to environmental and financial constraints, the increase in the number of road vehicles is not keeping pace with infrastructure expansion (Tennøy et al., 2019), or at

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[2] Sometimes some other stations may be more attractive, but we do not consider these alternatives.

least proportional to road expansion (Chen & Klaiber, 2020). As a result, the evolution of car-centric mobility is hampered by the increasing congestion in dense urban areas (An, 2011). At the same time, transport plays an important role in development policies, which is to say that transport is an essential component of urban public policies (Pomonti, 2004).

Several cities are implementing strict policies to limit the use of old polluting vehicles. Low emission zones (LEZs) is a representative example used to combat air pollution and, to some extent, alleviate traffic congestion (Denèle et al., 2023). The implementation of these zones in urban areas is expected to limit the use of the most polluting vehicles and stimulate their replacement by cleaner vehicles, including the electric car, or to favor the modal switch to more sustainable alternatives like public and/or active transport. The growing environmental and energy concerns made the bicycle and electric scooters more popular (Taiebat et al., 2018), and the recent context of the pandemic has accentuated this trend. Walking and cycling can be exhausting and painful for longer distances, but they can be convenient for many urban trips that are usually only some kilometers long. These active modes generate few or no external costs (congestion and pollution) and their user cost is too low by comparison to the private car. Building on these advantages, several cities have upgraded their infrastructures and services to promote active modes (Kilani & Bennaya, 2023; Tammaru et al., 2023). In practice, such actions include the development of cycle-paths, parking areas for the bicycle and easily accessible sharing systems.

Bike-sharing systems (BSS) simplify bicycle access and relieve users from maintenance and parking responsibilities. The number of cities worldwide equipped with a BSS has increased from thirteen in 2004 to 814 in 2014, with more than 900,000 bicycles used in these systems (Fishman, 2016). BSS shows that cycling can be a competitive alternative to the private car and public transport (Li et al., 2019). Furthermore, (Wang & Zhou, 2017) have shown that the creation of BSS in several urban areas in the United States had a positive impact on congestion, especially during peak hours. This impact can be even greater for larger cities.

Some studies have evaluated the impacts of the BSS for areas around the university campuses. For the case of the University of Lyon (France), (Havet & Bouzouina, 2024) report that 11% of students and 15.5% of staff use bicycles to get to the campus. These shares are well above the national average. The authors find that the existence of the BSS favors the exclusive use of the bicycle, while the combination of cycling with other modes remains dependent on spatial factors and the accessibility to public transport.

Furthermore, walking and cycling have positive impacts on human health and cardiovascular diseases (cf., Pucher et al., 2010). Walking and cycling became more popular during the pandemic, and this trend is expected to persist in the long-term (Megahed & Ghoneim, 2020). Since the pandemic, several European cities (including Barcelona, Paris and Lyon) have taken major steps to promote the use of bicycles. The city of Lyon, for example, has developed BSS systems and bicycle lanes in several parts of its road network (Diallo et al., 2023). These initiatives and the pandemic have led to a 21% increase in the number of cyclists between 2020 and 2021.

Despite several advantages, there are some factors that limit the widespread choice of the bicycle. These are related to the comfort, the required physical effort, and road safety concerns. The latter is a major issue, since sharing the same traffic lanes as cars and other vehicles exposes cyclists to serious risks of injuries in case of an accident (Buehler & Dill, 2016). To provide safer conditions for the users of the bicycle, several local authorities have upgraded the infrastructure with dedicated cycle-paths (Duthie & Unnikrishnan, 2014).

In relation with the current study, (Kilani & Bennaya, 2023) considered a medium size city and evaluated the impacts of the growing use of the bicycles on traffic flows and pollution. Using micro-simulation, the authors identified a threshold value of 15% in the share of the bicycle beyond which a large decrease in congestion and pollution is obtained. Similarly, (Bennaya & Kilani, 2023), who consider a symmetric circular city, examined the effectiveness of a modal shift to an intermodal system integrating cycling and/or walking with public transport (bus). Their results confirm that the modal switch to active transport has positive effects on road congestion and air pollution. The current study brings several technical improvements to the models used in the previous two studies.

(Parry & Small, 2009) highlight the fact that the presence of external effects such as traffic congestion, greenhouse gas emissions and fine particulates disrupt the equilibrium with respect to the optimum. They describe the equilibrium as an individual action in which each agent seeks to reduce his or her total cost, regardless of the impact of this reduction on others. As for the optimum, it represents a situation in which each user compensates for the external effects he/she generates. Fare reductions and subsidies to the public transport sector encourage modal shift towards this mode (cf., Parry & Small, 2009). Moreover, as (Kraus, 2003) and (Kraus, 2012) have pointed out, the introduction of car tolls is an effective road pricing tool, encouraging users to switch to public transport and, consequently, helping to reduce external effects. To encourage the use of public transport, road pricing can be considered but usually faces users' opposition and remains unpopular. The improvement of service quality of public transport is a preferred solution in practice. A limited supply of public transport, or a low service quality, will certainly produce a massive use of the private car (Kilani & Houassa, 2018).

Some earlier studies have considered dedicated bus lanes. (Mohring, 1979) considered a set of simplified models and showed that subsidies to public transport are more effective when combined with dedicated bus lanes. (Berglas et al., 1984) follow a similar analytical approach and evaluate the benefits from separated lanes. They show how separation improves welfare when the two modes are sufficiently differentiated in how they generate congestion, or in how their respective users are sensitive to congestion. Tolled and untolled roads were considered and the positive impact from the dedicated lanes is shown to hold under both regimes. (David & Foucart, 2014) consider the two-mode problem and identify a lock-in in “bad” equilibria (the car is the most used mode), where even a welfare maximizing central planner is unable to decentralize the optimum. (Pandey & Lehe, 2024) reconsider the Downs-Thomson paradox under the case of dedicated bus lanes and show that increasing the road's capacity does not necessarily produce the paradox.

During the last fifteen years, several cities have tried to promote intermodal transport which is seen as an effective strategy for optimizing the efficiency of the transport system. Intermodal transport offers a flexible solution to the specific needs of users by promoting complementarity between modes, such as switching from individual transport to walking, cycling and/or public transit. For example, (Lorente et al., 2022) showed that the intermodal system is particularly efficient during peak hours. In addition, (Baum et al., 2019) examined variants of a bike-sharing service and a non-shared cab as auxiliary transport that takes over public transport networks. Their methods combine public transport and auxiliary modes, and due to its complexity the results of the study are rather broad.

It is also worth mentioning that most of studies related to active transport either use a simplified, macroscopic and mesoscopic, simulations (Diallo et al., 2023; Kilani et al., 2022), conduct limited descriptive discussions (Krause et al., 2020) or conduct an econometric studies with a restrictive scope (Fernández-Heredia et al., 2016). With the objective to extend the existing studies toward more realistic and more general frameworks, we develop a structured microsimulation analysis based on a representative city.

3 Methodology and description of the case study

We first give an overview of the simulation framework (Subsection 3.1) and then describe the case study we develop (Subsection 3.2).

3.1 The simulation framework and workflow

The development of a micro-simulation framework involves several steps, including a number of technical details that should be carefully addressed. The approach we adopt here has some similarities with the well-known four-step approach, but since we consider a dynamic multi-agent model (departure time is a choice variable), a more elaborate strategy is needed. Indeed, and in addition to the choice of the transport mode, each agent has to find an appropriate departure time to avoid large schedule delay costs induced by too early or too late arrivals.

An overview of the simulation framework is given in Figure 1. In the first step we provide the input needed for the simulation: the supply and demand parts. The supply includes several parts. The transport network is described by providing all the road links, where they connect and how many lanes each road section contains. We also need to indicate whether there are dedicated bus (or bicycle) lanes and how traffic is controlled at each intersection (traffic lights or right-of-way priority). To allow walking on appropriate areas, we specify the location of sidewalks and crossings over the network. Parking areas, with specific capacities for cars, are provided near the city-center and services of buses are described by indicating the operating lines and the service frequencies. Public transport consists of a single bus line that runs through the main road axis. Indeed, as we describe in the next subsection we conduct our analysis under the monocentric city framework. The service frequency is higher during the peak period, and public transport operators may adjust the frequency to improve the attractiveness of public transport. All the intersections are managed by traffic lights that apply for cars, buses, bicycles and pedestrians. The latter can cross the road only at the intersections. There are four parking areas available in the downtown area, and their total capacity is larger than the total demand for parking lots.

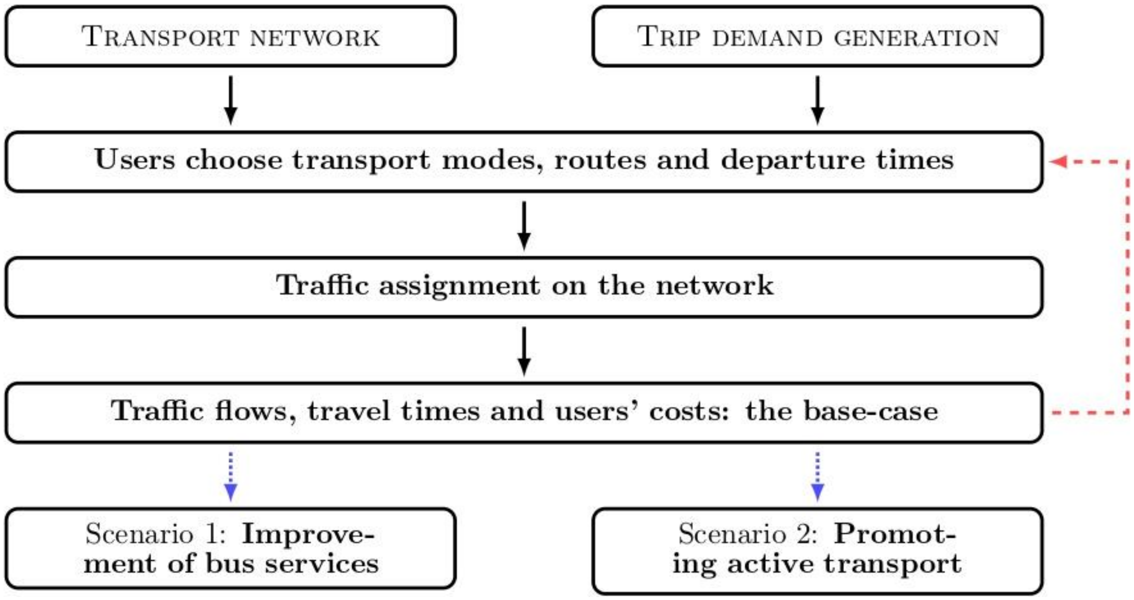

Figure 1. The main steps in the development of the transport model. The red loop corresponds to the calibration process

The demand creation requires the generation of a population of agents, assigning each one a home location in the city. The work locations are all in the central business district (CBD) in the city-center. The morning rush-hour is considered in this framework and each agent has a preferred arrival time and avoids arriving too early or too late to work. Furthermore, each user chooses among a set of available transport modes and selects the one that minimizes the generalized transport cost, the sum of the monetary cost and the non-monetary cost. The non-monetary cost takes into account the in-vehicle time, the wait time, the schedule delays (early and late arrivals) and, for the bicycle and walk, the physical effort when the travel distance is relatively long. More formally, an agent departing at time t^d arriving at time t^a, having the desired arrival time $t^\#$ and using the mode m has a generalized cost, denoted C^m, given by

$$C^m = a^m + c(d) + (1+w)\,\alpha\, t^w + \alpha\,(t^a - t^d) + \beta\,(t^\# - t^a)\,\boldsymbol{I_E} + \gamma(t^a - t^\#)\,\boldsymbol{I_L} + max(0, d - \tilde{d}^m)^2, \tag{1}$$

where am is mode specific constant, c(d) is the monetary cost when the trip distance is d (constant for public transport, and zero or too small for bicycle and walk), w is a factor reflecting how the agents dislike waiting with respect to being in the vehicle, t^w is the total wait time, $\tilde{d}^m$ is the threshold when the mode becomes physically exhausting (it is infinite for cars and public transport), α the in-vehicle time cost (per unit of time), β schedule delay penalty of an early arrival (per unit of time), and γ schedule delay penalty of a late arrival (per unit of time). I_E (resp. I_L) in Equation 1 is a binary variable equal to one if the agent arrives early (resp. late), and zero otherwise.

Initially, each agent randomly chooses a transport mode and a departure time. Then, according to these choices, trips are simulated in the network, and this allows us to draw a complete description of all the features and characteristics of each trip: travel times (all modes), wait time (public transport), travel conditions (crowding in buses) and emissions produced by each vehicle. The user cost in Equation (1) is then computed. Notice that several features are taken into account to make traffic flows consistent. For example, an agent will be able to get on the bus only when a space is available, i.e. when the capacity is not exceeded. The SUMO simulator (cf. Lopez et al., 2018) is used to implement this step. The emissions module is directly connected with the simulation output and relates emissions to relevant technical details (travel speed, accelerations, engine regime, fuel type) and distinguishes between old and new vehicles. The specific model used in parallel with the SUMO simulator is based on the HBEFA (Handbook Emission Factors for Road Transport) standards developed by the European Environmental Agency (EEA). A detailed discussion of this implementation can be found in (Tielert et al., 2010).

Then, on the basis of the computed user costs, each agent compares his/her situation with that of other agents living in the same area (at comparable distances from the city center). At this stage, we use a relatively simple heuristic that performs well in our case. Users with relatively higher costs, based on Equation (1) , review their departure times when the share of the schedule delay cost in their generalized cost is large. Otherwise, when the user cost is high but the share of the schedule delay cost is small, they are likely to change their transport mode. For each group (a number of users located at nearly the same distance from the city center) we compute an average user cost and the corresponding standard deviation. A user cost is considered as large when it is higher than the sum of the average cost and a fraction of its standard deviation, i.e. $\mu + s \cdot \sigma$, where μ is the average user cost, σ the standard deviation and s a given parameter set to 0.8 in our study.

A multinomial logit is used to model the choice of a new transport mode.[3] This probabilistic approach makes the modes yielding smaller costs more attractive (chosen with higher probability), and vice versa. This process is repeated iteratively until no user (or too few users) changes the departure time or the transport mode. For the case study described below, less than fifty iterations were enough to reach the equilibrium. When the model is at equilibrium we can compute all the components of the user costs and other statistics.

In this analysis, we assume that all the agents in the population share the same preferences and the same value of time. Users differ in their locations and their preferred arrival times. Those living at the same distance from the city-center need not use the same transport mode but, at equilibrium, the differences in their user costs are relatively small.

3.2 Transportation network and urban form

Our analysis is based on a simplified, though representative, linear city with a main axis linking the outskirts to the city-center (see Figure 2). The main axis is crossed by a number of radial axes, and the priorities at intersections are managed by traffic lights. Under this structure of a monocentric city, there is no route choice for cars. Users do not change the location of their houses and jobs (short, medium-term analysis). However, we need to provide routing for users of public transport since they have to select a station to

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[3] The multinomial logit model is known to suffer of the IIA property (Independence of Irrelevant Alternatives). Other formulations, like the nested logit or the mixed logit, may be used for better consistency, but since our framework is relatively simple and is not based on empirical estimations, we do not think that such sophistications will be necessary for the purpose of the current study.

ride a bus. In our framework, this is not straightforward because the walk to the station may involve crossings complicating the relevant route to the stations. In particular, users who need to cross the main road may choose a station which is not necessarily the closest one with respect to the bird’s eye distance. Also, when an agent is located in the middle between two stations, he/she is more likely to choose the one closer to the city center. We take into account such a behavior by introducing a small penalty for walk distances that are made in the opposite direction to the city-center. A set of rules describing the behavior of the users of public transport were implemented to assign a station to each user. For other modes the routing step is simple given the monocentric form of the city.

Dedicated lanes for buses and/or bicycles are considered as possible options that local authorities can use to favor alternatives to the private car. With dedicated bus lanes, users of public transport suffer less from congestion, and this usually reduces the relative attractiveness of the private car. For the bicycle, mixed traffic where they share the road with the cars involves substantial risk of accidents with severe consequences. The availability of dedicated lanes, separated from the main roads, significantly improves safety and increases the attractiveness of the bicycle.

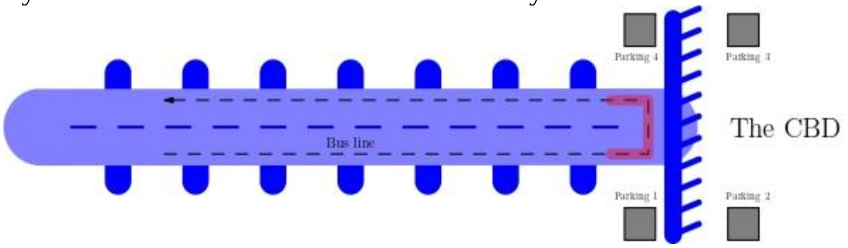

Figure 2. A description of the monocentric city

Figure 2 illustrates the geometry of the city that we consider in this analysis. The main road is nine kilometers long and has eight equidistant intersections with secondary lanes from which flows are generated. Travel speeds are equal to 50 km/h and 30 km/h on the main road and secondary roads, respectively. All the intersections are managed by traffic lights with a cycle time of ninety seconds. In the reference case, there are three lanes on each direction of the main road, and one lane in each direction for the secondary roads. The three lanes may be used by all modes, but when a dedicated lane is added, the lanes available for cars are reduced. With respect to the population, there are 3,000 agents making daily home-to-work trips. Trips are generated from the main axis (20%), corresponding to the share of households living there, or from the secondary roads linking the main residential areas (not shown in Figure 2) to the main road. Users choose among four modes: car, bus, bicycle and walk, but in the base-case scenario, we do not consider the bicycle because we assume that mixed traffic raises serious safety issues for bikers. Notice that public transport always needs a preliminary walk stage from the house location to the station (also from the drop-off station to the destination). But, the reported mode “walk”, will not refer to these trips and will correspond only to walk from the house to the work locations. Also, in some examined scenarios we allow users to combine the bicycle and the bus, but not in the base-case scenario.

Our simulation is limited to the morning rush-hour and covers the time window from 6:30am to 12:00pm, where we focus on the home-to-work trips of the active population. The preferred arrival times of the workers are uniformly distributed between 9:00am and 9:30am, producing a peak period for traffic flows between 7:30am and 10:00am, in most cases. The headway of bus services is 600 seconds (10 mins) during the peak period and 900 seconds (15mins) in the off-peak.

The monetary cost for car users includes the fuel cost (1.9 euros/liter in the base-case), the parking fees and the road tolls (both zero in the base-case), and a distance based operating cost (assumed 0.5 euros/km). For public transport (bus), the monetary cost corresponds to fares that we assume equal to one euro for the daily trip. Most single ticket fares in Western European cities are about two euros, and our choice is an average value between these fares and public transport passes allowing passengers to benefit from significant discounts. For soft modes (bicycle, walk), the monetary cost is zero. The time cost includes the time spent in the vehicle, the walking time, the wait time at red lights, time lost due to congestion, and waiting time for buses in the station. The active modes (walk and bicycle) are also physically exhausting for large distances. We add quadratic terms in the cost function when the traveled distance is above a specific threshold value. The threshold is set to 1 km for walk (10-minute walk) and set to 4.5 km for the bicycle, the latter being consistent with (Philips et al., 2018). We also include a parameter that reflects the attractiveness of the mode with respect to other attributes (cf. Equation 1). For example, the bicycle may be related to high risks of severe accidents when there are no dedicated lanes. These mode specific constants are also useful to calibrate the model to produce realistic modal shares.

After less than fifty iterations, we achieve a user equilibrium, where the number of trips by car is 2,053 (68.43%), by bus is 243 (8.10%), and by walk is 704 (23.46%). These shares are consistent with values observed in some empirical studies (see for example, Kilani et al., 2022, for the North of France). The average user cost (generalized cost) in the base-case is 30.88 euros. Fuel consumption and emissions of several pollutants (CO_2, CO, HC, NOx, PMx) are computed. Since the quantities of emissions are highly correlated (most of these are proportional to fuel consumption), we only report CO_2 emissions which are 8.19 kg per car-trip in the base-case.

The model is checked to produce sensible impacts with respect to changes in parameter values. For example, an increase in the fuel cost by 10% produces a reduction in fuel consumption (number of trips by car) to slightly less than 5%, a value that is consistent with econometric estimations that are reported in (Wardman, 2001).

The user equilibrium corresponds to a representative situation where the private car is overused and produces high congestion and large amounts of emissions. This situation is responsible for environmental problems pushing local authorities in adopting transport reforms that aim at reducing pollution. Most of the policies focus on the switch from the private car to alternative modes, such as public transport or active modes (walk, bicycle). Subsidies to public transport have been put in place for several decades now (Parry & Small, 2009), but they did not produce expected impacts, and in most developed countries the share of public transport does not exceed 10%. Breakthrough and more explicit policies, like low-emission zones and roads pricing, do not seem to be popular and many local authorities are not taking the step to implement such measures. From the pandemic and the development of electrically assisted bicycles and scooters, active modes are the focus of an active research to see how they may attract new users and how they can combine with, and improve the attractiveness of, public transport.

Several reforms insist on reducing the space allowed for cars by developing cycle-paths and dedicated bus lanes. The impacts of these reforms on car users are not clear since, on one hand, they benefit from less interaction with distinct vehicles but, on the other hand, have less space at their disposal. Such policies will be examined in the two following sections.

4 Improving public transport services

The attractiveness of public transport depends on several factors including service frequencies, accessibility to walkers, regularity and comfort. In the base-case equilibrium described in the previous section, service frequencies involve a significant waiting time for bus users. As a first experiment, we have progressively increased the frequency of bus services (smaller headways) and checked that the user costs for bus decreased, producing a modal switch to public transport. The benefit from public transport, however, is limited by: (1) the system capacity and the discomfort users can suffer from crowding; (2) congestion produced by the new buses on the road. This second impact is particularly important when buses do not have dedicated lanes. Initially, the marginal impact of increasing the frequency is important, but it reduces as the frequency increases because the waiting time cannot decrease further while, at the same time, the congestion produced by the additional buses increases travel times (for cars and buses).

To compare distinct reforms, we examine a first set of three scenarios: S_1, free public transport; S_2, increase in fuel prices by 15%; and S_3 optimized service frequencies. For the latter scenario, we have increased the frequency until the benefit from a marginal increase becomes relatively small (we assume that the constraint related to the operating costs is not tight). In this case, we obtain a headway of 120 s (two minutes) during the peak period and 300 s (five minutes) during the off-peak. The impacts on mode choice and with respect to the locations of the households are reported in Table 1. Agents are segregated in three groups called Ring 1, Ring 2 and Ring 3, with respect to their locations. Agents in Ring 1 are those who are located near the city center and those in Ring 3 are those who are in the outskirt. The remaining agents, those in the middle, belong to Ring 2.

Scenario S_1 shows that free public transport slightly increases the share of the bus from 8% to 9%, but this is accompanied by a 3% reduction in the trips by walk. At the same time, the number of users of the car increases, which may seem at odds with expectations at a first instance. But this obtains because the increase in the use of public transport mostly benefits to users located in the outskirts. Users near the city-center suffer from crowded buses where they do not find an available space (a seat or standing place). Indeed, many users in Rings 1 and 2 who continue to use the bus wait a long time before being able to get on since most of the buses arrive at their stations with loadings exceeding available capacity. The increase in the cost, induced by the large wait time, will encourage some agents to consider other alternatives, and the car becomes an attractive one.

Scenario S_2 shows that a 15% increase in fuel prices increases the attractiveness of the bus and, to a lesser extent, walking. By comparison to S_1, there is a significant reduction in the number of private car users, from 71% to 64%. As a result, the decrease in congestion produces a slight decrease in the average user cost. However, although the monetary cost decreases, the time cost for those making the modal shift to walking increases. The increase in the frequency of public transport produces larger switch from the private car to public transport by comparison to the impacts from S_1 and S_2. Scenario S_3 shows an almost 11% reduction in car users, while the number of bus users increases by 3%. The higher frequency is a major determinant in the demand for public transport. With more buses sharing the road with cars, the level of congestion increases providing a further reason for modal switch. The increase in congestion induces an overall increase in the share of walk. Under this scenario, the average generalized cost falls from 30.9 euros to 27.6 euros.

We can also notice that from S_2 to S_3, the average generalized costs decrease significantly for agents living in the outskirt, i.e. Rings 2 and 3. The increase in fuel cost (scenario S_2) decreases the modal share of the private cars (by seven points) and produces a modal switch to public transport and walk. The overall impact is positive on the user cost because congestion decreases and less expensive modes are more used. Scenario S_2, that can be interpreted as a road pricing scheme, is the most effective in reducing congestion producing a significant drop in CO_2 emissions, despite a larger share of cars (longer rush-hour and less congestion).

Table 1. Results for the first set of examined scenarios

Scenarios		S_0	S_1	S_2	S_3
Modal share (%)	Car	68.4	71.0	64.0	60.0
	Bus	8.1	9.0	9.9	11.0
	Walk	23.5	20.0	26.1	29.0
User cost (euros)	Ring 1	10.8	13.4	10.8	11.3
	Ring 2	33.7	47.1	32.9	32.1
	Ring 3	41.4	59.2	38.9	38.3
	All	30.9	32.5	29.7	27.6
CO_2 (kg/car)		13.4	12.2	7.7	8.1

S_0: base-case scenario; S_1: free public transport; S_2: increase in fuel price; S_3: high frequency bus services.

The development of a dedicated lane for the buses reduces travel time for the passenger, but the final impact may depend on whether the road segregation is full or partial. In many real case situations, cities develop dedicated bus lanes but leave some (short) sections with mixed traffic. It is then important to check if in this case bottlenecks still form and to what extent they can limit the benefit from the dedicated bus lane. With the detailed simulation that we are considering, this problem can be observed in the road section just near the CBD, where the bus must turn-around in the opposite direction to the city-center. There are two cases. In the first case, the buses do not have a dedicated lane (or infrastructure) to make the turn-around maneuver, a bottleneck forms and congestion increases. This occurs on the road section indicated in red color in Figure 2. In the second case, the buses have a specific lane that allows them to make the turn-around without interacting with other modes. We have only reported results related to the second case, where the buses have the dedicated lane to perform the turn-around maneuver. We must notice, however, that from the simulations we have conducted, when the buses share the road with cars in such an important intersection, a large bottleneck is created and the benefits produced by the dedicated bus lane are almost completely wiped out.

The results corresponding to some scenarios based on the development of a dedicated bus lane are reported in Table 2. Under scenario S_1' a road lane is dedicated to buses and there is one less lane available to the cars (total road width is unchanged). Scenario S_2' differs in that the dedicated bus lane adds to the existing lanes (wider road). Scenarios S_3' adds free public transport to S_1' while scenario S_4' adds an increase in fuel price to S_1'. Scenarios S_5' and S_6' both add high service frequencies for buses to scenarios S_1' and S_2', respectively.

The dedicated bus lane yields a positive impact on user costs in almost all cases. It produces an important modal switch to public transport, which can even dominate the car share when the bus frequency is high as in the last two scenarios. Under scenario S_1' the share of public transport increases from 8% to 27% while the shares of the car and walk drop to 66% and 6%, respectively. The average user cost decreases to less than 27 euros. When the dedicated lane is added to the existing road as in S_2', the user cost decreases even more, but since road congestion is smaller, the decline in the share of the private car is smaller. The number of trips by walk are reduced but not as in S_1'. The users who benefit the most from the new lane are those who live in the outskirts. Users in Ring 1, by contrast, do not benefit, because the buses are less accessible and the impact on congestion near the city center is limited (walk remains an available option).

Adding free public transport to the dedicated bus lane increases the ridership of public transport, but the large part of the modal switch comes from the walkers. The impact of the car use is rather limited and the user cost remains almost unchanged (compare S_1' and S_3') and does not impact significantly the modal switch from the car to the bus. In this case, an increase in gasoline price yields better impacts in decreasing the use of the private car, but the user cost is relatively high. This is because the monetary cost for car users increases and is not compensated enough by the modal switch.

The best outcome is clearly obtained under S_5' and S_6' indicating the urgency to accompany the dedicated bus lane with an important increase in service frequencies inducing shorter headways. The increase in service frequencies has two effects. It reduces the average wait time at the stations and it prevents the bus system from operating at maximum capacity which allows all users, even those getting on the bus near the CBD, to find a space in the first arriving bus. Since under scenario S_6' we extend the existing road capacity to provide the dedicated lane the overall impacts are higher than in S_5'. In both cases, public transport attracts more than half of the commuters, road congestion and CO_2 emissions are at particularly low levels.

Table 2. Examination of scenarios based on the development of dedicated bus lanes

Scenarios		S_1'	S_2'	S_3'	S_4'	S_5'	S_6'
Mode shares	Car	66.2	68.0	68.5	67.0	38.0	44.0
(%)	Bus	27.2	23.0	26.0	27.0	58.0	51.8
	Walk	6.6	9.0	5.5	6.0	4.0	4.2
User Cost	Ring 1	8.9	11.7	9.0	9.5	9.0	10.6
(euros)	Ring 2	32.2	28.7	30.8	32.6	12.9	13.6
	Ring 3	34.9	30.2	35.6	35.6	17.1	15.1
	All	26.51	24.87	26.32	27.21	14.3	13.85
CO_2 (kg/car)		6.4	6.3	6.7	6.5	3.9	3.7

S_1' : dedicated bus lane with fixed road length; S_2' : dedicated bus lane with wider road to accommodate the new lane; S_3' : dedicated bus lane and free public transport; S_4' : dedicated bus lane and increases in fuel price; S_5' : S_1' and high frequency bus services; S_6' : S_2' and high frequency bus services.

Summing up, car users benefit from additional lanes (larger road capacity), in particular when there is a dedicated bus lane. For users of public transport, the increase in the number of lanes matters only when traffic is mixed. The combination of dedicated bus lane with optimized service frequencies induces the most significant benefits on user cost and CO_2 emissions, and this is true even when the road width remains unchanged. Buses are less sensitive to congestion than cars because travel time is longer due to stops in the stations and their accelerations near traffic lights are smaller.

The public transport operator can improve the quality of the services by optimizing the stations' locations, or the number and the space between the stations. In a set of simulations that we did not report here, when the inter-space is large, users have to walk long distances to reach the transport line. At the same time, users benefit from less stops at intermediate stations during their trips. In general, as highlighted in (Vuchic, 2005), spacing is large in the suburb and decreases when the transport line approaches the city-center. Bus stops are also the cause of delays for other modes, private cars and bicycles in our case, when all modes share the same road lanes. We find that while the increase in frequencies reduces the user cost, changing the spacing between the stations yields mitigated impacts, and the definitive result depends on the distribution of the users along the main road. Since we consider the short-term, where users' locations are exogenously given, our model is not appropriate for a comprehensive analysis of this policy and we plan to consider this discussion in the future. In the next section, however, the spacing between the stations will be considered in some scenarios because it is relevant to intermodal transport and the accessibility of public transport.

The benefits from the improvements of public transport are indisputable, but these may need substantial financial resources making it difficult to be adopted by local authorities. We extend our analysis to evaluate the benefits from developing active transport, where flexible alternatives, like the bicycle (or electric scooters) are available for the daily home-to-work trip.

5 Promoting active modes

From the pandemic and the outbreak, an increase in the use of the bicycle has been observed in several cities. This trend has been encouraged by the more accessible technologies producing more efficient batteries. Active mobility offers several advantages in urban areas. It is much less expensive than the private car and is less sensitive to congestion during the peak periods. Since most trips in urban areas are less than five kilometers, the bicycles and electric scooters can attract a significant share of the population.

These modes have some drawbacks, however. In particular, both bicycles and scooters are usually singled out as raising road safety issues. Also, and in particular by bad weather, both modes suffer from the lack of comfort required by most users. Indeed, the objective of a sustainable transport system is not to fully remove the private car, but to develop more multimodal and flexible alternatives to which the user can more easily switch. The road safety issue can be efficiently addressed by developing separated cycle-paths where bikers do not interact with cars. Also, the accessibility to the bicycle can be made easier through the BSS. Several cities are indeed going in this direction and are extending the network of their cycle-paths. Contracting with private firms is ongoing with the objective to provide smarter BSS.

In our analysis, we consider the upgrade of the infrastructure by providing dedicated bicycle lanes and making it possible to park the bicycle easily near the downtown area. In developing the dedicated bicycle lane, we reduce the space available to cars. So, the promotion of active modes induces a penalty to car users providing a stronger incentive for modal switch. We also compare with configurations where the number of lanes for cars remains unchanged when the dedicated lane is provided.

So, we extend our framework and consider that in addition to the existing modes, users can use the bicycle. In a first step, in subsection 5.1, we assume that the bicycle is used for the full trip (only a short walk is needed when arriving at the city-center). Then, in subsection 5.2 we allow for the combination of the bicycle with the bus.

5.1 Cycle-paths and the attractiveness of the bicycle

In the previous scenarios, the bicycle has not been used because we set the mode specific constant to a large value. This constant may reflect the non-popularity of the mode and/or that users dislike the lack of safety or comfort of the mode. To make the bicycle more attractive we need to set the corresponding specific parameter to a smaller value. Doing so allows us to easily switch between distinct scenarios without a substantial modification in the scripts generating the simulations.

We start with the case of mixed traffic where the bicycles share the same lanes with cars and buses.[4] In this case the mode-specific parameter is reduced but remains higher than those for the other modes since, without cycle-paths, the bicycle remains relatively unsafe. We ran all previous scenarios with these modifications and found that a small benefit is induced by the increased share of the bicycle. By comparison to the base-case, the user cost slightly decreases from 31 euros to 29.4 euros and the share of the bicycle is about 3% corresponding to empirical values observed in some cities (e.g., Kilani et al., 2022). In the case of free public transport, user cost decreases to 28.7 euros, while it decreases further by 11% when the gasoline prices increases. High frequency services yield again the highest impacts with an important modal share to public transport. Overall, with mixed traffic, we still have similar impacts to those described above, and the bicycle is used by a tiny share of the population.

The situation is different when cycle-paths are proposed and the users feel safe when choosing the bicycle. The set of scenarios we consider and the output of the simulations are reported in Table 3. In all the cases reported in this table, the bicycle is an available alternative and cycle-paths are added along the main road. Apart these modifications, Scenario S_1'' is the same as S_1', while S_2'' adds dedicated bus lanes and S_3'' adds free public transport. Scenario S_4'' is a combination of S_2'' and S_3''. Finally, S_5'' combines high frequency services with cycle-paths and dedicated bus lanes.

From Table 3, the modal shares corresponding to scenarios S_1'' to S_4'' show that the provision of cycle-paths, independently of the other policies, significantly increases bicycle ridership to about 37%. The increase in the popularity of the bicycle is induced by a switch from the private car (which share decreases to less than 50%) in the four scenarios, and from public transport in scenarios S_1'' and S_3''. That is, the bicycle can be a major substitute for the bus when there are no dedicated bus lanes, even under free public transport. The substitution prevails, but is less important, when buses have their dedicated lanes (scenarios S_2'' and S_4''). Free public transport (Scenarios S_3''*)* still have a mitigated and limited impact, as the share of public transport remains below 10%. Under all scenarios, the share of the walk is much smaller than that in the base-case, as cycle-paths are provided and service quality of public transport improves.

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[4] Notice that this first case is rather an improvement of the model, to include the bicycle, than a scenario examination.

Table 3. Promoting the bicycle through the development of cycle-paths

Scenarios		S_1	S_2	S_3	S_4	S_5
Mode shares (%)	Car	48.0	38.0	46.0	38.0	24.0
	Bus	8.0	20.0	9.0	20.0	50.0
	Bike	37.0	37.3	37.8	37.1	23.0
	Walk	6.0	4.0	6.2	4.5	3.0
User Cost (euros)	Ring 1	9.8	9.5	10.4	10.5	9.0
	Ring 2	20.9	21.6	19.9	21.7	12.6
	Ring 3	29.8	26.1	27.3	25.9	13.9
	All	22.3	20.7	21.0	20.4	12.6
CO_2 (kg/car)		5.81	5.05	5.38	5.25	2.96

S_1'': Adding bicycle lane; S_2'': Adding both bicycle lane and bus lane; S_3'' : Bicycle lane and free public transport; S_4'' : S_2 with free public transport; S_5'' : S_2 and high frequency bus services.

The best scenario, and probably the most expensive to implement, is S_5'' where dedicated bus lanes are accompanied with high frequency bus services. In this case, the share of the private car is particularly small (below 25%) while more than three agents among four use more environmentally friendly modes. By comparison to the base-case, and the first set of scenarios (Table 1), there is an important decrease in the use of the private cars (and walk) and, in parallel, a large increase in the share of the bicycle and public transport, removing the substitution identified in scenarios S_1'' to S_4''.

Notice that agents located at the three rings benefit from a user cost reduction by about one third compared to the base-case. The differences, however, are small for agents living in Ring 1, and large for agents living in Rings 2 and 3: from an average value of 31 euros (Table 2) to an average value of 21 euros (Table 3) for agents living in Ring 2; and, from an average value of 34 euros (Table 2) to an average value of 27 euros (Table 3) for agents living in Ring 3. Walk is always an option for agents in Ring 1, so they manage to remain near their minimum transport cost independently of the implemented scenario. Agents near the city-center are less sensitive to transport reforms.

Finally, and as shown in the last line in Table 3, CO_2 emissions follow the same sorting for the user cost and decline below 3 kg/car in the last scenario.

5.2 Trips combining bicycles and buses

In the examination of the last set of policies we take into account intermodal trips, by allowing agents to combine the bicycle and the bus. In this case, the agent uses the bicycle for a first trip from home to the selected station, then continues by riding the bus to the city center. The procedures used to select the station and the corresponding route follow the same approach as the one used above (when the agent walks to the station). This combination of two modes can be seen as a new mode that adds to the four existing ones and we denote it by "b −Bus". Intermodal trips are particularly important when bus services are not well accessible. In our model, this can be taken into account through the spacing between the stations. In the base-case, and all the other scenarios examined before, we have considered eight stations along the main road, so that each agent is located at less than six hundred meters from the nearest station, i.e., less than six minutes walk and this can be considered as a good accessibility to bus services. To compare with lower accessibility, we'll consider below some scenarios where the spacing between the stations is larger. More precisely, we'll set five stations instead, and refer to this case as "large spacing between the stations."

We consider a set of scenarios that extend some of those examined in Table 3 and take into account intermodal trips. Table 4 reports the results of these simulations. Scenario S_1''' adds intermodal transport (bicycle and bus) to the base-case. S_2''' then differs from S_1''' with a dedicated bus lane; S_3''' is S_1''' with large spacing between stations; S_4''' combines S_2''' with free public transport; S_5''' combines S_2''' with high frequency of bus services; and, S_6''' combines S_3''' with high frequency of bus services. The first three scenarios consider improvements in the infrastructure, and the last three ones consider improvements in public transport fares or operations.

By developing cycle-paths and letting the agents consider the combination of bicycles and buses, we obtain an equilibrium where 6% of the agents combine the bicycle and the bus and this mostly for users in Ring 2 and Ring 3. By comparison to S_1'' we see that intermodal transport does not attract walkers (users in Ring 1 are not impacted) but attracts users of the bus (a decrease from 8% to 6%) and users of the bicycle (a decrease from 38% to 35%), and to a lesser extent users of the private car (a decrease by only 1%). Of course, by comparison to the base-case the impacts are higher.

Always by comparison to Scenario S_1'', reported in Table 3, there is an overall decrease in the user cost, but this remains limited to agents living in Ring 2 and Ring 3. The user cost for agents in Ring 1 slightly increases because they do not switch to intermodal transport and suffer from longer wait time because there are more buses arriving to their stations without available space.

Table 4. Taking into account intermodal transport by allowing users to combine the bicycle and the bus (the "b −Bus" mode)

Scenarios		S_1'''	S_2'''	S_3'''	S_4'''	S_5'''	S_6'''
Mode shares	Car	47.0	37.0	37.5	35.0	22.0	22.9
(%)	Bus	6.0	15.0	4.6	15.7	36.0	25.2
	b-Bus	6.0	7.0	16.2	8.0	16.0	26.2
	Bike	35.0	36.0	35.9	36.0	23.0	23.5
	Walk	6.0	5.0	5.6	5.3	1.7	2.2
User Cost	Ring 1	10.9	10.0	9.4	11.1	9.1	9.5
(euros)	Ring 2	22.3	21.4	21.5	21.4	13.9	13.8
	Ring 3	32.4	27.1	26.4	26.5	13.0	13.3
	All	23.4	20.9	20.6	20.7	12.4	12.7
CO_2 (kg/car)		6.13	5.28	5.15	5.21	3.02	3.1

S_1''': Cycle-paths and users allowed to combine the bicycle and the bus; S_2''': $S_1'''$and dedicated bus-lane; S_3''': $S_1'''$and large spacing between bus stations (five stations instead of eight); S_4''': S_2''': and free public transport; S_5''': S_2''':and high frequency bus; S_6''': S_3''':and high frequency bus services.

With dedicated bus lane (Scenario S_2'''), the modal share of the bus significantly increases to 15% while the share of the private car decreases to 37%. The number of agents who combine the bicycle and the bus increases only slightly (6% to 7%). Under Scenario S_3''', the bus is not too accessible (large spacing between the stations) and we find a decrease in the number of agents that use only bus, but this decrease is more than compensated by the number of agents adopting intermodal transport (b −Bus mode). The shares of the other modes remain almost unchanged or slightly increase, by comparison to Scenario S_2'''. In this case we identify a clear complementarity between the bus and the bicycle, but the overall ridership of the bus remains almost the same (despite the smaller number of bus stations).

Free public transport can be effective when it is implemented with dedicated bus lanes (cf. Scenario S_4''', eight bus stations in this case), but brings only a small marginal impact. Indeed, the impacts from S_1''' to S_4''' are comparable and slightly higher than those obtained when moving from S_1''' to S_2'''. Similar comparison holds for the user costs, which always improves, particularly for agents in Ring 1 and Ring 2. As in the scenarios reported in Table 2 and Table 3, the development of dedicated lanes, combined with an increase in the frequency of the bus services, yields the best impacts reaching a user cost of about 12.5 euros.

The last scenario (S_6''') adds high frequency bus services in the case of large spacing between the stations. The obtained results confirm that bicycles can complement buses so that more than 50% of the agents use public transport, even when the accessibility to buses is limited. The last line in Table 4 shows that CO_2 emissions remain also comparable to those obtained without considering intermodal transport.

By comparing results reported in Table 3 and Table 4, it is not clear that the combination of the bicycle and the bus in our framework brings an important social benefit. Indeed, the user costs remain comparable and the modal switch to public transport slightly increases. The latter is probably the most important since the intermodal alternative increases the flexibility of (accessibility to) public transport and provides higher motivations for some users to switch. But this occurs here for users living away from the city center. It is clear, however, that in the absence of a good accessibility to public transport services, intermodal solutions involving bicycles (or possibly electric scooters) play an important role in keeping the ridership of public transport high.

The development of active modes produces a significant decrease in the user cost. Our simulations show that congestion level and emissions decrease because several users switch from the private car to public transport. A set of other simulations that have been conducted, but not reported here, confirm these main findings.

6 Conclusion

We have considered a microsimulation framework where a number of agents living in a monocentric city travel to their job locations in the morning rush-hour. There are four transport modes: private car, public transport, bicycle and walk. Users can adjust their departure times to reduce the schedule delay cost conditional on the desired arrival time.

Several configurations have been considered. The base-case scenario considers a representative situation where the private car is the dominant mode with more than 70% share. The improvement of public transport is then considered through the allocation of bus dedicated lanes and through the improvement of service frequencies. We then consider the development of dedicated cycle-paths and evaluate the impacts on user costs and emissions of greenhouse gases and fine particulates. The results reported in Table 4 show that the combination of the bicycle and the bus does not provide significant improvements for the three groups of users. This is because the travel speed between the two alternatives are not too different if we take into account the stop time of the bus at the station. For longer distances, users living at the outskirts, the car remains an attractive alternative, unless high frequency bus services are in place.

Our analysis shows that the bus and the bicycle are rather substitutes in dense areas, with modal switch between both modes being important. For both modes, the demand depends mainly on the availability of a dedicated lane. When we allow users to combine both modes, we do not observe complementarity unless the spacing between bus stations is large. Indeed, with few stations, in-vehicle travel time decreases (less stops) making the bus attractive, but the passengers have to walk longer distances to the station. When the bicycle alternative is available (in parallel to cycle-paths), the walk trip is replaced by the bicycle and the accessibility to the bus remains good and yields a complementarity between the two modes.

Overall, we find that most of the examined policies induce positive impacts, but the best scenarios highlight the importance of the provision of cycle-paths and dedicated bus lanes combined with a high frequency of the services. The iterative algorithm we have used to evaluate the equilibrium performs relatively well (convergence within fifty iterations), even if it is based on a simple heuristic.

Our main conclusions may seem contrasting the main conclusion of (David & Foucart, 2014). However, the differences stem from the settings considered in each case. Indeed, they model the problem as a game between users and a central operator and point out the importance that the central planner needs to consider credible policies, and this may raise some issues to implement unpopular actions when voting is important. In our analysis, we rather focus on welfare improving policies and not on their institutional implementation. More importantly, in their model, the dedicated bus lane does not necessarily cover all the network but only a part of it. More precisely, the share of the network where the two modes are separated smoothly varies between zero and one. In this case, it may be possible that increasing this share does not (locally) produce a positive impact on welfare. Our framework is quite different since, when adopted, the dedicated bus lane covers all the main roads. As we have discussed above, with respect to possible turn-around maneuvers, when the two modes share some important road sections, the benefit from a dedicated bus lane may vanish. So, definitely our findings are not in contradiction with (David & Foucart, 2014). A more in-depth study can focus on this specific point for a more comprehensive comparison.

The model considered in this analysis relies on several assumptions. The simplified geometry may be seen as a limitation, but from a methodological perspective it ensures an easier tracking of the impacts obtained under the distinct scenarios. Our approach is transparent and can be replicated to other cases, including urban areas with multiple business centers (cf., David & Kilani, 2022). The case of a homogeneous population (with respect to the value of time) can be relaxed to address more realistic situations. Indeed, heterogeneity, with respect to users preferences and the structure of vehicle fleets are possible and should yield more general results.

Similarly, the combination of several transport modes are considered through a simplified approach. Comprehensive problems of route choice for users of public transport or intermodal transport can be challenging and involve dynamic programming at the level of agents (cf., Hamdouch et al., 2011). Our framework is appropriate for the implementation and examination of such features.

The analysis conducted in this paper can be termed short-term analysis (or medium-term since users are allowed to change their transport modes) because the agents do not change the location of their homes and their jobs. A more general approach will allow each agent to reconsider its location when transport supply changes. We leave this extension for future research.

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