Evaluating the Benefits of Promoting Intermodality and Active Modes in Urban Transportation: A Microsimulation Approach

Souhir Bennaya and Moez Kilani

Abstract The objective of this chapter is to show how microsimulation can be used to study urban transportation problems, in particular those issues related to sustainable transport and innovations. A theoretical, though representative, geometry of an urban area with a set of concentric and radial roads is considered for the analysis. Microsimulation, which provides a precise description of traffic flows, is used to draw a detailed accounting of emissions of pollutant gases and fuel consumption. In the base-case situation, the private car is the main transport mode. We then consider alternative scenarios where users are allowed to switch to public transportation or biking. A combination of walking, biking, and public transportation is also allowed. Under this intermodal setting, we find that congestion level, fuel consumption, and emissions of pollutant gases decrease significantly (up to 30%).

Keywords Urban transport · Microscopic simulation · Emissions and congestion · Active mobility · Public transport · Intermodal transport · Sumo traffic simulator

1 Introduction

Researchers from multidisciplinary perspectives, including economics, the environment, and transportation science, have been deeply investigating the paramount importance of reducing the emissions of greenhouse gases (GHG), the emissions of fine particles, and the consumption of fossil fuels. These objectives can be met only if ambitious reforms are identified and implemented. For example, to reduce road congestion, which is one of the main external costs generated by road transport, attractive alternatives to private cars should be proposed to users (Srisakda et al., 2022; de Palma et al., 2022).

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Transport modeling and simulation have become valuable tools for planning the never-ending growth of the number of vehicles running in large urban areas. At the same time, the quality of simulation tools has improved significantly during the last decade. They became more accessible and reliable (Costeseque, 2013). The potential strength of traffic simulation has gained the attention of several researchers intending to study the dynamic adaptation of the existing infrastructure and its influence on traffic (Berdai, 2004). During the last 20 years, several transport simulations were conducted on several urban areas, mainly in developed countries. The macrosimulation approach was used by Leclercq (2002) to study traffic models. Appert and Santen (2002) emphasized road traffic modeling and employed a macroscopic simulation model by applying cellular automata. Guillotte et al. (2009) underlined the multimodal travel of the inhabitants of Quebec City simulation employing a mesoscopic simulation model. More recently, Kilani et al. (2022) utilized macroscopic simulation to develop a regional multimodal transport model in northern France to evaluate the impacts of free public transport and road pricing on congestion and pollution reduction.

Mobility currently accounts for extensive environmental, economic, and social concerns. Indeed, skyrocketing travel flows indicate infrastructure shortcomings, namely, roads. This also highlights the vital need for more sustainable mobility insights (Curiel-Esparza et al., 2016). The last decade witnessed a growing awareness of the substantial impact of intermodality and active mobility (AM), especially local walking and cycling practices in standing as relevant transportation modes in urban areas (Gebhardt et al., 2016).

These modes may serve as time and money savers, traffic attenuators, and overall carbon footprint reduction (Pini & Lavadinho, 2005). They also have health benefits and look convenient under particular situations, such as the COVID-19 pandemic (Loske, 2020). In fact, the modal shift from individual motorized transport to active modes was clearly observed in several countries, including North America (Shaheen et al., 2013), China (Shaheen et al., 2011), England (Midgley, 2011), and Australia (Share, 2011; Fishman et al., 2012, 2013).

AM (walking, cycling) is interconnected with intermodality insofar as these modes can efficiently complement public transportation. Related studies prove the effectiveness of improving and complementing public transport systems to make them more appealing (Weliwitiya et al., 2019). Thus, intermodal travel behavior plays a vital role in urban transportation systems. In other words, there could be feeders of the public transport network in underserved areas.

In this chapter, we are particularly interested in intermodal transport as the combination of public transport and active modes. This covers bike-sharing systems or bike parking systems located near bus stations. Despite the effectiveness and feasibility of this concept, studies related to intermodality remain very limited and generally follow a qualitative or descriptive analysis. On the other hand, studies based on analytical modeling or simulation are usually restricted to unimodal trips and do not consider possible combinations of two or several modes.

Recently, some studies were conducted on this line of research, but with a focus on freight transport (Willing et al., 2017; Gohari et al., 2022). Mode combinations in passenger transport were studied for some shared services. For example, Lorente

et al. (2022), defined a method for intermodal assignment by combining public transport and carpooling. As a matter of fact, they have presented a new approach for a key component, with the mobility concept seen as a set of services, named MaaS (Mobility as a Service), hence integrating carpooling and public transport as components of intermodal trips. In this study, the authors proved that the whole intermodal system works effectively. Furthermore, Baum et al. (2019) discuss the variant of a bike-sharing service and a nonshared taxi as an auxiliary transportation mode that takes over public transportation networks, including them only as the first or last step of the trip (Last Mile Mobility). Their approach is to integrate public transportation along with auxiliary modes.

The results of these studies are very extensive and broad due to the complexity of this type of transport model. It is also worth mentioning that most of them integrate intramodality and are limited to macroscopic and mesoscopic simulations or theoretical studies. Therefore, our field of research focused on the study of effective methods to combine adequate public transportation systems and soft mobility.

This chapter will focus on studying the main stages of constructing a microsimulation transport model for a medium-sized city as a first step. In fact, the microsimulation model refers to a representation at the level of the agent with a fine description of the infrastructure and the interaction between the agents. For example, Fig. 1b below illustrates how the intersection details have been taken into account. On the one hand, simulation models at the urban scale often use macrosimulation and/or mesoscale simulation models to simplify (supply and demand) data processing and the implementation of the model (Axhausen et al., 2016). For example, intersections are oversimplified and (in general) are not explicitly taken into account. On the other hand, microsimulation requires too-refined and specific data, making it
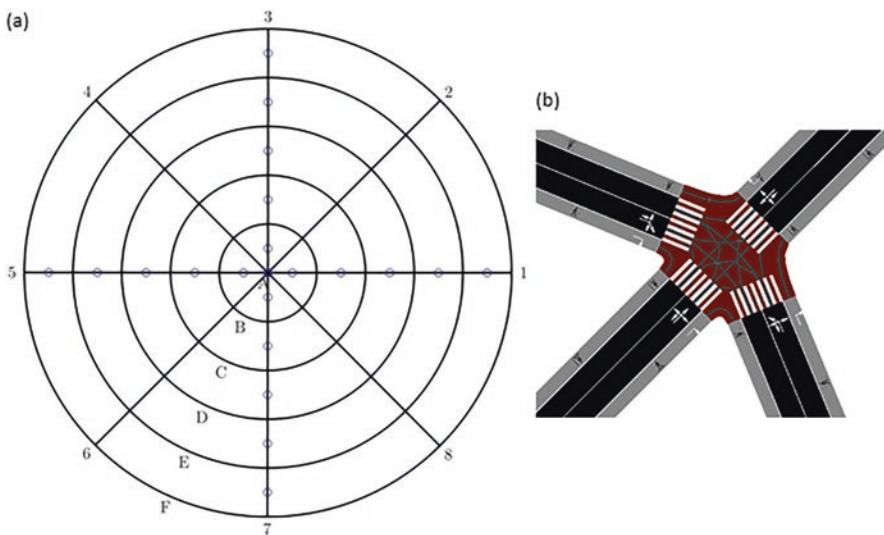

Fig. 1 Features of the network. (**a**) The network composed of several circumferential and radial roads. (**b**) An example of an intersection with its connections (Sumo framework)

difficult to generate demand and, more precisely, in the construction of origin-destination matrices (OD matrices). The benefit of this approach is that we produce a detailed description of all the movements of individuals, vehicles, and networks (positions, speeds, and accelerations).

After setting up the transport model, we will evaluate the effect of a modal shift toward sustainable mobility while integrating an intermodal system. We are particularly interested in the impacts on road congestion, pollution levels, and fuel consumption. Two scenarios of intermodal transport will be considered. In the first scenario, we model the combination of walking and public transport; in the second scenario, we consider the combination of cycling and public transport. For the simulation itself, we use the Sumo Traffic Simulator,[1] a microsimulation framework based on a car-following model (Lopez et al., 2018).

Comprehensive modeling of intermodal transport, where the chaining of transport mode is an endogenous choice, remains problematic for realistic models. This chapter reports these difficulties and proposes a modeling methodology to account for multimodal transport. The approach in this chapter can be replicated for other cases and can be conducted to develop realistic case studies.

The chapter is organized as follows. Section 2 describes the infrastructure and how demand has been produced. It also gives an overview of the modeling approach. Section 3 reports the simulation output for the base-case scenario and compares it with other scenarios where alternatives to the private car are made available. The last section concludes.

Note that all tables in this chapter report values produced by our simulations, and all the figures are also our own production.

2 The Transport Model

In this section, we describe the modeling framework and how the simulation framework is constructed. The used network is described in Sect. 2.1. The demand for trips is discussed in Sect. 2.2, and the workflow to conduct the simulation is described in Sect. 2.3.

2.1 Network

Recently, a number of empirical studies have stated that it is difficult to include the real dimension of a city, but we can work with simpler models that remain consistent with real-world cases.[2] A universal topology for all cities is difficult to provide,

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[1] An open-source traffic simulation package developed at the Institute of Transportation Research at the German Aerospace Center https://www.eclipse.org/sumo/.

[2] https://blogs.worldbank.org/sustainablecities/how-do-we-define-cities-towns-and-rural areas.

but several cities in the world can be described as simple patterns based on road geometries. The Manhattan example, with a set of perpendicular and parallel roads, is usually considered a good representation of North American cities. However, this geometry does not reflect the structure of European cities, which were historically developed around rivers or main paths to facilitate trade and transportation. In this case, the city center is surrounded by a set of circumferential roads, which expand to the outskirt, and a set of radial roads that connect the suburban area to the city center. The model we will develop below is based on a methodology that can address any urban form, but to keep our discussion simple, we focus on circular cities.

The example we use is based on the structure of the city of Mons in Belgium. Its area is 146.6 km^2 with a radius of $r = 4.83$ km^2. The road network of this city is illustrated in Fig. 1a. The city center is denoted by A, and the five circumferential roads are labeled B, C, D, E, and F. There are eight (half) radial roads labeled 1 to 8, respectively. The circumferential roads are equidistant. With this labeling, it is straightforward to locate each node on the network as a combination of a circumferential and a radial road. For example, "B3" is the intersection between circumferential road B and radial road 3. Road links connect two nodes. For example, road link "C3D3" connects node "C3" to node "D3".

This network represents the main road axis in the city. Secondary roads are not directly considered. The network has been edited to add sidewalks, cycle paths, and crosswalks that are of first importance in modeling walker behavior. Indeed, "walk" is important to take into account public transport, which involves a transport step from home to the station of departure and another step from the arrival station to the destination. To conveniently model walk patterns, users should be able to change from a sidewalk to the opposite one, and this generally occurs at intersections. In practice, it adds to the complexity of the intersection.

Indeed, as shown in Fig. 1b several connections are required to allow each vehicle to leave the edge it is exiting and enter the next edge in its route. These connections add to crossings available for walkers, making traffic management particularly complex at the intersection level. At this step, we need to remove inconsistencies that may prevent walkers from performing realistic movements or may lead to collisions between vehicles and/or walkers.

This is one of the most challenging steps in setting up the network. If we have taken into account its initial state, this leads to unrealistic traffic, and teleportation problems will be created. To avoid teleportation during the simulation, we solved all connection-related inconsistencies. We proceed in two steps. In the first step, only private cars, buses, and walking are considered. In the second step, we add biking and update the main radial roads with dedicated cycle paths.

Access points (i.e., stations) should be added to the network to account for public transport. A public transport user should walk to the station's exact location, wait for the bus line, and ride when the bus arrives. He or she then leaves the bus when he or she arrives at a station near the destination and walks to the destination. The design of a bus transport system is an elaborate process that includes the design of the lines, the construction of timetables for each line, and the assignment of buses and drivers to perform the desired public transport service. Since we mainly focus

on an illustration of these steps, we have implemented only two bus lines that run on two radial axes. The first ensures a round trip between the north and the south of the city (along edges 3 and 7 in Fig. 1a), and the second ensures a round trip between the city's west and east sides (along edges 1 and 5 in Fig. 1a). When using public transport, users in even-numbered edges need to walk through sidewalks and cross intersections to reach the station available on the nearest edge. This is also the case for users located on circumferential roads.

2.2 The Demand

For the construction of the OD matrices, we applied a gravitational-like model that we combined with a monocentric city shape. Activities are mainly located near the city center, while residential areas are in suburban areas. As we move away from the city center, the frequency of business activities decreases while the number of home locations increases. As a result, most traffic flows induced by home-to-work trips are realistically directed toward the city center (inward direction). The gravitational feature allows us to produce more trips on closer edges than far away ones.

The model involves three groups of trips. To easily refer to the trips, we used trip coding for the users. Trips with a simple commute to work are referred to as HWs. Trips with HW1 W2 codes refer to users with an intermediate trip, where W1 is the workplace of the first person and W2 is the workplace of the car driver. Home-School-Work (HSW) is specified for journeys having schools as an intermediate trip. Of course, several other trips can be considered. Specifically, multimember households with parents and children can have multiple trips involving chaining, for example, when parents need to take their children to school (HSW) or when couples want to drive one another to work (HW1 W2).

The transportation modes considered in this model are car, walking, bicycle, and public transport (bus). For cars, only two car types have been considered: diesel and gasoline. The European norm "6" has been chosen as an energetic class. For public transport, we designed four bus flows on the four main axes of the city. Each flow sticks to its corresponding line within a 4-h period and with a 15 min/20 min time frequency. Bus lines cover the north–south and east–west axes, axes 1, 3, 5 and 7 in Fig. 1a. Bus users may obtain the advantage of two types of routes: either one bus route for only one line user (e.g., origin at B1A1 and destination at E5F5) or two bus routes for two line users (e.g., origin at D5C5 and destination at D7E7).

Figure 2 depicts the multimodal transport with cars, buses, and pedestrians sharing the roads. The combination of these modes is also considered since some trips involve walking and public transport. At this station, some walkers board or alight from the bus.
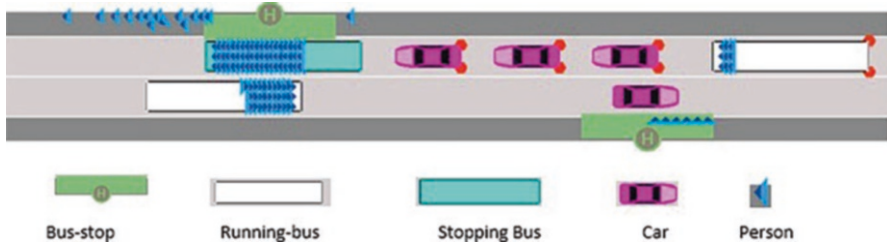
Fig. 2 Dynamics of cars and buses driving. (Source: Sumo framework, Author's calculation)

2.3 Overview of the Simulation Workflow

Several steps are needed to end up with a comprehensive transport model. An overview of the corresponding workflow is given in Fig. 3. The construction of the simulation framework starts with data collection and organization and ends with examining policy scenarios.

The basis of the model is the network, including the construction of public transport services and demand for trips. The network needs to include the features required by all transport modes, not only cars. This is particularly important in microsimulation. With more aggregate approaches (macrosimulation), several of these details are ignored or oversimplified. To generate the OD matrices, random sampling households and work locations were used. As explained above, these samplings' distribution assumed that the work locations' frequency increases near the city center. In contrast, the frequency of home locations increases as we move away from the city center. Immediately after generating the demand and network, each user can select a departure time along with a route for his trip. Nevertheless, as the common goal for all network users is minimizing traveling costs, they may also have the choice of selecting the shortest distance routes. With a large number of users, this generally leads to hyper congestion (severe level of congestion)[3] in the edges located in the city center. As several users would gain the ability to improve and shorten their travel period by employing alternative routes, this does not stand as a traffic equilibrium. Indeed, traffic equilibrium is achieved when all users cannot improve their situation by unilaterally modifying their choices. Therefore, an equilibrium is approached when some users improve their situation by avoiding the city center links, which are given by the shortest routes. In this case, they may use the outside city lanes to reduce travel time.

Individuals overvaluing time may change routes to improve their satisfaction (increase utility or reduce generalized cost). Thus, they would accomplish a time-gaining trip by longer albeit less congested routes, therefore achieving balance. This

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[3] The different levels of congestion are explained in the Fundamental Diagram of Traffic Flow (Li & Zhang, 2011).
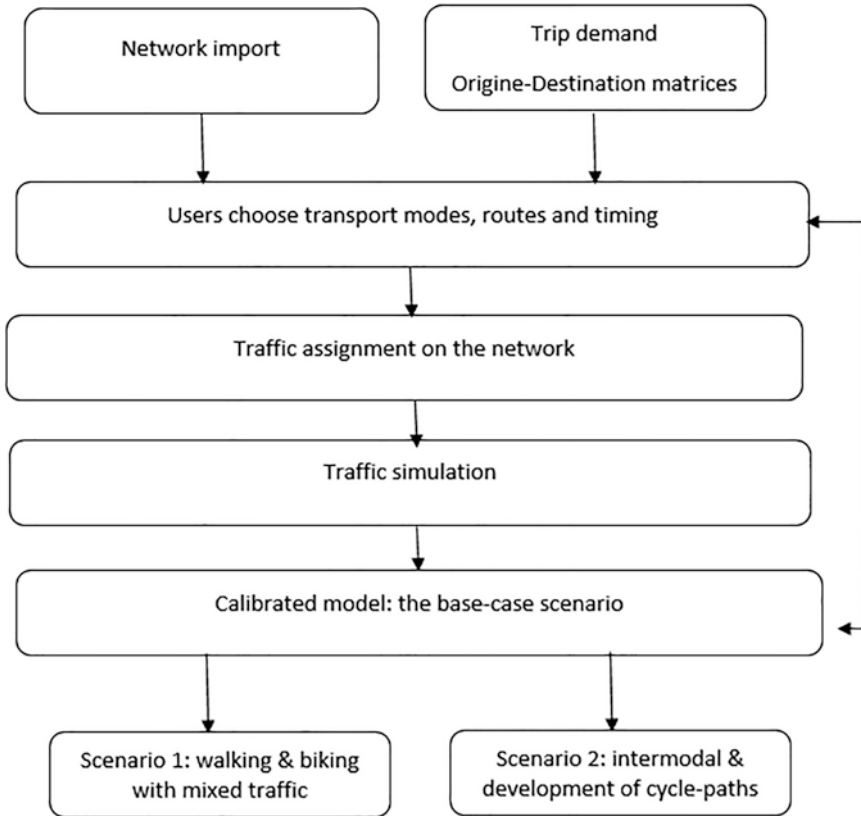
Fig. 3 The main steps in the development of the transport model

step should be repeated until the model reaches a stationary situation. The obtained model can then be used to evaluate transport policies.

This research will serve to measure the modal shift impact on active mobility as a first scenario and intermodality as a second scenario. We are interested in evaluating the impact of each scenario on congestion and pollution.

3 Transport Flows and Intermodality

In this section, a transport model for an average population size will be developed, and the amount of pollutant gas emissions and the level of congestion during the morning rush hour will be computed. Then, this initial situation will be compared with the results of a simulation where a modal choice that takes into account an intermodal choice (bike/walk and bus) is examined.

3.1 The Base-Case Scenario

Regarding our illustration, the first allocation hovers around investigating the congestion level, pollution, and energy consumption of 10,000 car trips over 4 h. Since we have a low traffic flow, network users will employ the shortest routes to minimize travel costs. In this simulation, the average travel speed is 36 km/h for the whole period.[4] Travel time consists of approximately 8 min/veh.

The simulation of daily traffic produces all statistics needed to compute fuel consumption for each car and the emissions of pollutant gases it produces. It then becomes straightforward to use models such as COPERT (COmputer Program to calculate Emission Road Transport) to evaluate environmental and energy impacts. After scaling the population size, we check that these values are consistent with those reported in the World Bank's data.[5] There are three GHGs (CO, CO_2, and HC) and two fine particle groups (PM and NO). These pollutants are measured in kilograms (kg), except for carbon dioxide (CO_2), which is produced in large quantities and measured in tons (t). Daily emissions of CO_2 are equal to 12 t, and emissions of carbon monoxide (CO) and hydrocarbon (HC) are measured in kilograms (their daily emissions are 184 kg and 3 kg, respectively). The emissions of fine particulates PMx are 0.51 kg, and those of NOx are 12 kg. The same model evaluates fuel consumption to approximately 5000 L. These values will be reported again in Tables 1 and 2, when we will be comparing the base-case situation with two alternative scenarios.

The distribution of trip distances produced by the calibrated model is given in Fig. 4. It is important to note that the share of shorter trips (less than 3 km) is higher than 15%, confirming that active modes (i.e., walking or biking) are attractive to many users, as reported in Schweizer (2008).

3.2 Public Transport Accessed by Walk

To reduce pollution and traffic density levels, the development of an intermodal system can be a good alternative. In our case, the intermodal system combines walking with public transport (buses). For each user performing such an intermodal trip, we need to find the station she uses to board the bus and the station she uses to alight.

We solve this problem by choosing the station near the home location (for boarding) and the station near the destination (for alighting). In a more general context, this choice may be influenced by crowding in vehicles and reliability, but to keep our analysis simple, we disregard these features in this model. To introduce intermodality, we assume that 30% of trips switch from cars to a combination of walking and public transport. For each of these trips, we find the corresponding bus line as
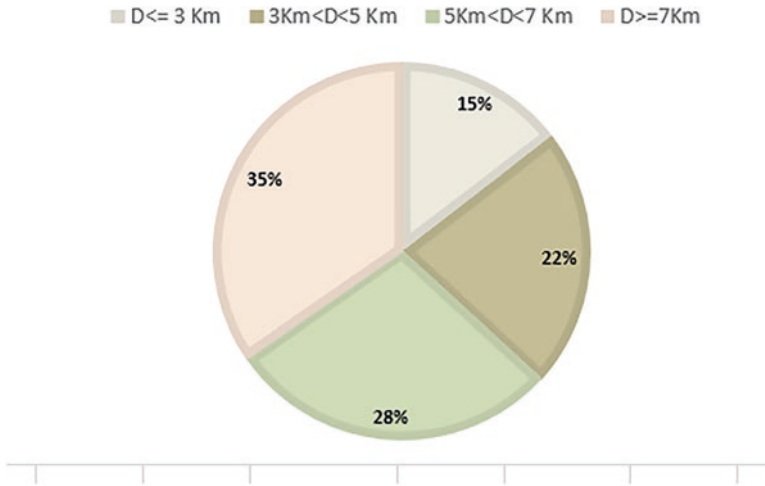

Fig. 4 Distribution of trips with respect to travel distances (produced by the model)

well as the boarding and alighting stations. AM (biking and walking) is particularly convenient for many urban trips when travel distance is short. AM reduces (monetary) user costs and produces much less congestion and pollution. To evaluate the impact of this change, we allow some users to switch to bikes or walk. We model this switch through a probabilistic model where walking and biking are more likely when the trip distance is smaller. Indeed, in the base-case scenario, 37% of trips are less than five kilometers long. AM are efficient alternatives for users making these trips. We adopt a simple choice model to evaluate the impact of a modal switch to bike or walk. Let us consider a total of n trips. We assume that the probability, denoted P_i, that trip $i = 1, \ldots, n$ becomes intermodal depends on the trip distance, denoted d_i, through the following logistic expression:

$$P_i = \frac{1}{1 + ae^{-\mu(d_i - d_0)}}$$

where d_0 is a parameter that corresponds to the threshold where switching to bike/walk becomes less probable, μ *is* a parameter that controls how P_i changes around d_0 and a *is* a positive parameter.

Note that as the value of d_i decreases, the value of P_i decreases quickly and vice versa. By adjusting parameters a and d_0, we can cover a large variety of possible cases to make intermodal transport more or less likely. A similar mode choice functional form will be adopted when intermodal trips involving biking are considered.

The simulation output shows that the average travel speed has decreased from 36 to 33 km/h. The average travel time decreases by 30%, from 8 to 5.6 min. This relief in congestion level is the consequence of the decrease in the network's running cars. From the values reported in Table 1, the quantity of GHG emissions, including CO_2,

Table 1 Emissions of pollutant gases and fuel consumption (output of the model)

Scenario	CO (kg)	CO_2 (tons)	HC (kg)	PMx (kg)	NOx (kg)	Fuel (kL)
Base-case	184	12	3	0.51	12	5
Walk-bus	126	8.4	1.6	0.45	10.74	3.6
Impacts in %	−32	−30	−47	−12	−10.5	−28

has witnessed a significant decrease and this impact is produced by modal shift. The magnitude of the decrease ranges from 30% (for CO_2) to 47% (for HC). This confirms that there is a clear benefit from the reduction in private car usage. For other pollutants (PMx and NOx), the impacts have the same sign with relatively smaller values. Fuel consumption, which is the source of all these emissions, decreases by 28%.

3.3   Biking as a Possible Alternative

We consider two situations. In the first one, traffic is mixed so that bikers share roads with cars and buses over the entire network. In the second one, cycle paths are developed along the main radial axes. This allows bikers to be safer but increases the complexity of the connections in the network. We use the same logistic expression as in the previous section to generate a modal switch to biking and walking.

3.3.1   Mixed Traffic

As discussed above, with mixed traffic, car usage for short journeys is expensive, and many users may prefer walking or biking. It is also a source of high external costs. In this simulation, we evaluate the impact of a modal shift toward active modes. As a result of the logit model we introduced above, some individuals with short trips will move to walking or cycling. We have also included the bicycle in the intermodal system. The user will likely switch to an intermodal trip involving walking when the distance between the home location and the nearest bus station is less than half a kilometer. With bikes, intermodal trips remain likely for longer distances between the home location and the nearest stations. Figure 5 illustrates a relatively complex morning commute trip. The user bikes to the nearest bus station, and this entails a short walk from the bike-sharing station to the bus station. She boards the bus to the station near the destination and then briefly walks to the bike-sharing station to take a bike to the office location (note that we may add a bike-sharing station near the office).

To evaluate the impacts of intermodal transport, we assume that a combination of cycling and buses replaces 30% of the trips initially made by private cars. We assume that 10% of trips, initially made by private cars, are made by a combination of walking and buses. Additionally, 8% of trips are made by bike and 5% by

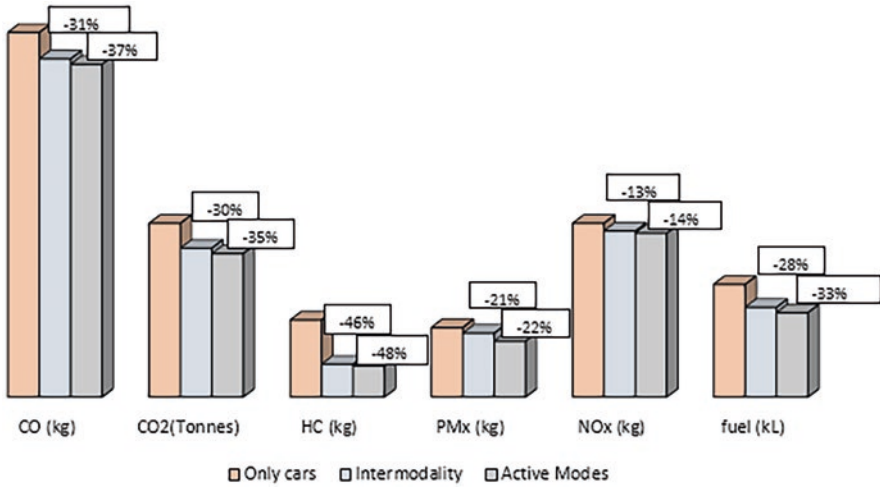**Fig. 5** Intermodality and bike sharing system

Fig. 6 Emissions of pollutant gases and fuel consumption (output of the model)

walking. Walking is under-considered in this model. Indeed, it is so because walking does not produce (or almost) external costs and only needs a very limited infrastructure supply. Therefore, it is mainly added for illustrative purposes.

The output of the simulations shows that with more trips made by bike and walk, the levels of congestion and emissions of pollutant gases decrease. The average speed during the simulation period decreases from 36 to 28 km/h, but this is spelled out by the bicycle's low speed compared to the car and the moderate congestion level in the base-case scenario. This travel speed decrease leads to a slight increase in the average travel time from 8 to 10 min. At the same time, if we focus on cars only, the average travel time decreases from 8 to 5 min, which implies traffic congestion decline.

With respect to emissions, Fig. 6 shows that integrating cycling and walking into the daily commute has a positive effect on pollution. As depicted, most pollutant gases have decreased from approximately 30% to 35%. For example, the CO_2 emissions decreased from 12 to 7.8 t instead of 8.4 t, and the CO emissions decreased from 184 to 117 kg instead of 126 kg. Including active modes in daily trips and intermodality systems also has a significant impact on fuel consumption. We achieved a drop of over 5% compared to the second simulation (from 5000 to 3330 L instead of 3600 L), as indicated in Fig. 6.

3.3.2 Cycle Paths

We upgrade the road network to add cycle paths on the north–south and east–west axes. The purpose of these new lanes is to provide bikers with separate and safe travel conditions. In this case, the cyclists are not allowed to share links with cars in the presence of cycle tracks. As shown in Fig. 7, however, traffic remains mixed when no cycle tracks are available. Running the simulation with the new network and the same traffic flows as the last simulation, we have achieved a significant effect on road safety for cyclists and other network users. The results show that cycle paths also have positive effects on road congestion. The average travel time decreased from 5 min under mixed traffic to 4.6 min.

Moreover, Table 2 reports the results of the four simulations. As indicated in the Table 2, it was found that emissions have been reduced to approximately 45% instead of 35%. Likewise, a 41% reduction in fuel consumption. We can then conclude that AM and intermodal systems as well as bicycle lanes have a significantly positive effect on fossil energy consumption, pollution, and traffic congestion.
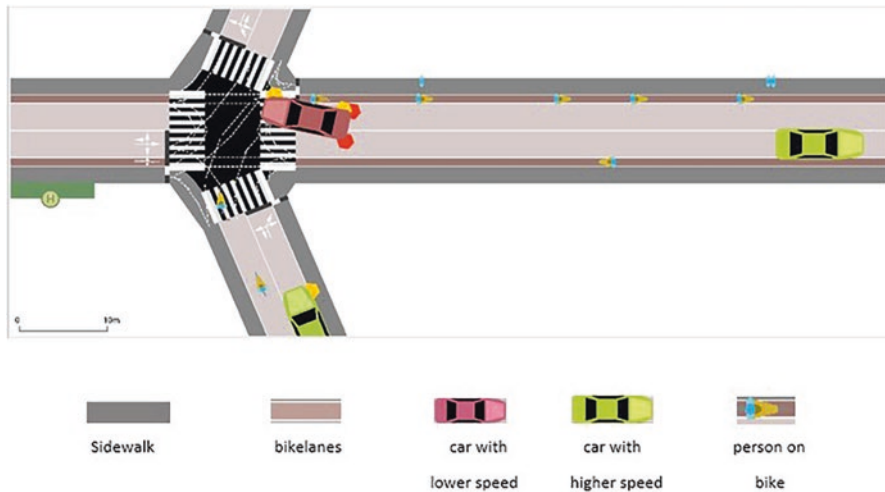

Fig. 7 Dynamic traffic with cycle paths

Table 2 Emissions of pollutant gases and fuel consumption (output of the model, update of Table 1)

Scenario	CO (kg)	CO_2 (tons)	HC (kg)	PMx (kg)	NOx (kg)	Fuel (kL)
Base-case	184	12	3	0.51	12	5
Intermodality impacts in %	−32	−30	−47	−12	−10.5	−28
Active mobility impacts in %	−36	−35	−48	−22	−13	−33.4
Cycle paths impacts in %	−37.5	−43.2	−55.6	−27.4	−15.4	−41.6

4 Conclusion

We have developed a microsimulation transport model for a representative city, and we have used it to discuss how the combination of several transport modes, including active modes, impacts energy consumption, traffic flows, and emissions of pollutant gases. We used the Sumo simulation engine to compute each vehicle's travel speed, acceleration, and location at each time t of the rush hour. The development of such a model has indisputable advantages for the planning of urban transport and the examination of distinct reforms of mobility. We have examined scenarios and focused on the issues of global warming and the limitation of fossil fuel energy consumption.

According to this study, the intermodality system was found to blend public transport with active modes. As a quantitative result, when we reduce the usage of private cars by 30%, through a modal switch toward a combination of walking and public transport, we obtain a significant decrease in the emissions of pollutant gases (at a comparable proportion to this modal share switch). The integration of another intermodal system that includes biking and buses, as well as cycling and walking as an alternative for short trips, has resulted in an increase of 35% instead of 30% in the decline of congestion. The results can be enhanced by 45% if we incorporate cycle paths in the city's main axes. We have also obtained another interesting result. For example, a reduction of one-third in CO_2 emissions, GHG, and even the rush hour gets shorter. In addition, bike lanes have shown a significant positive impact on road safety. It can be deduced that this has led to a reduction in external costs. Our methodology can be replicated for other case studies, including real cities of distinct geometries. All the modeling steps are transparent and based on data now made available for several cities. The use of microsimulation is the main contribution of our analysis. As shown in the output of the simulation, we trace back all the events at a very detailed level. This approach (microsimulation) is now limited to cities with less than 100,000 inhabitants, but more ambitious applications based on microsimulation will be possible in the near future.

This model may be improved in several directions. In particular, a more sophisticated combination of transport modes can be considered. These modes can include parking areas used by those who combine private cars and public transport modes. We may also extend the framework to consider user activities and how they are scheduled during the day and with respect to the dynamics of traffic flows. For example, one user may consider shopping activity in the morning (and not late in the afternoon) to avoid severe congestion. Updating the modeling in this direction requires an elaborate decision model describing how users choose among the several available alternatives and modes. We leave this task for future research.

At the same time, the model can be employed to examine other policy scenarios. Infrastructure upgrading can be considered through the development of dedicated cycle paths, for example. Additionally, it can be used to investigate the increase in the market share of electric vehicles. Electric vehicles (or bikes) can be examined through the deployment of solar panel barriers that provide clean energy sources.

Modeling the electric grid can be considered an extension module that connects vehicle consumption to electric production units to assess these solutions' overall energy and financial accounts.

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