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Estimation of the Impact of Traveler Information Apps on Urban Air Quality Improvement

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ABSTRACT

With the rapid growth of vehicle population and vehicle miles traveled, automobile emission has become a severe issue in the metropolitan cities of China. There are policies that concentrate on the management of emission sources. However, improving the operation of the transportation system through apps on mobile devices, especially navigation apps, may have a unique role in promoting urban air quality. Real-time traveler information can not only help travelers avoid traffic congestion, but also advise them to adjust their departure time, mode, or route, or even to cancel trips. Will such changes in personal travel patterns have a significant impact in decreasing emissions? If so, to what extent will they impact urban air quality? The aim of this study is to determine how urban traffic emission is affected by the use of navigation apps. With this work, we attempt to answer the question of whether the real-time traffic information provided by navigation apps can help to improve urban air quality. Some of these findings may provide references for the formulation of urban traffic and environmental policies.

1. Introduction

The transportation sector plays a vital role in every nation's economy. With the rapid development of China's economy, there has been a boom in road transportation, which is one of the largest sources of air pollution. Since the contradictions between the rapid growth in the number of vehicles and the limited transportation infrastructure resources are increasingly serious, many cities—and particularly metropolises—are facing traffic congestion and severe air pollution. These issues will result in huge economic losses to society and will restrict the sustainable development of these cities [1,2]. As an effective approach to solve urban traffic problems, intelligent transportation systems (ITSs) improve traffic system efficiency and air quality to a certain degree [3].

With the development of information communications technology (ICT) and the popularity of smart phones, traveler information apps are widely used in ITS [4–6]. These apps include electronic maps, navigation aids, parking guidance, and more. Among the navigation apps that are available in China, the most popular are Auto Navi Map and Baidu Map. Travelers can obtain a great deal of information through apps on their mobile devices, allowing them to know the current enroute (or even pre-trip) traffic conditions on the roads ahead. As a result, travel plans (e.g., travel mode, departure time, and travel route) can be adjusted to increase travel efficiency. Therefore, the potential capacity of the whole network can be better utilized and fuel consumption can be saved; emissions can also be reduced. In summary, the environmental benefits of traveler information apps are a key topic to be explored both now and in the near future. However, little research is available on the influence of traffic information on urban air quality. Although abundant research exists on the impact of traffic information on urban traffic, most of these studies still focus on traditional traffic information-dissemination approaches, such as radio, television, variable message signs, and Internet websites. However, such approaches are not the best way to acquire real-time traffic information, especially during trips. In the past two or three years, the use of apps to acquire traffic information has been popularized and promoted. However, little research exists on this kind of real-time information release, and even less on its environmental benefits.

Using multimethod modeling, a traveler-behavior model, a traffic simulation model, and an emissions model were integrated through the AnyLogic simulation platform and the MOVES (short

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for Motor Vehicle Emission Simulator) emission model. An agent-based model (ABM) was built to simulate travelers' behavior under real-time traffic information provided by navigation apps. The traffic model simulates the agents' behaviors within the network, and the emission model calculates the emission inventories at the project level. This study focuses on the relationship between traveler's behaviors and environmental benefits, and can provide a reference for the formation of urban traffic policies.

2. Methods

2.1. Model summary

A comprehensive model combining traveler behavior prediction, traffic simulation, and emission calculation was developed in order to analyze the environmental performance of traveler information apps on a dynamic space-time scale. Fig. 1 presents the schematic of the comprehensive model. First, we built an ABM of traveler behavior, considering the impact of traffic information. We then built a microscopic traffic simulation model to simulate changes in trip production, trip attraction, distribution, model split, and traffic assignment, as influenced by diverse travelers' behavior. The data of each vehicle (e.g., position, speed, and accelerated speed at each time stamp) were collected and stored in a database as the input of the next step. Finally, we calculated the quantities of several pollutants using a project-level emissions model.

For this study, the AnyLogic simulation platform and the MOVES emission model were chosen to build the comprehensive model. The theoretical basis of AnyLogic is complex system theory; this platform supports three modeling methods in any combination: system dynamics (SD), ABMs, and discrete-event models (DEMs) [7,8]. In our model, an ABM and a DEM were combined to simulate travelers' behavior and traffic operation, respectively—a combination that is difficult to establish using traditional traffic simulation software. This innovation brings the simulation results quite close to reality. The microscopic emission model was built using the US Environmental Protection Agency (EPA)'s MOVES model, which is an advanced motor vehicle emission simulator that is used around the world.

2.2. Traveler-behavior modeling

ABM provides an effective method of simulating behavior by building the whole system from the bottom up. ABM regards each entity in the system as an agent, and attempts to describe the system in terms of the behavior and interactions of agents. Compared with the traditional aggregate model, which simulates a system from the top down, ABM carries the advantages of being closer to reality and having greater efficiency, maneuverability, and portability [7–9].

AnyLogic was used to develop an ABM of traveler behaviors. The process of developing the ABM comprised three main steps. First, the agents—that is, the objects of the simulation—were chosen. Second, the behavior of the agents was defined. Complex behaviors, including dynamically changing departure times, travel modes, and routes, can be simulated by the ABM of travelers, in addition to basic attributes (e.g., gender, age, and probability of using apps to obtain traffic information) and driving attributes (e.g., preferred speed, maximum acceleration, maximum deceleration, and frequency of changing lanes). Finally, the agents were put into the simulation environment and allowed to interact with each other and the environment. Thus, the presentation of the simulation is a combination of many agents' behaviors [7,8].

The belief–desire–intention (BDI) agent model is an event-driven execution model. Taking the BDI model as a reference [10–12], environmental and traffic facilities were set as the *belief* of the traveler. The destination arrival was set as the *desire* of the traveler, and the *intention* of the traveler comprised behaviors, such as searching for an optimal route, perceiving other vehicles, changing lanes, avoiding, overtaking, waiting, and so on. At the beginning of each simulation step, the traveler agent chooses certain behaviors from the *intention* set as the activities in the next step, as presented in Fig. 2.

2.3. Traffic simulation modeling

A newly added software library in AnyLogic 8, the Road Traffic Library, allows modelers to build professional traffic simulation models [13]. Compared with other traffic simulation software, AnyLogic has an open system architecture and compatibility with

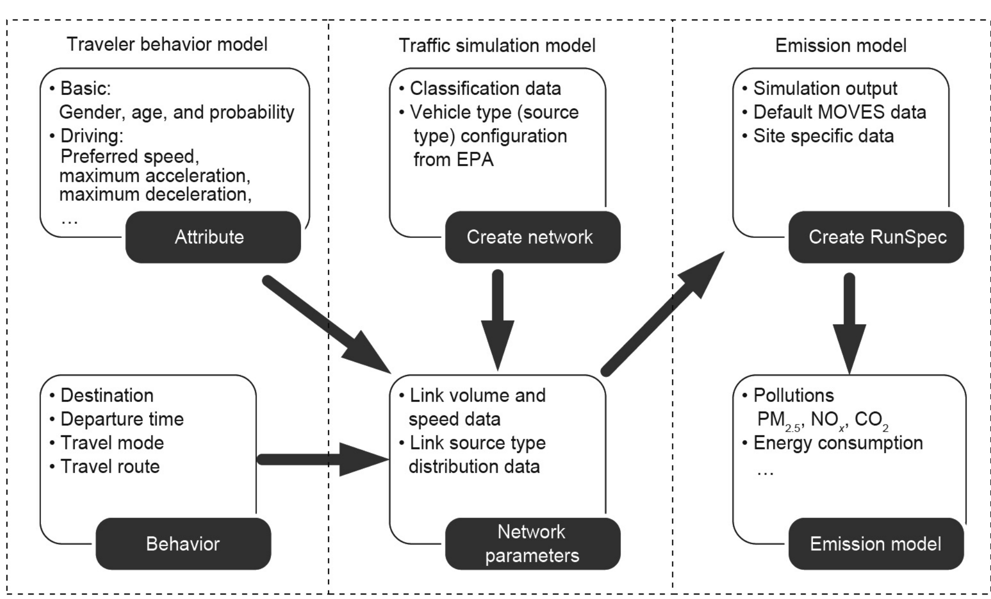

Fig. 1. Schematic of the comprehensive model. RunSpec: run specification.

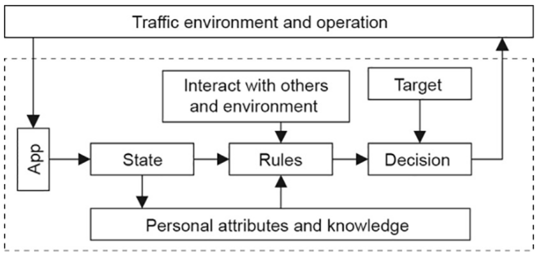

Fig. 2. Schematic of the traveler agent.

other software and applets, thus providing greater flexibility for traffic simulation modeling [7,8,13–15].

Traffic simulation with AnyLogic generally comprises four parts: environment modeling, traffic flow defining, running the simulation, and result analysis. The aim of environment modeling is to provide the necessary simulation environment for the agents. Environment objects were constructed by defining them graphically, adding corresponding objects, and setting up animation properties. Commonly used blocks included Road, Intersection, Stop Line, and Parking Lot [13,14].

A traveler's driving behaviors are a series of traffic-related activities that occur during the process of traveling, and which are affected by environmental, physiological, and psychological factors. Thus, the activities of the vehicles were defined in a flowchart style by dragging the objects from the Road Traffic Library stencil, setting properties, and connecting objects in a timed sequence. In the run time, vehicles exist within the defined environment and move according to simulated physical rules. The commonly used blocks to simulate vehicle behavior included: Car Source, Car Dispose, and Car Go To. In addition to these modules, we used Traffic Light and Road Network Descriptor [13,14].

2.4. Emission modeling

The MOVES model is used to create emission factors or emission inventories for both on-road motor vehicles and non-road equipment [16]. MOVES can be used to estimate national-level, state-level, and county-level inventories of critical air pollutants, greenhouse gas emissions, and certain mobile-source air toxins from vehicles. The MOVES model is different from previous US EPA mobile-source emission models in that it was deliberately designed to work with databases that allow and facilitate the import of data specific to a user's unique need. The MOVES model includes a "default" database that summarizes relevant emission information for the entire United States. The data for this database come from many sources, including US EPA research studies, US Census Bureau vehicle surveys, Federal Highway Administration travel data, and other federal, state, local, industry, and academic sources [17].

The most current version is MOVES2014a, which was released at the end of 2015 [16]. In this version, the emission factor has been further adjusted and enriched, and the result of calculations is more accurate. Fig. 3 shows the emission estimation process in MOVES. The MOVES model has four central parts: the total activity generator (TAG), operating mode distribution generator (OMDG), source bin distribution generator (SBDG), and emission calculator (EC) [18].

The formulation of emission calculation in the EC is as follows:

$$\mathrm{TE}_{\text{process, source type}} = \left(\sum \mathrm{ER}_{\text{process, bin}} \times \mathrm{AC}_{\text{bin}}\right) \times \mathrm{AJ}_{\text{process}} \quad (1)$$

where TE is the total quantity of emission; process represents the emission process (e.g., running exhaust, starting exhaust, evaporation, and so on); bin represents the speed bin of the source type; ER is the emission rate; AC represents the activity; and AJ is the adjustment factor [17].

The data and data manager are different when using MOVES to estimate inventories at different levels. For a project-level motor vehicle emission simulator, the manager that is used to input and manage data is the project data manager. Building a project-level emission model includes three steps: setting a run specification (RunSpec), creating a project-level database to store the necessary data, and model calculation. More specifically, the RunSpec is created first in order to specify the characteristics of the particular scenario to be modeled; it includes a Description (a text description of the RunSpec), a Scale (model type, analysis scale, and calculation type), Time Spans (the time period for which MOVES will calculate emissions), Geographic Bounds (the geographic area), Vehicles/Equipment (the types of vehicle included in the network), Road Types (the road type(s) included in the model), Pollutants and Process (pollutants and processes), and others. Next, characteristic traffic data from the simulation and site-specific data are imported and stored in the newly added database. Characteristic traffic data from the simulation include the traffic composition and percentage of trucks; the length, volume, average speeds, and grades of each road segment; a distribution of vehicle ages; an operating mode distribution for running emissions; and so forth. Site-specific data include information regarding the regional characteristics, such as fuel information and meteorology conditions. Finally, the emission inventories are obtained after running the emission model [16].

3. Case study

3.1. Study area

In order to study the influence of traveler information apps on air quality, we selected a representative urban road network. The network includes an eastbound expressway and an urban road, which are connected by ramps, and a traffic-signal-controlled intersection with two phases on point H, as shown in Fig. 4. The first signal phase is for northbound and southbound flow, while the second is for eastbound and westbound flow. The split time of either phase is 60 s. When a traffic incident occurs at point C, one of the three lanes is closed and the capacity of this segment decreases, resulting in traffic congestion. As long as the congestion continues, real-time information is sent to travelers through apps to provide a decision-making basis for travel adjustment. Based on experience and preference, some travelers will choose to go along the expressway continuously (B → C → D → E; Route 2), while others will avoid congestion by exiting and taking the alternative urban road through the ramp, and then going back to the expressway at the next entrance (B → G → H → I→D → E; Route 1). Each traveler's decision will affect the whole traffic network performance and the air quality. A multimethod process was used to build a comprehensive model to study the relationship between travelers' behavior and environmental benefits.

3.2. Modeling

3.2.1. Building the traveler-behavior model

Since the travelers in this model are on the way to their destination, we only consider their enroute path changes. Due to individual differences, travelers optimize their travel activities respectively by utilizing the mobile navigation apps' services.

As described earlier, we built an ABM of the travelers' behavior in order to analyze the dynamic relationship between travelers' behavior and traffic network performance. In this model, the

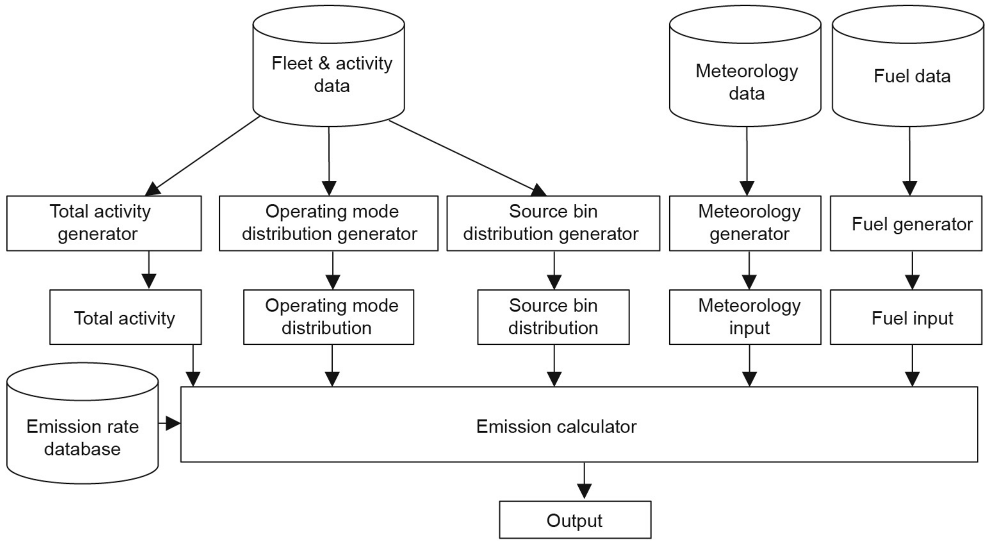

Fig. 3. The emission estimation process in MOVES.

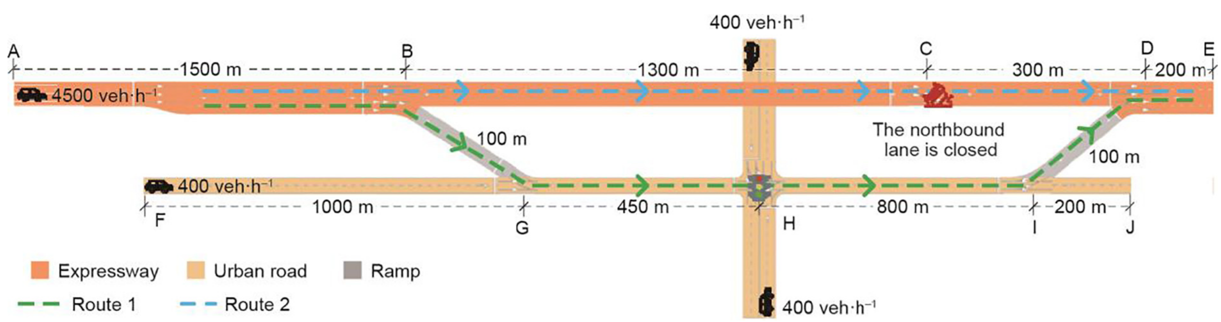

Fig. 4. Schematic diagram of the simulated road network. The distance between two points is subject to the value marked in the figure. veh: vehicles.

default route for travelers is the expressway, Route 2 (Fig. 4). When there is traffic congestion on Route 2, the traveler agents check the real-time traffic information that is available through apps on mobile devices and adjust their travel path according to the value of the estimated travel time. Some travelers tend to choose Route 1 (Fig. 4) to save time, while others tend to remain on the expressway. When the congestion spreads further on the expressway, more and more travelers will accept the information released by the apps and exit the expressway at the next ramp in order to avoid congested roads.

3.2.2. Building the traffic simulation model

The road network was established using environmental markup blocks from the Road Traffic Library, as described earlier and shown in Fig. 4. The details of each link are also presented in Fig. 4.

After the environment of the traffic simulation model was constructed, we defined the vehicles' activities and assigned travelers to a specific route, as shown in Fig. 5. Traffic information was updated automatically and released to the travelers through apps. Finally, once the traffic simulation model was running, macroscopic and microscopic data were collected to evaluate the environmental benefits. The former comprised traffic flow volume, average speed, and so on, while the latter included the acceleration and speed of each vehicle at each time stamp. In addition, the traffic volume of each link, the traffic density of the roads, the travel distance, and other statistical data were output both qualitatively and quantitatively.

3.2.3. Building the emission model

As mentioned earlier, the output data from the microscopic traffic simulation model were used as the input for the project-level emission model [19]. A summary of the MOVES project-level parameters used in this study is provided in Table 1.

4. Analysis and discussion

The environmental performances with and without the apps' guidance were simulated and analyzed. Because travelers are increasingly developing the habit of using apps to acquire traffic information, the impact of the penetration rate of these apps on environmental benefits was studied further.

4.1. The benefits of apps

When real-time traffic information is acquired through apps on mobile devices, travelers can dynamically adjust their travel paths. As a result, the average speed and traffic density of the expressway and urban road fluctuate periodically, as shown in Fig. 6(a) and (b), respectively. When the level of service on the expressway is high (Stage 1), travelers preferentially choose Route 2. With the arrival of more vehicles, the average traffic density in Route 2 continuously increases and the congestion spreads. As the expressway becomes more and more congested (Stage 2), more travelers preferentially change to Route 1. As a result, the average traffic density of Route 1 gradually increases in the first few minutes. In addition, since some of the travelers change their path, the average traffic

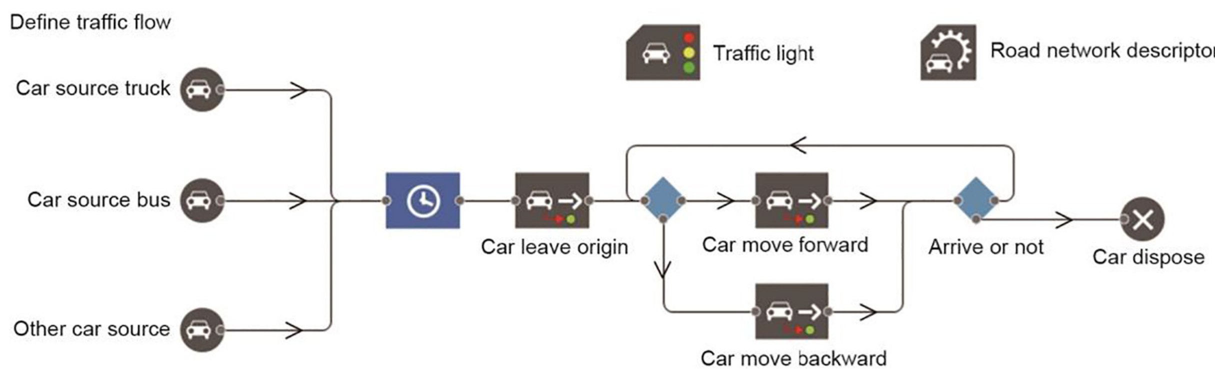

Fig. 5. Defining a vehicle's activities in a flowchart style.

Table 1
Summary of project-level parameters.

Item	Detail
Location	Nanshan District, Shenzhen
Calendar year	2016
Month	June
Time	8:00–9:20 AM
Temperature	28–32 °C
Humidity	75.0%
Roadway type	Urban restricted access and urban unrestricted access
Type of vehicles	Passenger cars, buses, and long-haul combination trucks
Type of fuel	Gasoline for passenger cars; diesel for buses and trucks
Roadway length	12 links, see Fig. 4
Link traffic volume	Expressway: 4500 veh·h^{-1}; urban road: 400 veh·h^{-1}
Link passenger car composition	85% passenger cars
Average road grade	0–5%
Link average speed	20–50 km·h^{-1}
Pollutant process	Running exhaust emissions
Output	$PM_{2.5}$, NO_x, CO_2, and fuel consumption

density of Route 1 rises to a certain extent and then remains stable. At the same time, the congestion of Route 2 is gradually alleviated and the average speed of Route 2 increases. When the estimated travel time of both routes is almost equal, most subsequent travelers again preferentially choose Route 2, leading to a periodic trend [20].

When real-time traveler information is not available, the arrival vehicles at point C cannot pass in a timely manner; thus, the length of congested road gradually increases, and the traffic conditions become increasingly worse. Furthermore, the average travel time from node A to node D without the guidance of an app is 461 s, whereas the average time with an app's guidance is 373 s—a reduction of 19.1%. The simulation results show that the traffic information released by apps can help travelers to avoid congestion by diverting traffic volume before a bottleneck in the traffic system [20]. This result is quite similar to the work published in *Nature Communication* [3].

The results of the emission model show that the environmental benefits are the same as the traffic benefits. In other words, with the guidance of apps, the pollutants emitted by vehicles can be decreased by a certain degree, as shown in Table 2. In addition, about 29.5% of the energy consumption of the entire traffic system during the simulation time can be saved. In terms of the main vehicle pollutants, the reduction rate of NO_x is 23.6%, and the reduction rate of $PM_{2.5}$ is 6.8% higher than that of NO_x.

4.2. Apps penetration rate

In order to compare the impact of the penetration rate of different apps on the environmental performance, we ran simulations with different parameters. The results show that as the apps' penetration rate rises, more travelers choose Route 1 when congestion occurs, as shown in Fig. 7. When the penetration rate is about 95%, the proportions of travelers choosing Route 1 and Route 2 are almost equal, mainly due to travelers with a high tolerance threshold value who are reluctant to change their route.

However, the relational curve between the environmental benefits and the penetration rate is similar to a "U" curve. In other words, both a higher penetration rate and a lower penetration rate will reduce the environmental performance of the whole network, as shown in Fig. 8. When the penetration rate is about 30%, about 10% of vehicles shift to Route 1 when congestion occurs, which significantly improves the environmental benefits. For example, the CO_2 emission is reduced from 4923 to 3473 kg·h^{-1}—a decrease of more than 29%.

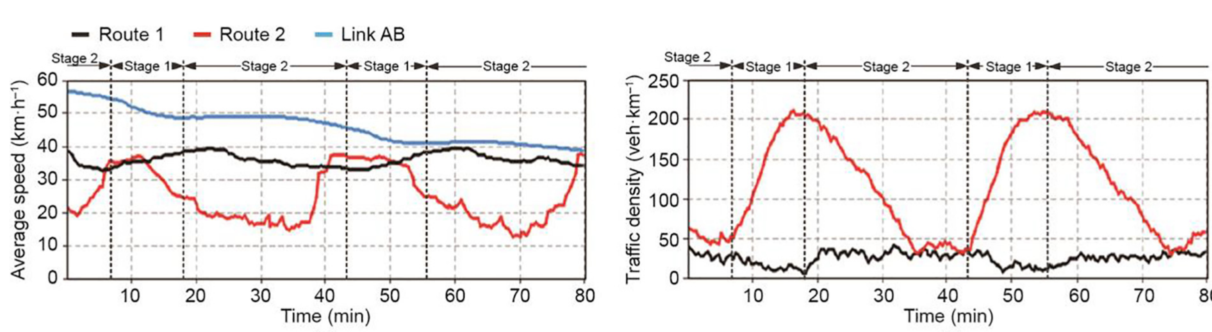

Fig. 6. Simulation result with the guidance of apps. (a) Average speed; (b) traffic density of the expressway and urban road.

Table 2
Environmental benefits from app's guidance.

	$PM_{2.5}$	NO_x	CO_2	Energy consumption
Without app's guidance	0.92 ($kg\cdot h^{-1}$)	17.8 ($kg\cdot h^{-1}$)	4 923 ($kg\cdot h^{-1}$)	67 732 ($MJ\cdot h^{-1}$)
With app's guidance	0.64 ($kg\cdot h^{-1}$)	13.6 ($kg\cdot h^{-1}$)	3 473 ($kg\cdot h^{-1}$)	47 768 ($MJ\cdot h^{-1}$)
Environmental benefits (reduction rate)	30.4%	23.6%	29.5%	29.5%

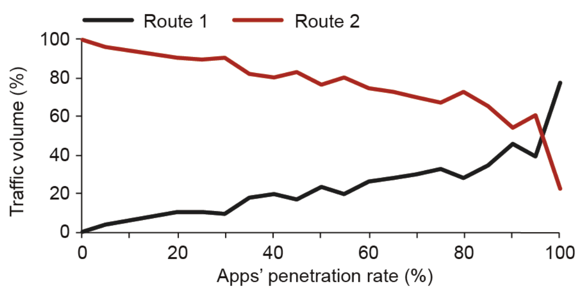

Fig. 7. The relationship between route choice and the apps' penetration rate.

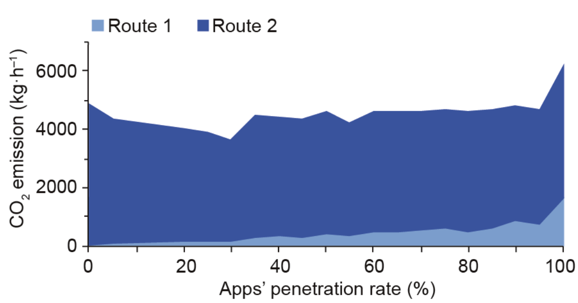

Fig. 8. The relation between the CO_2 emission of vehicles and the apps' penetration rate.

5. Conclusion

This study uses ABM as a core model to simulate travelers' behavior with real-time traffic information; starting from behavior research, it establishes a comprehensive model that integrates a traveler ABM, a traffic simulation, and an emissions model. This model realizes communication between travelers and the service provider, as travelers obtain real-time traffic information by navigation apps on their mobile devices, and their trips are mapped into the traffic network. This communication brings our comprehensive simulation closer to reality than a traditional traffic simulation, resulting in more accurate results for the emission inventories.

The simulation results show that the traffic information released by apps can not only help travelers to avoid congestion by diverting traffic volume before a bottleneck in the traffic system, but also reduce motor vehicle emissions. Regarding traffic benefits, our results are quite similar to those published in *Nature Communication* [3]. All relevant pollutants can be reduced when travelers use the guidance of navigation apps, especially $PM_{2.5}$ and NO_x. In addition, a sensitivity analysis of the apps' penetration rate shows that this benefit is optimal when the penetration rate is about 30%.

The comprehensive model established in this paper can be used to assess the environmental impact of apps on project level even city level, and can provide technical support for urban traffic operation and management.

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Compliance with ethics guidelines

Wenke Huang and Mingwei Hu declare that they have no conflict of interest or financial conflicts to disclose.

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