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Research Article

Assessing the Potential of the Strategic Formation of Urban Platoons for Shared Automated Vehicle Fleets

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This paper addresses the problem of studying the impacts of the strategic formation of platoons in automated mobility-on-demand (AMoD) systems in future cities. Forming platoons has the potential to improve traffic efficiency, resulting in reduced travel times and energy consumption. However, in the platoon formation phase, coordinating the vehicles at formation locations for forming a platoon may delay travelers. In order to assess these effects, an agent-based model has been developed to simulate an urban AMoD system in which vehicles travel between service points transporting passengers either forming or not forming platoons. A simulation study was performed on the road network of the city of The Hague, Netherlands, to assess the impact on traveling and energy usage by the strategic formation of platoons. Results show that forming platoons could save up to 9.6% of the system-wide energy consumption for the most efficient car model. However, this effect can vary significantly with the vehicle types and strategies used to form platoons. Findings suggest that, on average, forming platoons reduces the travel times for travelers even if they experience delays while waiting for a platoon to be formed. However, delays lead to longer travel times for the travelers with the platoon leaders, similar to what people experience while traveling in highly congested networks when platoon formation does not happen. Moreover, the platoon delay increases as the volume of AMoD requests decreases; in the case of an AMoD system serving only 20% of the commuter trips (by private cars in the case-study city), the average platoon delays experienced by these trips increase by 25%. We conclude that it is beneficial to form platoons to achieve energy and travel efficiency goals when the volume of AMoD requests is high.

1. Introduction

Automated vehicles (AVs), also known as self-driving vehicles, bring a unique opportunity for reshaping urban mobility systems, thereby changing the way people travel. Combining electric and automated vehicles with ride-hailing services brings forth new automated mobility-on-demand (AMoD) services in future cities. In AMoD systems, the convergence of vehicle automation, electrification, and shared mobility has the potential to provide safe, economical, efficient, and sustainable urban mobility [1, 2]. However, there are considerable uncertainties about achieving these benefits.

While the large-scale deployment of AMoD systems for urban mobility is still in its infancy, a broad spectrum of research focuses on investigating the potential of operating AMoD systems in different urban or regional application scenarios. One potential application is that AMoD could provide a solution for private car users in urban areas, leading to reduced parking demand, ownership cost, energy consumption, and emissions [3, 4]. Moreover, AMoD services could act as feeders to complement the high-capacity PT systems. Integrating an AMoD feeder service into the traditional PT system could increase the accessibility of PT services and improve the traffic externalities (e.g., congestion and emissions) due to increased demand for PT systems [5, 6].

However, taxi-like services offered by AMoD systems in urban areas as competitive alternatives to public transportation (PT) may draw customers away from the traditional PT system. As a result, AMoD services could reduce public transit ridership and cause congestion due to increased vehicle movements (i.e., zero-occupancy movements and movements to serve more demand) [7–9].

Like AMoD services in urban areas, a promising application of AMoD systems is to replace fixed-route and low-frequency buses in areas where demand is scattered and low (e.g., rural areas and industrial parks). Compared to existing bus services, AMoD systems could provide direct services to customers with improved availability and accessibility; the operating cost of AMoD services in such application areas is much lower than those of conventional bus services [10].

A primary research priority is studying different operational aspects of urban passenger AMoD systems in future cities. Recent advances in vehicle automation have enabled vehicles to drive and connect without human intervention. With the help of connectivity and automation technology, AVs can exchange information for coordinated movements in platoons at closer following distances.

Vehicle platooning has been a popular research theme in recent applications of intelligent transportation systems. The impact of platoon operations on urban traffic has been studied, assuming that AVs are already in platoons. However, intriguing questions arise when introducing vehicle platooning in passenger AMoD systems in which shared, automated, and electric vehicles (SAEV) provide on-demand services to travelers in urban areas:

(1) What are the impacts of the formation and operation of such urban platoons on the service quality offered to travelers and traffic efficiency related to road network travel times?
(2) How do changes in traffic conditions by platoon operations affect the travel-related energy consumption of traffic participants across the urban road network?

To answer these questions, an agent-based model (ABM) has been developed to provide performance evaluations of forming platoons in urban passenger AMoD systems of the future.

The paper is organized as follows. In Section 2, we summarize the existing literature on platoon operations and the formation of platoons, identify the challenges of forming platoons in urban AMoD systems, and present the main contributions of this paper. Section 3 gives an overview of the modeling framework and discusses the model specifications. A detailed description of the model implementation and its application are provided in Section 4. Section 5 analyzes the simulation results. The main conclusions and policy implications are presented in the final section, and future work directions are recommended.

2. Background

Platooning systems have attracted increasing attention with the rapid progress in automated and connected vehicle technologies. Much work has been done to investigate platoon communication technologies and platoon control strategies [11]. Recent literature has focused on platoon planning: at a low level (e.g., trajectory level), detailed platoon maneuvers (e.g., merging and splitting) are designed and simulated [12]; at a high level, planning and optimization of routes and schedules in the platoon formation are studied [13]. Moreover, vehicles with synchronized movement in platoons can have faster reaction times to dangerous situations and fewer human errors, reducing rear-end crashes. For a detailed analysis of platoon safety issues, the reader is referred to the literature review research by Axelsson [14] and Wang et al. [15]. In this study, we address the problems of forming platoons and assess the travel and energy impact on a future urban mobility system. We herein provide background information about the potential implications of platoon operations on energy consumption, and traffic efficiency. Besides, we review the literature on the strategic formation of platoons.

2.1. Energy Impact of Platoon Operations on Highways. Platoons of vehicles provide significant potential for energy savings on highway driving. The close-following mechanism can considerably reduce the energy consumed by platoon vehicles to overcome the adverse aerodynamic effect [16]. Several field experiments in research projects, such as the COMPANION project, the PATH platoon research, the SARTRE project, and the Energy ITS project, have been conducted to investigate the potential of platoon operations in reducing energy consumption [17].

2.2. Impact of Platoon Operations on Highway and Urban Traffic. Platoon operations can improve highway throughput due to the shorter headways between platoon vehicles [18]. Using communication technologies (e.g., vehicle-to-vehicle or vehicle-to-infrastructure technologies), platoons of vehicles can also smooth out the vehicle-following dynamics on highways [19]. Besides, platoon operations can improve urban road capacity and reduce delays when crossing signalized intersections [20].

2.3. The Strategic Platoon Formation on Highways. In the above literature, the energy and traffic studies on platooning systems considered vehicles that are already in platoons and used platoon operations to increase road throughput and reduce energy consumption. Some studies investigated the problem of coordinating vehicles in platoons on highways. Hall and Chin [21] developed different platoon formation strategies to divide vehicles waiting at highway entrance ramps into different groups according to their destinations. Once formed at the highway entrance ramp, platoons remain intact to maximize the platoon driving distance. Saeednia and Menendez [22] studied slow-down and catch-up strategies for merging trucks into a platoon under free-flow traffic. Larsson et al. [23] defined the platoon formation problem as a vehicle routing problem to maximize the fuel savings of platoon vehicles. Studies by Liang et al. [24] and van de Hoef [25] investigated the problem of coordinating many trucks in platoons to maximize fuel savings. In the formation of platoons, trucks can adjust their speed without regard to traffic conditions. Larson et al. [26] developed a distributed control system in which trucks can adjust speed to form platoons to save fuels. Johansson et al. [27] developed two game-theoretic models to study the platoon coordination problem where vehicles can wait at network nodes to form platoons. In Table 1, we compare the newly developed functional components and the performance analysis of the AMoD system with the new components in our modeling framework with the referred studies in the literature.

2.4. Challenges for the Platoon Formation in Urban AMoD Systems. The formation of platoons in urban AMoD systems poses challenges. First, the current state-of-the-art models consider the traffic demand for the platoon formation in an oversimplified way. Travel demand is generated according to trip lengths, destination distributions, and vehicle arrival patterns. Different distributions could be used to generate travel demand while capturing its uncertainty. However, in AMoD systems, the zero-occupancy vehicle trips of picking up the assigned travelers introduce uncertainty in the traffic demand on the road network. This uncertainty, therefore, requires explicit modeling of the interaction between SAEVs and travelers.

Second, existing studies overlook the effect of forming platoons on travelers in the platoon vehicles. In the future, the AMoD system that we are studying, a fleet of SAEVs directly provides on-demand services to travelers between service points. The formation of platoons requires the synchronization of different vehicles in the same coordinates. In the formation of platoons, vehicles may wait for other vehicles to form platoons, causing delays for travelers. The impact of forming platoons on the travelers in the platoon vehicles must be captured.

Third, existing studies investigate the effect of reduced aerodynamic drag via platooning on energy consumption in highway driving. However, due to higher traffic demand on the urban transport network, the potential for energy efficiency is primarily influenced by traffic conditions rather than by reducing air resistance. Coordinated movements of platoon vehicles could improve traffic throughput. As a result, the energy consumption of traffic participants (SAEVs) will be affected by platoon operations. Moreover, current studies aimed to investigate the traffic impact of platoon vehicles using predefined platoons. Therefore, the impact of forming platoons on travel conditions and energy consumption of SAEVs in urban driving needs to be assessed for future scenarios.

Fourth, platoon sizes (the maximum number of vehicles in a platoon) and the maximum time spent forming platoons are not restricted. This relaxation can lead to overestimation of the platoon driving distances and energy savings by forming long platoons. In AMoD systems, forming a long platoon may cost travelers more time in the situation where vehicles wait for other vehicles. Setting limits on platoon sizes and time spent in the formation can prevent long platoons from disrupting the urban traffic and causing long delays for travelers. Therefore, the platoon size restriction and maximum time spent in the formation of platoons need to be taken into account when coordinating SAEVs in platoons. The impact of the time and platoon size restrictions on the formation of platoons, and the level of service offered to travelers and on energy consumed needs to be studied.

2.5. Urban AMoD System Characteristics in Future Cities. The AMoD systems envisaged for the future will probably be available in the 2030s to 2040s, when SAEV fleets have become common and affordable [28, 29]. SAEVs, in this paper, considered to be purpose-built microvehicles, are intended to cover the whole trips of commuters. While providing on-demand services for morning commuters in lieu of private cars, SAEVs can be coordinated in platoons at service points. Although purpose-built SAEVs could occupy less space, SAEVs cannot form platoons anywhere because of urban driving conditions characterized by narrow streets and traffic congestion. One idea is to define what in this paper is designated as “service points”: platoon formation and dissolution (platoon is disassembled) locations across the service area. Examples of service points for the platoon formation in today’s urban transportation systems could include public parking garages, public charging service points, petrol service points, empty bus stops, and some parking spaces along the canals in cities.

2.6. Research Contributions. This paper aims to develop an agent-based model (ABM) to study the impact of forming platoons in future urban AMoD systems on people’s travel and energy usage. Agent-based modeling is suitable for our research questions. The ABM has the advantage of representing entities at a high resolution; the interaction of entities (e.g., vehicles and travelers) can be captured realistically; it is flexible to model a system at different description levels (e.g., vehicles and platoons formed by vehicles) to evaluate different aspects of the system and to make changes to assumptions (e.g., formation policies) for different scenarios. Taking into consideration the limitations of current studies identified above, we summarize the main contributions of this paper as follows.

First, the ABM originally developed in this paper includes a high level of detail. The individual travelers are modeled, and their attributes are initiated according to the regional travel demand data and the realistic departure time data. The interaction between SAEVs and travel requests is explicitly modeled by developing a vehicle-to-travelers assignment component, in which SAEV pickup trips and drop-off trips are represented. The modeled interaction between vehicles and travelers captures the uncertainty of traffic demand between areas of origin and destination.

Second, the formation behavior of waiting at service points, defined as the hold-on strategy, is explicitly simulated for platoon leaders and their followers. The platoon formation policies that determine when a group of vehicles leaves a service point as a platoon are the maximum elapsed time of the platoon leader and the maximum platoon size. Either one of the two policies can trigger a release of a platoon. The AMB simulates platoon formation operations of vehicles, which allows us to measure the impact of forming platoons on travelers. Moreover, the formed platoons are flexibly represented with specified information (e.g., the platoon route, the vehicle sequences, and the speed) at an aggregate level to model platoon driving and its impact on traffic conditions.

Third, a mesoscopic traffic simulation model is used to represent the traffic dynamics throughout the road network. The mesoscopic traffic simulation model can simulate each vehicle's movement, while a macroscopic speed-density relationship is used to govern congestion effects. The traffic simulation model can incorporate the impact of all SAEV trips, including unoccupied pickup trips and occupied drop-off trips, on the traffic over the road network. Furthermore, the relationship established between road capacity and platoon characteristics is used to assess the impact of formed platoons on traffic conditions.

Fourth, an energy consumption model is linked with the mesoscopic traffic model to efficiently calculate the energy consumed by individual SAEVs for travelers' trips. It can also produce the energy estimate of intended trips, thus ensuring that the assigned SAEVs have sufficient power to complete their journeys.

The travel and energy potential of forming platoons under different formation policies and demand levels in AMoD systems is assessed using the urban road network of the case-study city, The Hague, Netherlands, through a set of defined key performance indicators (KPIs).

3. Model Specifications

For building the ABM, we introduce the following main assumptions regarding the platoon formation of SAEVs in AMoD systems:

(i) All travel demand is produced and attracted between what have been designated as service points which are connected to the network nodes. Service points are thus locations where travelers can be picked up or dropped off by a vehicle. This is reasonable for the situation where many service points are designated in a service area.

(ii) We assume that vehicles wait at service points to form platoons instead of using slow-down and catch-up strategies. The major drawbacks of slow-down and speed-up strategies are that urban traffic flow can be disrupted when driving slowly, and accelerating vehicles may violate urban road speed limits. Moreover, slow-down and speed-up strategies are very difficult for urban driving, which is characterized by one or two lanes for each direction and traffic congestion.

(iii) We assume that there are enough parking places for SAEVs to form a platoon at the service points. SAEVs are purposely designed to be space-saving microvehicles (Renault Twizy for the reference model). Moreover, there are size restrictions on the platoon size.

(iv) We assume a future scenario where AMoD services are used to serve all private car trips in an urban area; the usage of conventional vehicles is not considered.

The framework presented in Figure 1 includes a fleet management center and a traffic management center. The fleet management center mainly matches vehicles with travelers and coordinates the formation of platoons. The traffic management center primarily represents the network traffic dynamics and finds the time-dependent shortest routes for vehicles based on the current network traffic conditions. The fleet management and traffic management components capture different aspects of the system components' interactions. The modeling framework can evaluate system performance with regard to defined KPIs based on the realistic travel demand data and the existing road network.

The model assumes that OD trip demand and aggregated departure times are given. The demand generator in the simulation model will generate individual travel requests with an origin location, destination location, and request time according to the given OD matrix and departure time distribution. According to real-time information about the travel requests, the vehicle assignment component matches the available vehicles with incoming travel requests. Once the assignment has been done, the information on travelers' locations is sent to the assigned vehicles, and travelers are notified about the vehicle details. The assigned vehicle will be dispatched to pick up the traveler, the state of the assigned vehicle transition from idle to in-service state.

The traffic management center provides the time-varying traffic conditions, forming a basis for subsequent route calculations. A mesoscopic traffic simulation model is used to represent traffic patterns over the road network, which can be captured by simulating the movement of SAEVs along their routes as they carry out the travelers' journeys. The traffic simulation model manages static and dynamic information to determine the current network traffic conditions. The static inputs to the traffic simulation model are the traffic network representation, including links and nodes, traffic capacity, free-flow speed, and road length, while the dynamic information is concerned about the information on road segments upon which individual vehicles and/or platoon vehicles are travel. Based on the current network traffic conditions provided by the traffic simulation component, the time-dependent shortest routes between points are computed, which is a string of ordered road segments to be traversed.

The energy consumption model estimates the energy consumption of individual vehicles over the road network. The energy consumption of individual vehicles is computed as a function of the link travel speed. The charging component is responsible for finding charging points for low battery vehicles. Vehicles can be charged at every service point after completing the journey of a traveler. The time delay due to the charging operations is considered.

The platoon formation component in the fleet management center coordinates in-service vehicles in an existing

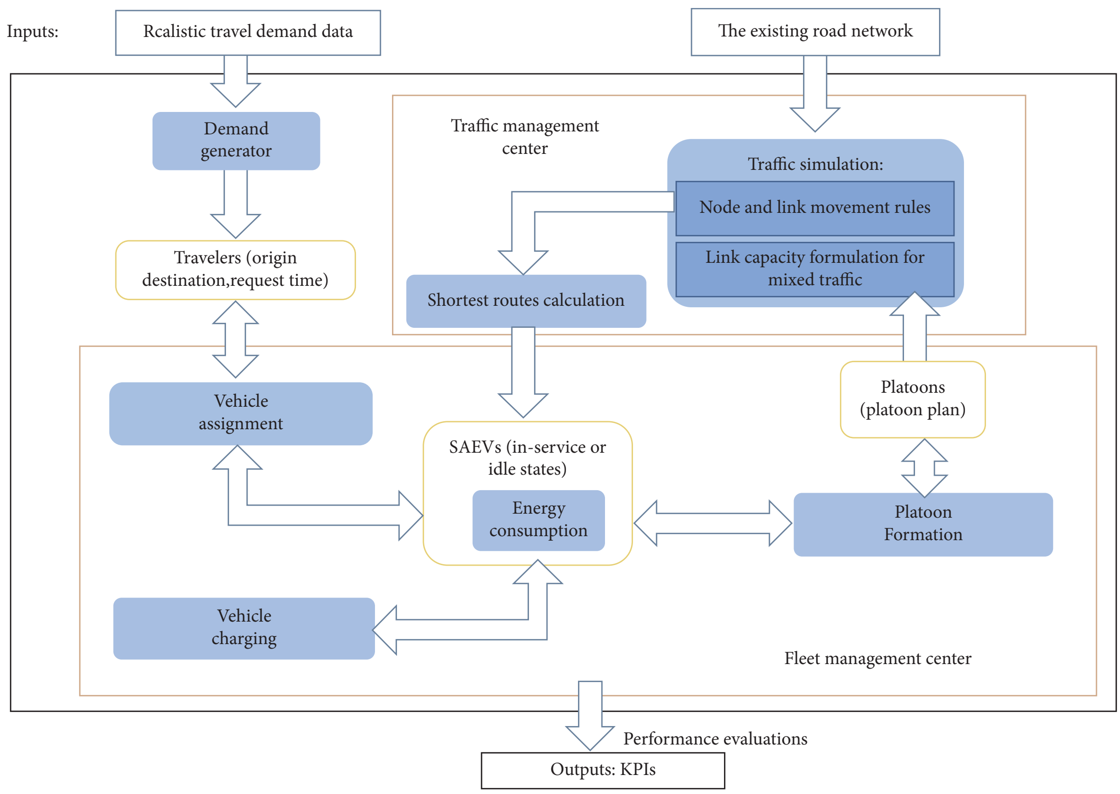

Figure 1: The conceptual simulation framework.

platoon at designated service points according to their destinations. Also, a new platoon can be initiated when one of the grouped (in-service) vehicles arrives at the formation location. Once the platoon agent type is created, the platoon agents manage the information about the platoon plan, including platoon routes, the number of platoon vehicles, platoon speed, and the assigned leader and its followers with the determined vehicle sequence. The traffic simulation model in the traffic management center can account for the impact of the operations of formed platoons on traffic dynamics. Figure 2 illustrates the platoon formation and its potential. The detailed descriptions of the functionalities are explained in the following sections.

3.1. Energy Consumption of the SAEVs. Existing studies estimate the energy consumption of electric vehicles on the network level as a function of travel distance, which means translating the kilometers driven into an estimate of energy consumed [30, 31]. However, the strong correlation between energy consumption and vehicle speed is not considered. We attempt to estimate the energy consumption of SAEVs and account for traffic congestion by making it a function of experienced travel speed. It is linked to a mesoscopic traffic simulation model in which the effect of forming platoons on traffic conditions is considered. The energy consumption model is thus capable of accounting for the effect of platoon driving. The energy consumption model contains a set of regression models for different vehicle types. These regression models can be used to calculate the energy consumption associated with one vehicle traversing each road segment based on the speed of the vehicle and the length of the road segment. The calculation method is explained as follows.

First, the average speed for individual SAEVs traversing the corresponding road segment is calculated. Second, the energy consumed by the SAEVs per unit distance is estimated using the regression model in equation (1), which describes the relationship between energy consumption and travel speed. Third, the total energy consumption on the route between the origin and destination is calculated as the sum of energy consumed by the individual SAEV in each road segment. The formula for calculating total energy consumption is shown in equation (2)

$$E = \alpha + \beta * S_i + \gamma * S_i^2, \tag{1}$$

where α, β, and γ are coefficients; S_i is the travel speed of an individual SAEV traversing road segment i; E is the energy consumption per unit distance.

The total energy consumption of each SAEV to complete the pickup trip or drop-off trip can thus be calculated as

$$E_t = \sum_{i=1}^{n} E_i * L_i, \tag{2}$$

where n is the total number of road segments between the locations (e.g., the locations of the assigned vehicle and the origin of the travelers, or the locations between the origin of the traveler and his/her destination) ; L_i is the length of each

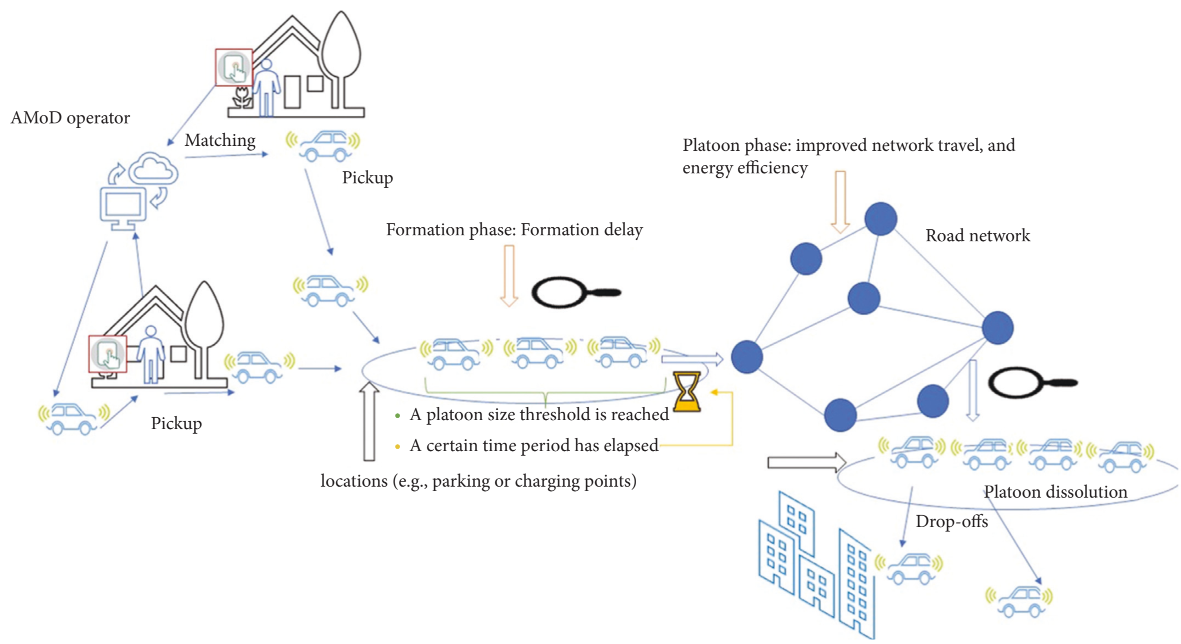

Figure 2: An illustration of the platoon formation and potential impacts.

road segment i. E_t is the total energy consumption of an SAEV to complete the pickup trip or drop-off trip.

We estimate the energy consumption of different types of vehicles. Each vehicle type corresponds to a regression model derived from the laboratory dynamometer tests [32]. The coefficient for different vehicle types is given in Table 2 in Section 4, where the application of the model is presented.

3.2. Real-Time Vehicle Assignment. The vehicle assignment component assigns available vehicles to serve travelers as travel requests come in, which are generated according to the aggregate travel demand (explained in Section 4.2). The vehicle assignment component will assign the nearest available SAEV with enough battery power to serve a traveler to his/her destination. For that to happen, there must be a real-time estimation of how much energy is needed if that traveler is satisfied, and this is estimated for each candidate vehicle based on its particular vehicle type.

The process of finding available vehicles for travel requests goes as follows. First, the energy consumption of an individual vehicle to complete the intended trip is estimated based on the energy function. The estimate of energy spent on transporting the intended traveler can be calculated using equation (3). Second, based on the estimated energy consumption of the intended traveler, available vehicles with sufficient remaining battery capacity that can undertake the traveler's journey are filtered from the group of idle vehicles; finally, a vehicle located at the shortest Euclidean distance within the search radius is chosen from the filtered pool of available vehicles

$$E_e = \eta * E_t, \quad (3)$$

where η is a safety coefficient used to ensure that the estimated energy for a traveler's intended trip is not less than the actual energy consumed by individual vehicles to complete the trip that might happen if traffic changes. E_e is the estimated energy required by an individual vehicle to complete the trip of a traveler.

The function in equation (3) estimates the energy needed to complete travelers' trips based on the link travel speeds at the moment when a traveler calls the service, while the actual energy consumed uses the experienced speeds of vehicles in equation (2) to calculate the energy spent after completing the traveler's trip. The proper estimate of energy spent to complete the trip of an intended traveler ensures that the assigned vehicle has sufficient battery capacity to reach the traveler's destination.

Once an available vehicle with sufficient remaining energy is assigned to a traveler, the time-dependent shortest path (lowest duration) from the current vehicle location to the traveler's location is computed. After the vehicle arrives at the pickup location, the time-dependent shortest path from the traveler's location to its destination will be determined. The computation of time-dependent shortest routes is based on the Dijkstra algorithm.

3.3. Mesoscopic Traffic Simulation. The modeling framework for the proposed system needs to simulate the operations of many vehicles to transport all the city's private car commuters over a realistic urban road network. A mesoscopic traffic simulation model that includes link movement and node transfer is incorporated into the agent-based modeling framework [33, 34]. The mesoscopic traffic simulation model combines a microscopic level representation of individual vehicles with a macroscopic description of the traffic patterns. In the link movement, vehicular movements are simulated. Vehicle speed on the road segments is updated according to the established macroscopic speed-density relationship. A modified Smulders speed-density relationship (equation (4)) is used to update the vehicle speed based on the link density

Table 1: Comparison of the strategic platoon formation studies at the route level.

Studies	Modeling components								Impact analysis				
					Platoon policies		Coordination strategies				Energy consumption		
	Many vehicles	Road network level	Demand and supply interaction	Mixed traffic	Platoon sizes	Formation time constraints	Speed adjustment (Slow down or catch up)	Hold-on strategy	Platoon vehicles	Traffic throughput	Traffic	Aerodynamics	Service level (waiting and travel times)
Hall and Chin [21]	✓				✓	✓		✓	✓	✓			
Larson et al. [26]	✓	✓				✓	✓		✓			✓	
Saeednia and Menendez [22]						✓	✓		✓				
Larsson et al. [23]	✓	✓				✓			✓			✓	
Liang et al. [5]						✓	✓		✓			✓	
van de Hoef [25]	✓	✓				✓	✓		✓			✓	
Johansson et al. [27]	✓	✓				✓		✓	✓				
Our approach	✓	✓	✓	✓	✓	✓		✓	✓		✓		✓

Table 2: Coefficients in the regression model for different vehicle types.

Coefficient	α	β	γ
NissanSV	479.1	−18.93	0.7876
Kia	468.6	−14.63	0.6834
Mitsubishi	840.4	−55.312	1.670
BMW	618.4	−31.09	0.9916
Ford	1110	−96.61	2.745
Chevrolet	701.2	−35.55	1.007
Smart	890.8	−43.12	1.273
Nissan2012	715.2	−38.10	1.271

$$v(k) = \begin{cases} v_0\left(1 - \dfrac{k}{k_j}\right), & k < k_c, \\ \gamma\left(\dfrac{1}{k} - \dfrac{1}{k_j}\right), & k \geq k_c, \end{cases} \tag{4}$$

where k is the link traffic density. $v(k)$ is the speed that is determined by the traffic density k; v_0 is the free-flow speed. k_c is the link critical density; k_j is the link jam density. γ is a parameter. The value of the parameter can be derived as $\gamma = v_0 k_c$.

Node transfer means that vehicles transfer between adjacent road segments. A vehicle moving from an upstream link (road segment) to a downstream link will follow the defined rules:

(1) The vehicle is at the head of the upstream link queue. In other words, there are no preceding vehicles stacking in the waiting queue.

(2) The number of outflow vehicles has been checked to determine whether a vehicle can leave the road segment it is traversing.

(3) The number of storage vehicles has been checked to determine whether the downstream link has enough storage units to accommodate the upcoming vehicle.

The mesoscopic traffic simulation model, including link movement and node transfer, can provide the required level of details in estimating the speeds and travel times of individual vehicles on the network while balancing the trade-off between computational cost and traffic model realism.

A platoon that includes multiple platoon vehicles is considered a platoon entity. The rules for the movement of individual vehicles are applied to individual platoons in which the properties (e.g., the number of platoon vehicles) are considered in the node transfer.

3.4. Traffic Simulation for Platoon Vehicles. In the literature, the strategic platoon formation was studied while ignoring the traffic (as shown in Table 1: comparison of the platoon formation studies at the route level). We fill this gap by developing a simulation component for mixed operations of platoon AVs and nonplatoon AVs on top of a mesoscopic traffic simulation. The functional component for the mixed operation of platoon AVs and nonplatoon AVs can capture the traffic impact of forming platoons across the road network. The relationship between road capacity and different penetration rates of platoon AVs is established to assess the impact of the platoon formation on traffic conditions. Chen et al. [35] proposed a formulation to describe the correlation between platoon characteristics, including the proportion of platoon vehicles, intervehicle spacing levels, and the macroscopic capacity. The formulation reveals how the single-lane capacity changes for different penetration rates of platoon AVs. The derived macroscopic capacity formulation for mixed traffic solves the problem of determining the macroscopic traffic variables (used in the mesoscopic traffic simulation) based on platoon characteristics. Therefore, we can combine the macroscopic capacity formulation in the mesoscopic traffic simulation that applies the macroscopic speed-density function to govern the movement of the vehicles that we use in the simulation methodology. The single-lane capacity is expressed as

$$C_c = \frac{C_a}{1 - (N/M + N) * (1 - \alpha)(1 - (L/N))}, \tag{5}$$

where C_a denotes the lane capacity for all vehicles traveling regularly. L is the number of leaders. N is the total number of platoon vehicles. M is the total number of regular driving vehicles (i.e., AVs are not in platoons). α is the ratio of platoon spacing to regular spacing.

As shown in equation (5), the capacity C_c depends on the penetration rate of platoon vehicles $\varphi = N/M + N$ and the number of leaders (L). A smaller distance spacing between platoon vehicles allows an increase in the lane capacity. The lane capacity increases as the penetration rate of platoon vehicles, φ, increases. Moreover, for the same number of platoon vehicles N, the more the leaders L are created, the fewer the capacity increases.

We use the following definitions of different critical spacing types according to the operational characteristics of vehicle platooning. The critical spacing when vehicles travel regularly (e.g., AVs that are not in platoons) is defined as d_a. We define $d_p = \alpha d_a$, where $0 < \alpha < 1$. We assume that the critical spacing between a platoon vehicle and a regular driving vehicle that is not in a platoon is also d_a.

Notice that regular driving AVs that are not in platoons follow the regular driving distances of conventional vehicles, while platoon vehicles move at a reduced spacing. The formulation of the capacity of one lane (for one direction) shows how it can be improved by increasing the penetration rate of platoon vehicles and the number of leaders or platoons (each platoon has one leader). The detailed derivations of equation (5) can be found in Appendix.

3.5. Platoon Formation Mechanism. Spontaneous or on-the-fly platoon formation without proper prior planning can cause a high frequency of joining and leaving operations by the vehicles which might disrupt traffic and decrease safety [27, 36]. This type of platoon might not ensure a high rate of in-platoon driving. In AMoD systems, many SAEVs are assigned to take travelers from place to place (service points) in urban areas; therefore, they will be continuously routed to different destinations. The platoon formation for a fleet of vehicles that provide on-demand transport is more effective if done in a coordinated way. SAEVs can be coordinated in a platoon using the hold-on strategy while providing direct on-demand service between service points designated as the platoon formation locations over the AMoD network.

The formation behaviors of platoon participating vehicles are realistically represented. In relation to coordinating vehicles in the platoon formation, a vehicle can be assigned to an existing platoon as a follower vehicle. A vehicle can be connected to other vehicles to initiate a new platoon, either as a platoon leader or as a follower. In the first case, arriving vehicles at a service point are assigned to an existing platoon according to the destinations of travelers assigned to them. There are no existing platoons at a service point in the second case, or the arriving vehicles cannot be assigned to an existing platoon. Arriving vehicles at the service point are divided into different groups. For vehicles in each group at a service point, the first vehicle to arrive is designated as the platoon leader. Once a platoon leader is assigned, the platoon is initiated.

The hold-on strategy of the platoon leader is used to organize arriving vehicles (in-service vehicles with passengers) into platoons at a service point according to their destinations. Coordinating empty SAEVs (that are assigned to pick up passengers) could increase the out-of-vehicle waiting times, leading to great discomfort. The hold-on time of a platoon leader is the time from when the leader starts to wait for other vehicles until the moment the platoon is formed and starts to move. The release of a platoon (the moment when it departs) depends on not only the number of vehicles that it has (there is a maximum number of vehicles in a platoon) but also on the time that the platoon leader has been waiting. That is, the release of a platoon can be triggered by reaching the maximum vehicle size or the maximum hold-on (waiting) time of the platoon leader, as explained before. We denote the time threshold of platoon leaders as T and the maximum number of platoon vehicles as V. The physical constraints of road segments directly set a threshold for the number of vehicles in a platoon. Algorithm 1 explains the platoon formation mechanism.

The formation approach uses global knowledge about all arriving vehicles for each service point to assign them to an existing or newly created platoon. Vehicle sequence in a platoon is determined based on the arrival time of a vehicle at the platoon formation location. The platoon leader makes decisions on behalf of the followers to trigger the platoon release. Once a SAEV is assigned to serve a traveler, it has the origin and destination of the traveler, and its shortest route is calculated using the Dijkstra algorithm. In a platoon, platoon followers will adjust their routes from their original shortest routes to the shortest route of the platoon leader. A plan is created for a formed platoon, including platoon ID, a leader and its followers, a platoon route (origin, destination, and road segments), and the vehicle sequence in the formed platoon (see Algorithm 2). Once a platoon arrives at the destination service point of travelers, all platoon vehicles are detached from their formed platoon (arriving vehicles are grouped according to their destinations—platooned vehicles in a platoon have the same destination service point), and then will drop off the passengers at the destination service point—the state of the vehicle transitions from in-service to idle state. Notice that the volume of AMoD services could be high during morning hours, which leads to many arriving vehicles (in-service vehicles) at a service point. Also, there are platoon size restrictions in urban driving conditions. Many platoons could be formed by grouping vehicles with the same destinations, while organizing other vehicles with different destinations may cause detours and be against vehicles with the same destination. Considering the urban formation locations, driving conditions, and the high demand during peak hours, we did not model the scenario where a vehicle with a different destination detaches from a platoon to drop off a passenger, and the other platooned vehicles continue to the next service points.

4. Model Application

The detailed conceptual framework is implemented in the AnyLogic multimethod simulation modeling platform coded with Java programming language. The data used in the simulation experiment is explained below.

4.1. The Topology of the Road Network in The Hague. Figure 3 displays the road network of the Zuidvleugel region (around Rotterdam and The Hague). The blue color indicates the part of the road network that is used for the simulation study, which includes eight districts of The Hague and the towns of Voorburg, Rijswijk, and Wateringen. The dots are the centroids of the traffic analysis zones (TAZs), which are the origins and destinations of all travel requests. The data containing the aggregated OD matrix, departure time distribution, and information about the study area centroids and the road network are exported from OmniTRANS transport planning software.

4.2. Detailed Travel Demand. The OD trip table containing a total of 27,452 trips made by cars is used as the input to generate time-dependent travel requests. The OD trip table specifies travel demand between TAZs in the AM peak hours over the study area. The departure time fractions shown in Figure 4 are used to calculate the number of trips between OD pairs per 15-minute time interval from 5:30 am to 10:00 am. A demand generator (see Appendix) generates time-dependent travel requests based on the aggregate travel demand. Individual travel requests are characterized by the origin zone, destination zone, and time of the request.

4.3. Simulation Parameters. The traffic parameters provide information about the traffic flow characteristic of the regular driving vehicles (that are not in platoons). In platoon

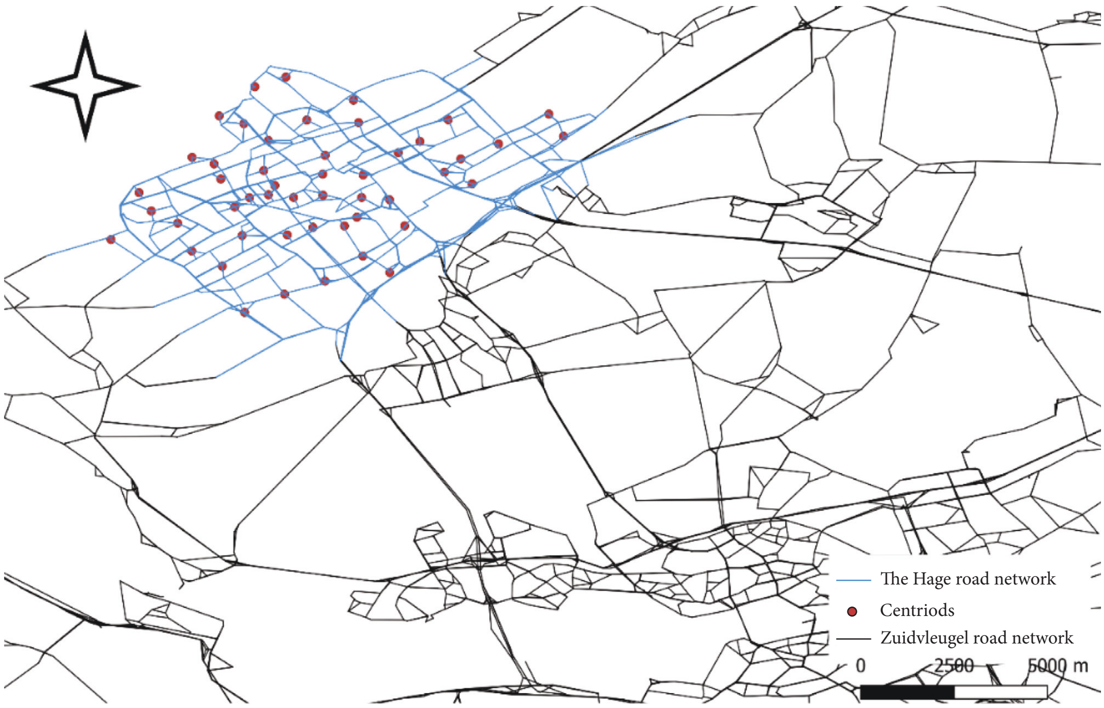

Figure 3: Road network of The Hague in the Zuidvleugel road network.

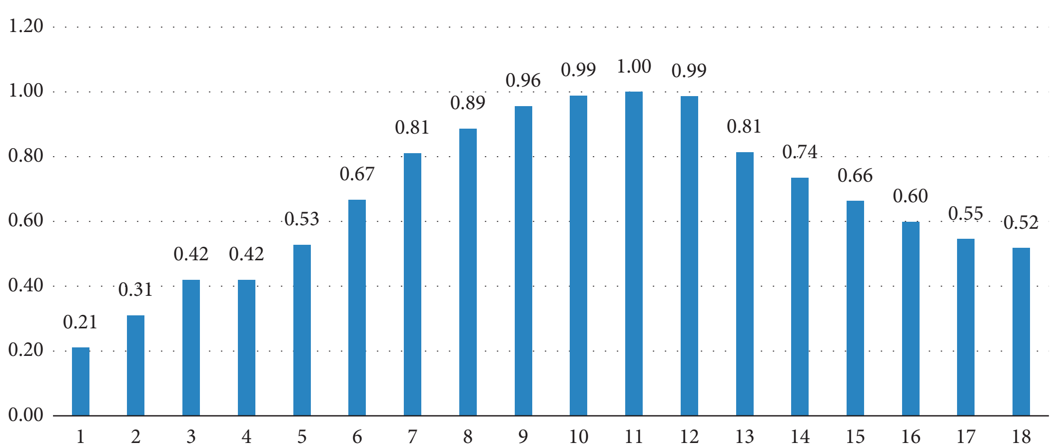

Figure 4: Departure time fractions for 18 time intervals from 5:30 am to 10:00 am.

driving, intervehicle distance (d_p) is determined based on the field experiments [37, 38]. We test different platoon formation strategies and compare their performance while treating the parameter d_p as fixed.

The vehicle models used for the energy estimation are these commonly sold electric vehicles: Nissan Leaf SV 2013, Kia Soul Electric 2015, Nissan Leaf 2012, BMW i3 BEV 2014, Ford focus Electric 2013, Mitsubishi 1 MiEV 2012, Chevrolet Spark EV 2015, and Smart EV 2014. The coefficients used in equation (1) are adopted from the work by reference [32] (see Table 2).

We assume that SAEVs can be charged rapidly to 80% of the battery capacity in 30 minutes at every service point. All types of SAEVs initially have a battery level of 24 kWh. The value of η used in estimating the energy consumption in equation (3) is determined based on a trial-and-error approach. It must be guaranteed that no travelers are stranded due to insufficient battery power of assigned vehicles. We repeatedly ran the simulation model by increasing the value of η until the estimated energy E_e is sufficient for each assigned vehicle to complete the intended trip. SAEVs are deployed over the designated service points in proportion to the amount of travel demand at the corresponding service point. 49 TAZs are connected to the road networks using zone centroids. The 49 locations of the centroids in the road network are designated as service points in the urban AMoD system. Table 4 gives a summary of the main model parameters.

INPUT: information about a list of arriving vehicles $A = \{a_0, a_1, \ldots, a_m\}$. The information Z_{a_i} for vehicle a_i can be represented by a set $\{a_i, r_i o_i, d_i\}$. Origin o_i is the service point that vehicle a_i is moving towards and destination d_i represents the next service point. r_i is the shortest route between o_i and d_i.
FOR each arriving vehicle a_i in the set A
  Compare information $\{a_i, o_i, d_i\}$ $(i = 1, 2, \ldots, m)$ to the information $Z_{p_j} = \left\{p_j, r_{p_j}, o_{p_j}, d_{p_j}\right\}$ $(j = 1, 2, \ldots, n)$ of existing platoons' leaders $P = \{p_0, p_1, \ldots, p_n\}$
  IF $(Z_{a_i}(o_i, d_i) == Z_{p_j}(o_{p_j}, d_{p_j}))$ AND platoon size s_j of the platoon p_j is not reached)
    Add vehicles a_i to the platoon p_j as a follower;
    Adjust the vehicle's shortest route r_i to the platoon shortest route r_{p_j};
    Remove vehicle a_i from the set A;
  ENDIF
  Continue
  FOR each arriving vehicle a_X in the set A
    IF((a_i is not connected to a_X)AND$(a_i \neq a_X)$AND $Z_{a_i}(o_i, d_i) == Z_{a_x}(o_x, d_x)$AND the number of connected vehicles for $a_i <$ platoon size V))
      a_i and a_X are paired, and the connection between a_i and a_X is established;
      IF a_X is not in the destination group d of vehicle a_i
        Let the vehicle a_X join the destination group d ;
      ENDIF
    ENDIF
  ENDFOR
  Remove vehicle a_i from the set A;
  Vehicles that are not paired move as individual vehicles;
ENDFOR
OUTPUT: Platoons of vehicles and regular driving vehicles that are not in platoons

Algorithm 1: Pseudocode for the formation of platoons.

INPUT: Groups of vehicles
FOR grouped vehicles in each destination group D
  Determine the leader for the grouped vehicles $d_k \in D$;
  Initiate a platoon p_k according to the platoon leader's information (location and shortest route);
  Assign the other vehicles in the group into the new platoon as followers;
  Determine the vehicle sequence according to the arrival time;
  Adjust the shortest routes of the followers in p_k to the shortest route of the platoon leader r_{p_k};
ENDFOR
OUTPUT: Platoon plans, including platoon ID, a leader and its followers, a platoon route, the vehicle sequence

Algorithm 2: Pseudocode for determining platoon plans.

5. Simulation Results and Discussion

Twenty-five effective simulation scenarios are considered for the following purposes. First, scenarios for platoon formation policies are simulated to investigate how the formation of platoons affects the level of service provided to travelers. Second, demand for AMoD services with or without forming platoons may influence the AMoD service levels provided. Therefore, we design simulation scenarios with different demand levels. Third, simulation experiments are conducted to evaluate the impact of forming platoons on energy consumption for different car models under different formation policies. Table 5 gives detailed explanations of the main KPIs.

5.1. Analysis of Service Levels in Platoon Scenarios

5.1.1. Platoon Delays of Travelers in Platoon Vehicles. We analyze the system's performance with the platoon formation in terms of the platoon delay of travelers in the platoon vehicles at different demand levels. As shown in Table 6, demand for AMoD services (as input) is varied from 100% to 20% of the total private car trips in the study area. Fleet sizes at different demand levels in Table 6 are calculated based on the same scale factor as the decrease in the travel demand. For every demand level, platoon formation policies (T, V) (T stands for the time threshold and V for the platoon size threshold)) are defined. We simulate the scenarios with platoon formation policies (T2, V2), (T4, V4), (T6, V6), and (T8, V8), where T2 means the maximum waiting time is 2 minutes and V2 represents the maximum platoon size equals 2.

Simulation results in Table 6 show that the increased values of two attributes (from (T2, V2) to (T8, V8)) for the platoon formation lengthen the platoon delays of travelers in platoon vehicles. Under the platoon formation policies (T8, V8), the platoon delay of travelers inside platoon

Table 3: Summary of traffic-related parameter values for different road types.

Road types	Capacity (vehicles per hour per lane)	Free-flow Speed (km/h)	Saturation flow (vehicles per hour per lane)	Speed at capacity (km/h)	Jam density (vehicles per km)
Urban road 1	1200	50	1200	35	120
Urban road 2	1200	50	1200	35	120
Urban road 3	1575	50	1575	35	120
Urban road 4	1600	50	1600	35	120
Urban road 5	1633	50	1633	35	120
Rural road	1350	50	1350	35	120
Local road	900	50	900	35	120
Local road	900	30	900	25	120

Table 4: Summary of the main model parameters.

Category	Value
The perimeter of the study area	46 km
The size of the study area	139 km^2
Time steps for speed update	6 seconds
Intervehicle distance (d_p) in platoons	6 meters
Avg. fleet size per service point (vehicles) for 100% demand	170
Service points (centroids of the zones)	49
Road segments	836
Road nodes	510
Total travel demand	27452 trips
Maximum number of platoon vehicles	{2, 4, 6, 8} vehicles
Time threshold for platoon leaders	{2, 4, 6, 8} minutes
Charging time	30 minutes
Coefficients η	3.05
Battery initial capacity	24 kWh
Average travel time under light traffic	18 minutes

vehicles is about 3.67 minutes, which is more than five times the platoon delay of travelers under the policy (T2, V2). Results suggest that the formation of platoons can cause long unexpected delays for travelers in the platoon vehicles.

Moreover, results suggest that the delay of travelers in platoon vehicles tends to increase as the demand level decreases. For example, the delay of travelers in platoon vehicles increases by 25% when demand falls from 100% to 20% of the total private car trips under the formation policy (T8, V8). Few travelers requesting AMoD services cause more delays for the travelers in platoon vehicles, while a relatively large number of AMoD users lead to smaller platoon delays. There tends to be an inverse relationship between the demand level and platoon delays.

In order to look into the platoon delay encountered by travelers in more detail, the delay of travelers with platoon leaders are presented in Table 7. Results indicate that the delays experienced by the travelers with platoon leaders are approximately twice that of other platoon vehicles with the formation policy (V8, T8). That is, travelers who are with platoon leaders have to wait longer than travelers in other vehicles of the platoon. The platoon formation has considerably more impact on the level of service provided to travelers with the platoon leaders. Since vehicles in the formed platoon are arranged in order of arrival, the platoon leader arrived early at the service point and waited the longest for the other vehicles to form a platoon. The platoon delays are getting smaller and smaller for the followers that arrive later.

5.1.2. Congestion Levels and Network Travel Times. We investigate the impact of forming platoons on network traffic performance. The indicator of the network congestion level (explained in Table 5) is defined to evaluate travel conditions under different platoon formation scenarios. The congestion levels in nonplatoon scenarios are used as a baseline for comparison.

Moreover, we measure the network travel time of all travelers (in platoons and not in platoons) and platoon travel times of travelers in the platoon vehicles. Note that the platoon delay is not included in the network travel time, while the platoon travel time is calculated by the platoon delay plus the network travel time.

Results in Table 8 show that the platoon formation can reduce the congestion levels and network travel times for all travelers. Compared to the nonplatoon scenario, the formation policy (T2, V2) obtains a minimal reduction of 18% in the congestion level, resulting in a reduction in the network travel time of about 3 minutes. The formation policy (T8, V8) reduces the congestion level by up to 41.61%, which is equivalent to a reduction in the network travel time of about 7 minutes. This is because more vehicles are coordinated in platoons as the values of the two attributes (T, V) in the platoon formation policy are increased. As shown in Table 8, the total number of vehicular trips in platoons rose from 5564 to 8056 trips. Figure 5 shows that the number of platoon vehicles circulating in the transportation network increases (from the policy (T2, V2) to the policy (T8, V8)). The more the vehicles travel in platoons, the more the road capacity gets increased. The increased road capacity leads to an improvement in the network travel time.

Furthermore, as shown in Figure 6, the number of vehicles circulating in the transportation network decreases as the number of vehicles traveling in platoons (see

Table 5: Description of the main KPIs.

Key Performance Indicator	Description
Delay of travelers in platoon vehicles	The time delay of platoon vehicles is the average dwell time that platoon vehicles (platoon leaders and platoon followers) spend at formation points without moving.
Delay of travelers with platoon leaders (platoon delay for leaders)	The time delay of platoon leaders is the average dwell time that platoon leaders spend at formation locations without moving.
Network travel time	The network travel time is the in-vehicle time spent on average by all served travelers when vehicles are traveling from origin to destination. Platoon delays are not included in the network travel time for travelers in platoon vehicles.
Platoon travel time	The platoon travel time is calculated by the platoon delays plus the network travel time of travelers in platoon vehicles.
Congestion level	The congestion level describes how much longer, on average, vehicular trips take during the AM peak hours compared to the average travel time in light traffic conditions. The average travel time in light traffic in the case-study city is estimated based on the travel speed suggested by Ligterink [39].
90% quantile travel time	The 90% quantile travel time indicates the travel time which is longer than 90% of the trips.
The percentage of energy savings	The percentage of the reduction in the energy consumption of all the vehicular trips in the platoon scenarios compared to the nonplatoon baseline scenario.

Table 6: Average delay of platoon vehicles for different demand levels.

Demand levels	100%	80%	60%	40%	20%
The number of travel requests (trips)	27452	21962	16417	10980	5490
Avg. fleet size per service point	170	136	102	68	34
Platoon scenarios			Avg. delay of platoon vehicles (minutes)		
(T2, V2)	0.66	0.66	0.66	0.66	0.66
(T4, V4)	2.30	2.30	2.38	2.51	2.75
(T6, V6)	3.23	3.22	3.29	3.50	3.67
(T8, V8)	3.67	3.67	3.87	4.01	4.62

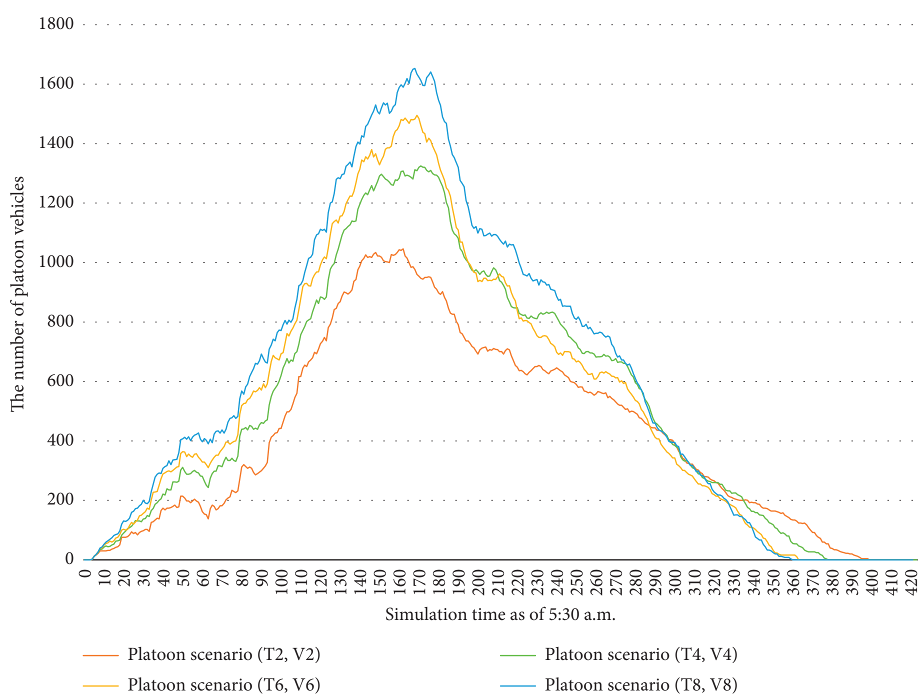

Figure 5: The number of vehicles traveling in platoons on the network over time.

Figure 5) increases. The formation of platoons decreases the number of vehicles circulating in the transportation network. When the number of vehicles circulating in the transportation decreases, travel conditions are improved. As a result, vehicles can travel faster through the road network.

As shown in Figure 6, the duration during which a high number of vehicles circulates in the transportation network

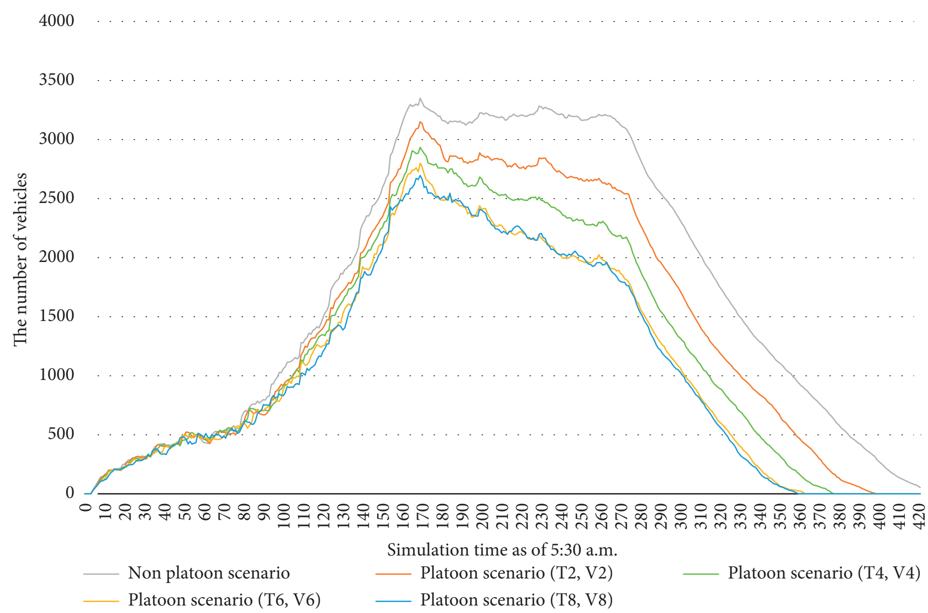

Figure 6: The number of all vehicles circulating in the network over time (in platoons and not in platoons).

is reduced in platoon scenarios compared to the scenario without forming platoons. The duration is shorter and shorter as more and more vehicles travel in platoons over the transportation network. The result suggests that the platoon formation could reduce the duration of urban road congestion.

We compare the 90% quantile travel time in the platoon scenarios to the nonplatoon scenario to take a closer look at how the formation of platoons affects network travel times. Shorter 90% quantile travel times imply reductions in the network travel times. Results in Table 8 show that the formation of platoons can reduce the 90% quantile travel times. The 90% quantile travel times are about 44 minutes for the policies (T6, V6) and (T8, V8), which is 30 minutes less than that in the scenario without the formation of platoons. The results indicate that the network travel conditions are significantly improved by the formation of platoons.

Overall, the formation of platoons could reduce the road congestion level and shorten the congestion duration. On average, travelers can travel faster across the urban road network. Moreover, the number of vehicles circulating in the transportation network affects the (network) reliability [40]. Therefore, the platoon formation has the potential to improve the travel time reliability.

5.1.3. Platoon Travel Times. The formation of platoons could cause platoon delays of travelers in the platoon vehicles while reducing network travel times. We found that the platoon travel time, including the platoon delay of travelers in platoons and network travel time, is shorter than the network travel time in the nonplatoon scenario. Results of simulating a high-demand scenario where the AMoD system serves 100% of commuter trips made by private car show that formation policies (T6, V6) and (T8, V8) have more than 1 minute less in the platoon travel times than the in-vehicle travel time of travelers in the nonplatoon scenario (see Table 8). The reason for this is that the reduction in the network travel times offset the platoon delays, leading to a shorter platoon travel time.

Although the platoon formation can reduce network travel times, travelers in the platoon leaders face longer unexpected delays. This led to a long platoon travel time (27 minutes) of travelers in the leaders, similar to nonplatoon scenarios where high congestion is present.

Moreover, we found that the formation of platoons cannot improve network travel time in the low-demand scenario. For example, the 90% quantile (network) travel time is found at around 13 minutes and is not reduced by the formation of platoons when the demand level is below 60% (see Table 9). This suggests that platoon driving has no effect on traffic when demand is low but only delays travelers in the platoon vehicles.

5.2. Energy Consumption Analysis with the Platoon Formation. We evaluate the impact of forming platoons on the system-wide energy consumption for different vehicle types. Results in Figure 7 indicate that the formation of platoons can reduce the total energy consumed by all vehicles in the AMoD system. The greatest reduction of total energy consumption ranges from 0.42% for the Kia Soul Electric 2015 to 9.56% for the Ford Focus Electric 2013. Moreover, more savings are achieved when the time threshold (V) and the vehicle size threshold (T) for platoon release are increased. The reason is that more vehicles are coordinated in platoons, which results in more vehicles driving in platoons. Less congestion occurs when more platoon vehicles circulate across the transportation network, indicating improvements in traffic efficiency. Therefore, more energy can be saved when platoons are formed.

Table 7: Platoon delays for platoon leaders and platoon vehicles under different operating policies.

The time threshold (minutes)	Nonplatoon (0)	2	4	6	8
The platoon size threshold (vehicles)	Nonplatoon (1)	2	4	6	8
Platoon scenarios	No platoons	(T2, V2)	(T4, V4)	(T6, V6)	(T8, V8)
Avg. delay of platoon leaders (minutes)	0	0.69	3.49	5.67	7.02
Avg. delay of platoon vehicles (minutes)	0	0.66	2.30	3.23	3.67

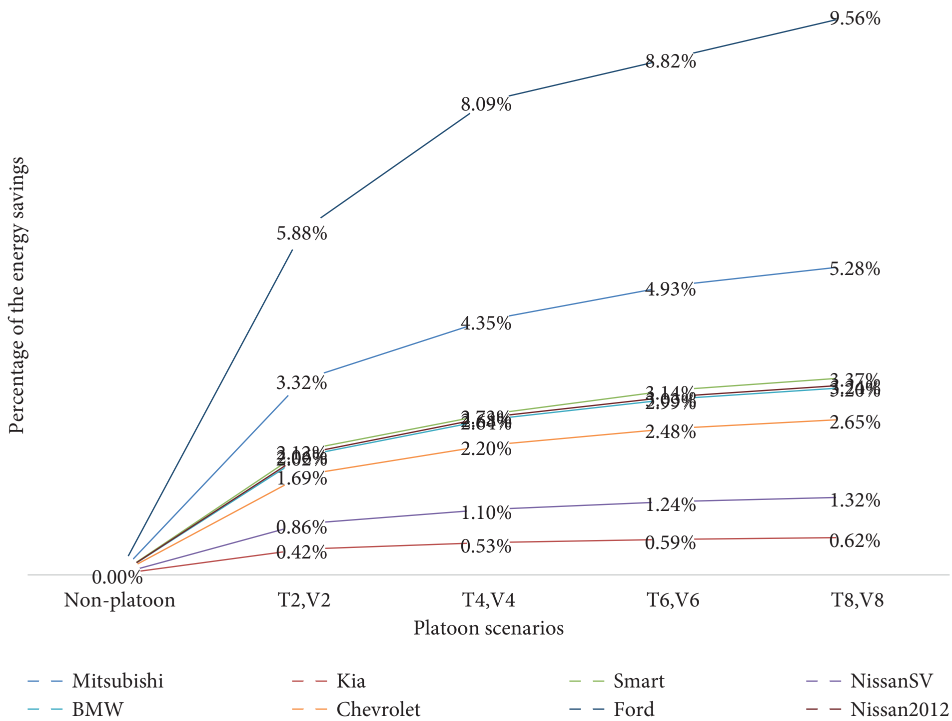

Figure 7: Total energy savings of AMoD systems for different types of electric vehicles (T represents the time threshold of platoon leaders, and V is the maximum number of platoon vehicles.).

Table 8: Congestion levels, network travel times, and platoon travel times at 100% demand level.

Indicators	Congestion levels (%)	Network travel time for all vehicles (minutes)	The total number of vehicular trips in platoons	90% quantile (network) travel times (minutes)	Platoon travel time of travelers in platoon vehicles (minutes)	Platoon travel time of travelers in platoon leaders (minutes)
Nonplatoon scenario	53.28	27.59	No	70.05	No	No
(T2, V2)	35.28	24.35	5564	59.86	25.01	25.04
(T4, V4)	20.39	21.67	6899	51.12	23.97	25.16
(T6, V6)	13.56	20.44	7611	44.20	23.67	26.11
(T8, V8)	11.67	20.10	8056	43.70	23.77	27.12

Results in Figure 7 show that energy savings are different from vehicle types when applying the same formation policy. The maximum saving of up to 9.56% is achieved for Ford Focus Electric 2013 in the (T8, V8) formation policy, while the Kia Soul Electric 2015 has the lowest energy saving of 0.42%. This is because the difference in vehicle characteristics for energy consumption leads to different energy savings. The energy consumption model contains a set of regression models corresponding to the different vehicle types. The regression model, derived from laboratory dynamometer tests, is used to calculate energy consumption as a function of travel speeds. In urban driving, the vehicles will consume more energy at lower speeds, while the energy consumption of individual vehicles will decline as the vehicle speed increases. Thus, vehicles will consume less energy per unit distance traveled with an increase in the travel speed. However, the modeled energy performance of different car types is different. The vehicle type with the sharpest gradient of modeled energy consumption-speed function will see the biggest reduction in energy consumption when having the

Table 9: The 90% quantile (network) travel time at different demand levels.

Demand levels	100%	80%	60%	40%
The number of travel requests (trips)	27452	21962	16417	10980
Avg. fleet size per service point	170	136	102	68
Indicator	The 90% quantile (network) travel times (minutes)			
Nonplatoon scenario	70.05	31.52	15.13	13.49
(T2, V2)	59.86	28.34	14.10	13.50
(T4, V4)	51.12	26.37	13.95	13.17
(T6, V6)	44.20	20.71	13.81	13.38
(T8, V8)	43.70	19.67	13.89	13.41

same increase in the vehicles' speed. The Ford Focus Electric 2013 has the steepest decline in energy consumption-speed function; therefore, when the speed of the vehicle increases, the Ford vehicle type has the most reduction in the energy consumption. The energy saving of the Kia Soul Electric 2015 that has the least steep gradient of the energy consumption function ranks at the bottom.

We find that the degrees of energy savings strongly depend on the vehicle types as well as platoon formation policies. Coordinating more vehicles in platoons can significantly improve the energy efficiency for some vehicle types. However, the improvement in energy efficiency for certain vehicle types is relatively small because of the energy consumption characteristics.

6. Conclusions and Recommendations

6.1. Main Conclusions. The formation of platoons in the urban AMoD system is more complicated because of the urban road network characteristics (narrow streets and multiple road segments between locations), platoon formation locations and policies, and the interaction between AMoD service users and SAEVs. The goal of this study is not to develop a very sophisticated method but to show through agent-based simulations how the formation of platoons in AMoD systems affects people's travel and system-wide energy consumption.

Shared AVs could lead to more traffic and longer travel times due to the additional zero-occupancy movements. In the scenario where SAEVs replace all morning urban commuter trips (100% demand) made by private cars in the case-study city, without the formation of platoons, a high network congestion level of up to 53.28% is observed.

However, the network travel times and congestion levels are improved in the formation of platoons. For example, a congestion level of 11% can be achieved under the policy (V8, T8). That is, for 30 minutes of travel time, 3.3 minutes of additional time must be spent during the rush hours. The extra time spent is far smaller than the time spent either in the nonplatoon situation where SAEVs replace the private car trips or in the current situation where private cars are used. In the first situation, travelers spent extra 15.98 minutes with a 53.28% congestion level. In the second situation, additional 10 minutes is spent in the case-study city (https://www.tomtom.com/en_gb/traffic-index/). In the formation of platoons, travelers are more likely to reach their destination on time or early with the improvement in the network travel times.

We also find that the 90% quantile travel times are significantly reduced in the formation of platoons. This suggests that the network travel times are improved without causing extremely long travel times when platoons are formed even though additional (zero-occupancy) movements are generated in AMoD systems.

Simulation results demonstrate that the number of total vehicles circulating in the transportation network is reduced by the formation of platoons, which could lead to improved network travel time and reliability. Furthermore, the improved network travel time and reliability could improve the quality of time spent in the vehicles across the transportation network. In this respect, the platoon formation could improve the quality of services offered to all service users (in platoons and not in platoons) when they travel on the transportation network.

On average, the platoon travel time, including the platoon delay and the network travel time, is less than the network travel time in nonplatoon scenarios where all morning commuters use AMoD service. That implies that travelers in the platoon vehicles could reach their destination faster even if they experience unexpected delays in the formation of platoons, suggesting improved service levels. In this respect, the benefits from network travel time savings may outweigh the cost associated with the platoon delays. Travelers may opt for the AMoD service in response to service improvements in the formation of platoons.

To be specific, we find that travelers in the platoon leaders experience longer platoon travel times due to longer unexpected platoon delays. In this regard, AMoD service users (morning commuters who were previously driving private cars) in the platoon leaders are provided with a low level of service. Travelers in the platoon leaders may be reluctant to use AMoD services.

We find the existence of an inverse relationship between platoon delays and demand levels. The platoon delays encountered by travelers in platoon vehicles are small in a high-demand scenario. This implies that forming platoons when the market penetration rate of AMoD services is high leads to lower platoon delays. In contrast, travelers face long unexpected platoon delays with fewer AMoD service users. In the former case, the network travel times can offset the platoon delays travelers' encounter in the platoon vehicles. Consequently, travelers in platoon vehicles have shorter platoon travel times (total travel times of travelers in the platoon vehicles). In the latter case, no congestion occurs in the transportation network when few travelers request services (this may happen during off-peak hours); coordinating vehicles in platoons only causes unexpected delays for travelers in the platoon vehicles. Forming platoons when demand is low (e.g., below 60% demand) only causes delays for travelers in the platoon vehicles, suggesting a lower level of service. As a result, travelers may not be willing to use the AMoD service. Therefore, a high penetration rate of AMoD service is expected to coordinate vehicles in the formation of platoons to benefit the service users in such vehicles in future AMoD systems.

An important finding is that the improvement in traffic efficiency leads to system-wide energy savings. Forming platoons in AMoD systems can save about 9.56% of the system-wide energy consumption for the most efficient car model studied in urban areas. However, energy savings strongly depend on the vehicle characteristics for energy consumption and platoon formation policies used. Demand for AMoD services and operating policies for forming platoons are important variables of interest for obtaining travel and energy benefits from platoon driving. Effective platoon formation strategies need to be developed for different car models to obtain a favorable effect on system-wide energy consumption.

At the city scale, the formation of platoons enabled by vehicle automation could reduce travel times and unreliability in the modeled urban road network. This may influence their choices of residence with the improvement in travel times and the reliability of urban commuters. It can be inferred that automated mobility systems may have a detrimental impact on urban sprawl, leading to rapid urban expansions. Moreover, platoon operations effectively reduce energy computation in urban mobility systems. While energy consumption is reduced, emissions reductions could also be achieved in the formation of platoons. Thus, platoon operations could bring benefits to operators with regard to energy savings and to society in terms of emissions reductions.

The findings of this study contribute to the growing body of literature on the study of shared AV fleets by quantifying the impact of innovative platoon formation operations on AV energy consumption as well as people's travel. We shed light on the energy aspect of platoons in urban AMoD systems to complement the existing studies on the fuel consumption of platoons on highways.

6.2. Recommendations for Policy and Future Research. The findings of this paper raise challenges for policy and for research. The findings suggest that the formation of platoons in AMoD systems can reduce system-wide energy consumption. Platoon operations can be considered as an effective energy-saving and decarbonization strategy to achieve the government's energy and environmental goals. Moreover, it is recommended that policymakers and transport operators consider the vehicle characteristics for energy consumption in conjunction with platoon formation policies to develop effective energy-saving platoon strategies in future AMoD systems.

Developing platoon formation strategies over urban road networks is recommended aiming at improving traffic efficiency, leading to travel time reductions. However, we find that the magnitude of demand for AMoD services could influence the users' travel times and quality of time. Therefore, the magnitude of demand needs to be considered when deciding whether to coordinate vehicles in platoons. For example, forming platoons below 60% demand over the urban road network only causes unexpected delays. Travelers are reluctant to use the AMoD service due to the long unexpected platoon delays. In this regard, we recommend not forming platoons in the uncongested network with fewer road users (e.g., below 60% demand in the study area, which is the case during off-peak hours). At the same time, vehicles can be coordinated in platoons when congestion occurs to reap the benefits of improving travel times and energy efficiency.

Furthermore, travelers, especially those who travel in the platoon leaders, may not be willing to use AMoD service due to the long unexpected delay and long travel time. For policymakers and transport operators, careful consideration is required to reward the travelers who suffer long unexpected delays in the formation of platoons, which the system's benefit from energy savings can be distributed.

Further research efforts are required to develop mechanisms for distributing the energy benefits, in order to incentivize engagement to make the system more sustainable, efficient, and equitable.

The modeling framework presented here still has some limitations that could be improved in future research. Relocation capability is not developed and implemented in the model. Relocation operations in anticipation of future demand can mitigate the imbalance between vehicle supply and travel demand. Relocating platooned vehicles in urban driving conditions can be further investigated.

The traffic simulation model can estimate the traffic impact of forming platoons using mesoscopic operating characteristics. It can meet the design requirements of determining time-dependent link flows and route travel time according to the relationship established between road capacity and the formed platoons. Hence, the traffic simulation model allows testing different strategies in forming platoons on the network level. However, the mesoscopic model applied to single-lane urban scenarios cannot capture the microscopic traffic behavior such as accelerating, overtaking, lane-changing, and traffic behaviors at intersections. Moreover, the relationship established between formed platoons and road capacity is only meant for the capacity of a single lane for each direction according to the platoon characteristics. This is acceptable for urban driving conditions in most (European) cities with narrow streets (one lane for each direction). However, the traffic simulation component cannot model mixed traffic conditions under multiple-lane scenarios. Operational capacities in multilane scenarios depend on lane policies to distribute platoon vehicles. Modeling multiple-lane capacity with the formation of platoons remains an unsolved challenge in the literature.

Appendix

A. The detailed derivation of a single-lane capacity formulation for mixed traffic

We use the following definitions of different critical spacing types according to the operational characteristics of vehicle platooning. The critical spacing when vehicles travel regularly (e.g., AVs that are not in platoons) is defined as d_a. The critical spacing for platoon driving is defined as d_p. Except for the platoon leader, the platoon followers will follow the preceding platoon vehicles at a distance of d_p when capacity C is reached. Since platoon vehicles have a smaller following distance, then $d_a > d_p > 0$. We define $d_p = \alpha d_a$, where $0 < \alpha < 1$. We assume that the critical spacing between a platoon vehicle and a regular driving vehicle that is not in a platoon is also d_a. It means that the critical spacing between a platoon leader and any preceding vehicle traveling regularly (that is not in a platoon) is d_a. The platoon size n_i is the number of vehicles in platoon i. We denote the number of platoons as P and the number of regular driving vehicles in the traffic as M. The total number of vehicles in platoons N is $\sum_{i=0}^{p-1} n_i$. We define the total number of platoon leaders L, where $L = P$ (each platoon has one leader).

According to the definitions and assumptions in this study, mean critical spacing in the work [35] is formulated as follows:

$$\begin{aligned} d_c &= \frac{\left(\sum_{i=0}^{p-1} n_i - L\right)\alpha d_a + (M+L)d_a}{M+N} \\ &= \frac{(N-L)\alpha d_a + (M+L)d_a}{M+N} \\ &= \left(1 - \frac{N(1-\alpha)(1-(L/N))}{M+N}\right)d_a, \end{aligned} \tag{A.1}$$

where $M > 0, N > 0$. Denote $\varphi = (N/M+N)$ and $\omega = (1-\alpha)(1-L/N)$, thus $0 < \varphi, \omega < 1$. Equation (A.1) can be rewritten as follows:

$$d_c = (1 - \varphi\omega)d_a. \tag{A.2}$$

The single-lane capacity C_c is expressed as

$$\begin{aligned} C_c &= \frac{v_0}{d_c} \\ &= \frac{v_0}{(1-\varphi\omega)d_a} \\ &= \frac{C_a}{(1-\varphi\omega)}. \end{aligned} \tag{A.3}$$

Clearly, we have $C_c > C_a$ $(M > 0, N > 0)$, where C_a denotes the lane capacity for all vehicles traveling regularly. The capacity C_c depends on the penetration rate of platoon vehicles φ and the number of leaders (L) $(\omega = (1-\alpha)(1-(L/N)))$. A smaller distance spacing between platoon vehicles allows an increase in the lane capacity—the lane capacity increases as the penetration rate of platoon vehicles φ. Moreover, for the same number of platoon vehicles N, the more leaders L are created, the less capacity increases. When all the vehicles (SAEVs) travel regularly $(N = 0)$, we have $d_c = d_a$, then $C_c = v_0/d_c = v_0/d_a = C_a$. Platooned vehicles can move with a reduced spacing d_p. If all vehicles are grouped into platoons $(M = 0)$, then $d_c = d_p$ and we have $C_c = v_0/d_c = v_0/d_p = C_p$. C_p denotes the lane capacity when all vehicles are driving in platoons. We get $d_p \le d_c \le d_a$, then $C_a \le C_c \le C_P$.

B. A demand generator

The proposed demand generation process is divided into two steps:

The first step is to generate a certain number of time-dependent travel requests for each zone over each time interval (i.e., 15 minutes). The total production of demand in the morning peak hours for each zone is calculated based on the origin-destination (OD) matrix, and the demand per time interval is estimated using the departure time fractions. In each time interval, a number of travel requests are generated, which are then distributed according to a discrete uniform distribution within this time interval. The generated travel requests in each time interval are associated with a specified time of requesting the service.

The second step is to determine a destination zone for each demand request. Observations of destinations for the generated trips in each zone are naturally available in the OD matrix. That is, the number of trips ending in every other zone is known. For each zone, a custom distribution of demand destinations is constructed from the observations. A destination zone for each travel request can be chosen using the Monte Carlo simulation process based on the destination distribution.

Data Availability

The data that support the findings of this study are available from the authors upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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