Optimal Strategy for Autonomous-Vehicle-Dedicated Lane Deployment on Freeway with City Planning and Market as Driving Force

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Abstract. This paper proposes a computationally effective mathematical procedure to deploy Autonomous Vehicle (AV)-dedicated lanes considering different AV market penetration rates and the influence of in-advance infrastructure construction behavior offered by the city planning department. With different expected AV market penetration rates, the corresponding limit of the total length of AV-dedicated lanes is put on the network to ensure the infrastructure construction moves ahead of the market performance of AVs, by improving the objective driving conditions to promote people's willingness and enthusiasm about AVs. MSA method is used to solve the UE traffic assignment problem with two types of traffic flows. A new measure to find optimal AV-lanes deployment location is formulated by calculating and comparing the instantaneous total paired-links travel time changes iteratively. The results show that the network can benefit from the newly constructed AV-lanes when the AV market penetration rate is lower than 55% and the total network travel time might increase once the AV market penetration rate is higher than 65%. Suggestions are given for city planners on how to use planning and zoning as tools to navigate the development of AVs to improve the overall living environment.

Keywords: Autonomous vehicles · Transportation modeling · City planning

1 Introduction

Autonomous Vehicles (AVs) have become a major component of future infrastructure planning. Many companies, including Tesla, are actively pursuing tremendous growth for the automation of vehicular transport. Deploying AVs on roads promises exceptional operational benefits. Some of the future advancements, such as V2X communications and platooning, pledge substantial safety and travel time refinement. The potential benefits that AVs will bring are emphasized by numerous studies [3, 4, 8, 10].

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Even though the advent of AVs is fast approaching, it does not mean that Conventional Vehicles (CVs) on roads are going to be changed to AVs in a moment. We will experience heterogeneous traffic flow until CVs can be completely phased out. Considering the purchase cycle of CVs and the expected high price of AVs, the transition period will last for a significant amount of time.

Therefore, governments are required to find ways to maximize the promising outcomes from the emergence of AVs during the transition period in addition to the period after. The behaviors of AVs are different from those of CVs. The characteristics of the mixed traffic flow of AVs and CVs should be considered properly. Taking those characteristics into consideration, governments will be able to plan future transportation infrastructure and weigh against different policy interventions to retrieve the full benefit of AVs.

Some infrastructure adaptations, such as AV-dedicated lanes [2, 5, 7, 10, 12, 14, 15] and AV-only links/zones [3], have been suggested as the ways to promote the adoption of AVs and improve the traffic flows. Accordingly, the impacts of AV-lanes and AV-only links/zones on traffic flow have also been studied. For example, Jordan Ivanchev et al. (2019) investigated how the road network performance of Singapore changes with the increase in the percentage of AVs in the region using AV-lane and no-AV-lane scenarios.

The expected growth of AV users points to the notion that the deployment of AV-dedicated lanes is one of the most optimal solutions to maximize the benefits of such technology. Examples of such benefits are to maximize the efficiency of AV Vehicles and to incentivize the adoption of autonomous vehicles. However, putting AV-dedicated lanes or AV-only links/zones does not always bring positive outcomes. Even when the capacity of a lane increases when the lane is transformed into an AV-dedicated lane, the overall performance of the whole road network could deteriorate [10]. Consequently, the location, total length, and the number of lanes of AV-dedicated lanes should be decided with deliberation. In other words, a network design problem should be defined to optimize the deployment of AV-dedicated lanes. This design problem must be capable of addressing the issue of decreased network performance in the initial stages of AV deployment. In short, the dedicated lanes must be deployed promptly while minimizing their impacts on the existing traffic conditions. The overall goal of the developed algorithm would be to compare the impacts of various AV-dedicated lane deployment scenarios and choose the best deployment locations and the number of lanes for each AV-dedicated lane.

2 Previous Studies

Any major shift in policy calls for many significant changes within the existing networks. Proposing dedicated highway lanes for autonomous vehicles means a significant expenditure, which includes excessive cost and time for the implementation procedure. While the execution of the idea requires much attention, it is pivotal to discuss what are some of the long-term impacts of the dedicated AV lanes. It is a clear prediction that dedicated AV lanes will improve operational capacity, however, a lot of research is underway to investigate its pros and cons.

Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) are potential methods of improving traffic flow. However, their interaction with mixed traffic flow hinders their progress. Through a microscopic traffic simulation, the estimated capacity of a given lane was 2050, 2200, and 4550 vehicles per hour for manual, ACC and CACC, respectively [14]. This data can be used to interpret that CACC cars can potentially double the capacity of a highway lane at significant penetration levels. The effects of AVs on Sweden's roadway infrastructure showed that the average delay, average number of stops and average speed could be improved by 56%, 54% and 34%, respectively [4]. However, a significant drawback of this analysis was that mixed traffic flows were neglected. Mixed flow conditions must have been considered to mirror real-world conditions. The idea of platooning promises up to 8500 vehicles per hour per lane only if dedicated lanes are provided and the vehicles can communicate with each other. This phenomenon is known as Automated High Systems [4]. The sole goal of platooning is to enhance existing operational capacity. The highway capacity can be significantly reformed through large platoons of AVs [11]. This concept leads to a reduction in the inter-platooning distance when larger platoons are arranged. On the contrary, if mixed traffic flows are considered, it might pose a negative impact. The negative effect on highway speed that arises after the saturation points must also be considered. The effect of AV dedicated lanes on average travel time can be studied by simulating various AV penetration rates. AV dedicated lanes penalize CV drivers while incentivizing buying AVs. However, the highway capacity will be underutilized during low levels of AV penetration [12]. These results were drawn under macroscopic conditions that ignored microscopic conditions such as lane interactions. A macroscopic analysis of network flows and system level can be utilized to develop a methodology that indicates when and where the AV dedicated lanes must be deployed [5]. It was identified that the time consumption required to produce saturation level AV penetration on highways would be fairly significant. Until those levels can be achieved, Autonomous Vehicle Toll Lanes would prove to be the optimal place holders [10].

Several studies have explored strategies to recognize AV-only Link/Zones on urban road networks. The mixed Routing Equilibrium Model can be used to find the mixed routing behaviors under the scenario of heterogeneous traffic flow and a mixed-integer bi-level programming model to optimize the deployment of AV Zones, in which only AVs can operate and are guided by a central controller. It is believed that the process of optimized locating of AV Zones has a great similarity with the Cordon design problem for Cordon Congestion Pricing, thus such questions could be solved by Simulated Annealing Algorithm (SAA) [3]. To incorporate real-world conditions an optimized time-dependent deployment planning approach of AV lanes on a transportation network with heterogeneous traffic flow, consisting of AVs and CVs must be adopted. This mathematical approach could minimize the social cost to promote the ubiquitous adoption of AVs. A multi-class network equilibrium model can be used to capture the flow distribution of AVs and CVs and a diffusion model must be developed to forecast the evolution of AV market penetration [2]. A unique fundamental diagram approach that reveals the pros and cons of dedicated AV lanes under various Connected Autonomous Vehicle (CAV) penetration rates and demand levels on a three-lane heterogeneous mixed-flow network is capable of deciding the optimal numbers of lanes dedicated to AVs by simulating the dynamic relationship between CAV dedicated lane performance, CAV performance, CAV penetration rate and density [15]. With a limited number of studies focusing on AV only Zones/Links, the following questions need further discussion:

A) There is a major drawback of AV-only links/zones that the CVs need to take longer detours to finish the trip, which is the main trade-off decision-makers have to make.
B) For AV zones (AVZ), the only one-AVZ scenario is considered and simulated, the effects and efficiency of multiple AVZs on transportation networks with different AV penetration levels are not detailed formulated.
C) The existing major methodologies did not consider enough reality constraints when locating the AV zone/links on the network such as the planning regulation, neighborhood conditions, street vitality levels, etc., and are often simulated on an imaginary network, which is rather simple compared to the real-world transportation network.
D) Only urban expressways and arterial roads are included in the modeling of the AVZ locating process, minor streets are often excluded.

Even though spatial deployment of AV-dedicated lanes or AV-only links/zones matters as much as their deployment strategy, a few studies have investigated the issue. Chen et al. (2016) and Guhathakurta and Kumar (2019) used network-level design approaches to decide where, when, how the dedicated lanes should be located. For AV-only links/zones, Chen et al. (2017) suggested a framework for designing AV-only zones in a network. However, the adoption of AV Links can cause a significant disturbance to the existing transportation networks around the world causing it to be an unwarranted approach, especially until extremely high levels of AV penetration can be achieved.

While some of the literature discussed previously proves its close relevance to the topic of this paper, however, it offers some key limitations. Such as, Chen et al. (2016) fail to consider the variant capacity of link a (ca) that would suffer a disturbance due to the share of AV on the respective link (ra). Furthermore, it limits the deployment of AV dedicated lanes to only a given set of candidate links. Liu and Song (2019) considered the capacity of a link a (ca) as a function of the share of AVs on a link a (ra) using a conversion approach to determine the human-driven vehicle equivalent of the share of AVs on the respective link. The suggested methodology in that paper suggests an optimal deployment model of a generalized semi-infinite min-max program with a solution algorithm using a genetic algorithm approach. This method is computationally costly and negatively affects the efficiency of an algorithm.

This study aims to address this gap in the literature. It will focus on developing a network-level optimization framework dealing with network design problems of the deployment of AV-dedicated lanes on a freeway network system. The developed algorithm will utilize the following inputs and outputs:

Inputs:

1) the road network of a city or metropolitan region
2) O-D demand matrix
3) AV penetration rate
4) limit of total AV-dedicated lane length

Outputs:

1) where to locate the AV-dedicated lanes
2) how many lanes would be AV-dedicated for each link with AV-dedicated lanes

Compared with the previous research, the developed algorithm will have the following benefits:

1) Incorporate relationship between ra and ca
2) Maintain an overall low computational cost
3) The candidate's links for potential dedicated AV lane deployment will not be predefined.

The developed algorithm will aim to find the best AV-dedicated lane deployment strategy that minimizes the average travel time cost of road users. After developing the algorithm, the outputs on using different AV market penetration rates will be presented to show how the road network increases its proportion of AV-dedicated lanes gradually as the AV market penetration rate increases.

3 Network Equilibrium Problem and AV Lanes Deployment Problem

3.1 Methodology

This paper offers a bi-level methodological framework to get the most beneficial strategy for the deployment of AV-dedicated lanes in terms of network performance. The first level is understanding the traffic flow characteristics of vehicles on a network when AVs and CVs co-exist, which leads to a mathematical formulation for user equilibrium (UE) traffic assignments of AVs and CVs on a given network with AV-dedicated lanes in some parts of the network. The second step is to develop an algorithm that decides the locations for deploying AV-dedicated lanes to minimize the negative impact of the installation on traffic flows. With a given AV market penetration rate and the limit of the total length of AV-dedicated lanes on the network, the developed algorithm will output where to deploy AV-dedicated lanes, how many lanes for each link will be transformed to AV-dedicated lanes.

Before getting into more detail, notations that will be used throughout the explanation of the proposed methodological framework need to be set. The defined notations are summarized as shown below in Table 1:

Table 1. Basic notations

Notation	Definition
N	Set of node index
A	Set of link index of mixed-flow links = $\{1, 2, 3, \ldots, n\}$
$\widehat{A}$	Set of link index of AV-dedicated links = $\{n + 1, n + 2, \ldots, 2n\}$
R	Set of origin nodes; $R \subseteq N$
S	Set of destination nodes; $S \subseteq N$
Krs	Set of paths connecting O-D pair *r*-*s*; $r \in R$, $s \in S$
M	Set of vehicle types = $\{1, 2\}$; CVs = *1* and AVs = *2*
y_a	Number of lanes on link $a \in A \cup \widehat{A}$
t_a	Travel time on link $a \in A \cup \widehat{A}$
l_a	Length of link $a \in A \cup \widehat{A}$
c_a	Capacity of link $a \in A \cup \widehat{A}$
r_a	Share of AVs on link $a \in A \cup \widehat{A}$
p_{av}	Market penetration rate of AVs
${x_a}^m$	Flow of vehicles of mode $m \in M$ on link $a \in A \cup \widehat{A}$; $x_a = \Sigma_{m\in M}\, {x_a}^m$
${f_k}^{rs,\, m}$	Flow of vehicles of mode *m* on path *k* connecting O-D pair *r*-*s*; ${f_k}^{rs} = \Sigma_{m\in M}\, {f_k}^{rs,\, m}$
${q_{rs}}^m$	Trip rate of vehicles of mode *m* between origin *r* and destination *s* $q_{rs} = \Sigma_{m\in M}\, {q_{rs}}^m$
${\delta^{rs}}_{a,\, k}$	Indicator variable; *1* if link *a* is on path *k* between O-D pair *r*-*s*, *0* otherwise
h_{av}	Minimum headway time of AVs (in seconds)
h_{cv}	Minimum headway time of CVs (in seconds)
α_a, β_a	Positive parameters for defining link performance function of link $a \in A \cup \widehat{A}$

One noteworthy point regarding the notations in Table 1 is that the set of link indexes is divided into two: A (set of link index of mixed-flow links) and $\widehat{A}$ (set of link index of AV-dedicated links). When the network has n links, A = {1, 2, 3, …, n} and $\widehat{A}$ = {n + 1, n + 2, …, 2n}. The pair of link $a \in A$ and link (a + n) represent a specific link in the real world. Even though both link a and link (a + n) are called ‘link’, they indicate the part of mixed-flow lanes and the part of AV-dedicated lanes, respectively. Thus, if no AV-dedicated lane exists on a network, ya (the number of lanes of link a) would be 0 for all $a \in \widehat{A}$. If there are some links with AV-dedicated lanes, ya (that $a \in \widehat{A}$) for the corresponding links will be positive integers. In this study, deploying an

AV-dedicated lane on the link represented by link a and link (a + n) is decreasing ya by one and increasing ya + n by one.

3.2 Traffic Assignment Problem Under UE Condition

Algorithm Setup. In this study, we assume that vehicles can change lanes at nodes only as other studies about AV-dedicated lane deployment did [3, 10]. Besides, for simplicity, the AV market penetration rate is equally applied to all trip rates.

The link performance function that modified the link performance function from Liu and Song (2019) is given below:

$$t_a = t_a^0\left(1 + \alpha_a\left(\frac{x_a}{c_a}\right)^{\beta_a}\right)$$

The t_a^0 is the free-flow travel time of link $a \in A \cup \widehat{A}$. The α_a and β_a are the constant parameters for the link performance function of link a. The c_a denotes the capacity to link a which is a function of the share of AVs on link a. The $\mathrm{c_a}$ below is the modified version of Ivanchev et al. (2019).

$$c_a = \frac{3600}{h_{av} r_a + h_{cv}(1 - r_a)} * y_a$$

Here the h_{av} and h_{cv} are respectively the headway time of AV and CV in seconds, which are constant numbers we concluded from related studies. The r_a is the share of AVs on link a. It is acquired by divide AV flow on link a by the total flow:

$$r_a = \frac{x_a^2}{x_a^1 + x_a^2}$$

Considering that we defined the set of vehicle types $\mathrm{M} = \{1, 2\}$, in which 1 represents CVs and 2 represents AVs and separated the set of link index into two sets, A and $\widehat{\mathrm{A}}$, the UE traffic assignment problem can be defined as shown below:

$$z(x) = \sum_{a \in A \cup \widehat{A}} \int_0^{x_a} t(w)dw$$

Subject to:

$$\textstyle\sum_{k \in K_{rs}} f_k^{rs,m} = q_{rs}^m \qquad \forall r, s, m \tag{1}$$

$$q_{rs}^1 = (1 - p_{av}) * q_{rs} \qquad \forall r, s \tag{2}$$

$$q_{rs}^2 = p_{av} * q_{rs} \qquad \forall r, s \tag{3}$$

$$f_k^{rs} = f_k^{rs,1} + f_k^{rs,2} \qquad \forall r, s, k \tag{4}$$

$$f_k^{rs,m} \geq 0 \qquad \forall r, s, k, m \tag{5}$$

$$x_a^m = \sum\nolimits_{r \in R} \sum\nolimits_{s \in S} \sum\nolimits_{k \in K_{rs}} f_k^{rs,m} \delta_{a,k}^{rs} \qquad \forall a \in A \cup \hat{A} \tag{6}$$

$$x_a^1 \geq 0 \qquad \forall a \in A \tag{7}$$

$$x_a^1 = 0 \qquad \forall a \in \hat{A} \tag{8}$$

$$x_a^2 \geq 0 \qquad \forall a \in A \cup \hat{A} \tag{9}$$

In the above optimization problem, constraint (1) ensures the conservation of flow. Constraints (2) and (3) show that the share of trips of AVs from an origin and a destination is p_{av} for every O-D pair. Constraints (5) holds the path flow non-negative. Constraint (6) defines the relationship between link flow and path flow. $\delta_{a,k}^{rs}$ in the constraint is an element of the node-link incidence matrix; its value equals 1 if link a is on the path k from origin r and destination s while being 0 otherwise. Constraints (7)–(9) describe the vehicles' behaviors on lanes, where AVs are allowed to use any lanes while CVs do not have access to the AV-dedicated lanes.

The UE traffic assignment problem can easily be proven as strictly convex on its feasible region and its equivalence can be established by comparing KKT conditions of UE with the defined network equilibrium conditions (1)–(9).

AV Lanes Deployment Model. After getting the traffic flow assignment result by solving the UE problem, we need to decide where to deploy AV-dedicated lanes and how many lanes to deploy for each link. Thus, we devised a concept named 'the instantaneous total travel time change' of a link (represented as link a and link $(a + n)$ in the model), which indicates the change in the total travel time of vehicles on the link when one lane from the mixed-flow part (link a) is assigned as an AV-dedicated lane. This situation is equivalent to decrease y_a by one and increase y_{a+n} by one. It will change the capacities of link a and link $(a + n)$ so that t_a and t_{a+n} change. Thus, the link flows x_a and x_{a+n} will be adjusted while keeping the sum of them the same. Based on the new traffic flow assignment on link a and link $(a + n)$, the new total travel time of vehicles on both links can be calculated. The instantaneous total travel time change means the new total travel time of vehicles on link a and link $(a + n)$ subtracted by the original value of total travel time before assigning a lane from link a to *an* AV-dedicated lane.

The process of calculating the instantaneous total travel time change value of one link subject to the AV-dedicated lane installation can be explained in more detail using the graphics and equations below:

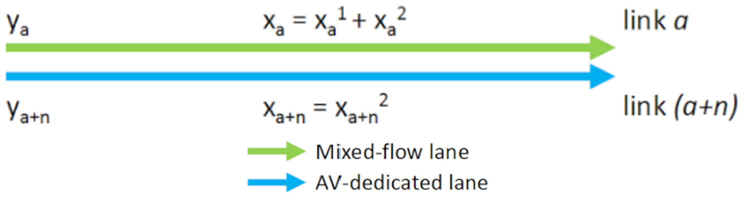

Fig. 1. The original condition of link a and link $(a+n)$ and flows on the links (representing one link in the real world)

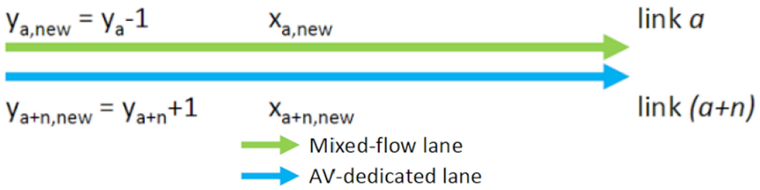

Fig. 2. The new condition of link a and link $(a+n)$ and flows on the links (representing one link in the real world)

The functions to calculate the instantaneous link travel time of a link (link a and link $(a+n)$ combined) are:

The original travel time of link a:

$$t_a(x_a) = t_a^0\left(1 + \alpha_a\left(\frac{x_a}{\frac{3600}{h_{av}r_a + h_{cv}(1-r_a)} * (y_a)}\right)^{\beta_a}\right)$$

The original travel time of link $(a+n)$:

$$t_{a+n}(x_{a+n}) = t_{a+n}^0\left(1 + \alpha_{a+n}\left(\frac{x_a}{\frac{3600}{h_{av}} * (y_{a+n})}\right)^{\beta_{a+n}}\right)$$

The new travel time of link a:

$$t_{a,new}\left(x_{a,new}\right) = t_a^0\left(1 + \alpha_a\left(\frac{x_{a,new}}{\frac{3600}{h_{av}r_{a,new} + h_{cv}\left(1-r_{a,new}\right)} * \left(y_{a,new}\right)}\right)^{\beta_a}\right)$$

The new travel time of link $(a+n)$:

$$t_{a+n,new}\left(x_{a+n,new}\right) = t_{a+n}^0\left(1 + \alpha_{a+n}\left(\frac{x_{a+n,new}}{\frac{3600}{h_{av}} * \left(y_{a+n,new}\right)}\right)^{\beta_{a+n}}\right)$$

Thus, the original total travel time $= t_a(x_a) * x_a + t_{a+n}(x_{a+n}) * x_{a+n}$
The new total travel time $= t_{a,new}\left(x_{a,new}\right) * x_{a,new} + t_{a+n,new}\left(x_{a+n,new}\right) * x_{a+n,new}$

$$y_{a,new} = y_a - 1 \text{ and } y_{a+n,new} = y_{a+n} + 1.$$

After $y_{a,new}$ and $y_{a+n,new}$ are decided, $x_{a,new}$ and $x_{a+n,new}$ needs to be decided. We assume that the vehicles will adjust their lane choices such that the UE condition is satisfied. Because of the increased capacity and reduced travel time of link $(a + n)$, the AVs on link a will move to link $(a + n)$. Thus, if the travel time on link a is still larger than that of link $(a + n)$ even after all the AVs on link a move to link $(a + n)$, all the AVs on link a will move to link $(a + n)$ since CVs cannot use link $(a + n)$ even though the travel time is shorter on link $(a + n)$. However, if the travel time on link a is still smaller than that of link $(a + n)$ after all the AVs on link a move to link $(a + n)$, some of AVs are not going to move to link a such that the travel time of link a become identical to that of link $(a + n)$. The way $x_{a,new}$ and $x_{a+n,new}$ are decided is described in the below equation with an *'if'* condition:

$$\text{If } t_{a,new}\left(x_a - x_a^2\right) > t_{a+n,new}\left(x_{a+n} + x_a^2\right),$$

$$x_{a,new} = x_a - x_a^2, x_{a+n,new} = x_{a+n} + x_a^2.$$

Otherwise,

$$x_{a,new} = x_a - \left(x_a^2 - b\right), x_{a+n,new} = x_{a+n} + \left(x_a^2 - b\right),$$

such that $t_{a,new}\left(x_a - \left(x_a^2 - b\right)\right) = t_{a+n,new}\left(x_{a+n} + \left(x_a^2 - b\right)\right)$.
Accordingly,

$$\text{If } t_{a,new}\left(x_a - x_a^2\right) > t_{a+n,new}\left(x_{a+n} + x_a^2\right),$$

$$x_{a,new}^1 = x_a^1, x_{a,new}^2 = 0, x_{a+n,new}^1 = 0, x_{a+n,new}^2 = x_{a+n} + x_a^2,$$

Otherwise,

$$x_{a,new}^1 = x_a^1, x_{a,new}^2 = b, x_{a+n,new}^1 = 0, x_{a+n,new}^2 = x_{a+n} + (x_a^2 - b).$$

With the results, $r_{a,new}$ and $r_{a+n,new}$ can be calculated easily using the new flows of AVs and CVs.

By comparing the instantaneous total travel time change of all the mixed-flow links with more than 1 lane (all the link a that $a \in$ A and $y_a > 1$), the algorithm chooses the one with the minimum change and let one lane from the link be an AV-dedicated lane. The reason for restricting the mixed-flow links of which the instantaneous total travel time changes are examined to the links with more than one lane is that it is necessary to provide at least one lane for CVs to ensure mobility and accessibility of CVs until they vanish entirely.

This process of choosing the link for AV-dedicated lane installation repeats until the total length of AV-dedicated lanes reaches the limit we set before running the algorithm or there is no mixed-flow link with more than one lane. It is possible to easily imagine that the government has an idea about the different levels of AV market penetration rate and the associated limit on the total length of AV-dedicated lanes as shown in Table 2. Before the start of the algorithm, we need to set the $\mathrm{p_{av}}$ that also decides the limit.

Table 2. AV market penetration rate (p_{av}) and corresponding AV lanes length cap (L)

Market AV penetration rate (%)	Limit on the total length of AV-dedicated lanes (% of the total length of all the lanes)
$p_{av} < 10\%$	$\mathrm{Q}_1\%$
$10\% \leq p_{av} < 20\%$	$\mathrm{Q}_2\%$
$20\% \leq p_{av} < 30\%$	$\mathrm{Q}_3\%$
$30\% \leq p_{av} < 40\%$	$\mathrm{Q}_4\%$
$40\% \leq p_{av} < 50\%$	$\mathrm{Q}_5\%$

When we have a predefined limit on the total length of AV-dedicated lanes, we can let the algorithm test two conditions below, after 1) choosing the link of AV-dedicated lane installation, 2) assigning one lane from the link to the AV-dedicated lane, and 3) assigning the entire traffic of all the O-D pairs under UE condition with the updated network. If either one of the conditions (10) and (11) is fulfilled, the algorithm stops to add an AV-dedicated lane. If not, the algorithm compares the instantaneous travel time changes for all the mixed-flow links with more than one lane to find the link to deploy an AV-dedicated lane.

$$y_a = 1 \quad \forall \mathrm{a} \in \mathrm{A} \tag{10}$$

$$l_b + \Sigma_{a \in \hat{A}} l_a y_a > \mathrm{L} \quad \forall b \in A \tag{11}$$

The flow chart of the algorithm is shown in Fig. 3.

With Table 2, it is possible to simulate how the deployment of AV-dedicated lanes grows as $\mathrm{p_{av}}$ increases. For example, we can run the algorithm with a network without any AV-dedicated lanes, after setting $p_{av} = 5\%$, and $L = \mathrm{Q}_1\%$. After that, using the output network with AV-dedicated lanes from the algorithm run, we can set $p_{av} = 10\%$ and $L = \mathrm{Q}_2\%$ to run the algorithm again. The algorithm run will add more AV-dedicated lanes to the network. Continuing this process again and again by increasing p_{av} value step-by-step will give results that show the growth of AV-dedicated lanes on the network. This will give a vivid idea of how the government can deploy AV-dedicated lanes at the right locations promptly.

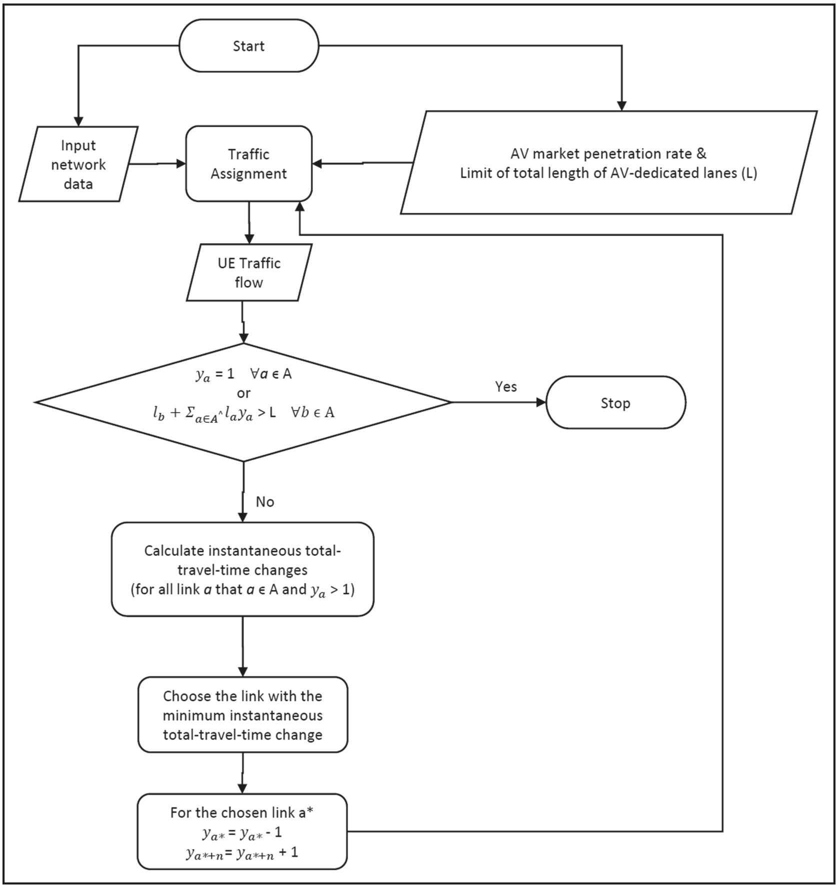

Fig. 3. The flowchart of the bi-level algorithm

4 Solution Framework and Numerical Example

4.1 Solution Framework

The Frank-Wolfe algorithm is used with the Method of Successive Averages (MSA) for user equilibrium (UE) traffic assignments. When the algorithm for AV-dedicated lane deployment starts, the first step is to assign all the O-D demand for AVs and CVs on the network. In the iterative process of the Frank-Wolfe algorithm for UE traffic assignment, the MSA enables finding the solution with relative ease by removing the need for calculating the move size for each iteration.

With the resulting UE solution, the algorithm moves on to the next step for calculating the instantaneous travel time for each mixed-flow link and then chooses the one with the smallest instantaneous travel time change that occurs one lane of the mixed-flow link becomes an AV-dedicated lane. A positive instantaneous travel time change of a link indicates that the installment of an AV-dedicated lane has a negative impact on traffic flow, while a negative instantaneous travel time change implies a positive impact on traffic flow. After assigning one lane from the chosen link to the AV-dedicated lane, the algorithm gets back to the stage of UE traffic assignment on the updated network with the new AV-dedicated lane. This process repeats until when all the mixed-flow links have just one lane or when the total length of AV-dedicated lanes reaches the preset limit.

4.2 Numerical Example

Basic Settings. A few parameters are determined based on the values from relevant previous studies. For the sample freeway network in use, it is assumed that all the links in the network have 90 km/h (25 m/s) as the free-flow speed which is in the range of the common freeway speed limit. Accordingly, ${t_a}^0 = l_a/25$, where ${t_a}^0$ is the free-flow travel time of link a in seconds and l_a is the length of link a in meter. Adopting the calibrated α_a and β_a for roads with 90 km/h as a free-flow speed by Ivanchev et al. (2016), $\alpha_a = 1.2$ and $\beta_a = 5$ for all a. For minimum headways, h_{av} and h_{cv} are set to 1.0 s and 1.8 s, respectively, referring to the values from Ivanchev et al. (2019).

Experimental Network. The solution framework discussed in this section is based on the network diagram shown in Fig. 4. This network is adopted from Zheng Li's post about a user-equilibrium solution [9]. The numbers inside the node represent the node number. As shown in Table 3, the network consists of four O-D pairs and nineteen links. There are two origin nodes are labeled as 1 and 2 and two destination nodes are labeled as 3 and 4. The length of all links is 10 m, except for link 8 (8–12) and link 10 (9–16) that are 14 m and 22 m, respectively. Each link has four lanes with a free-flow speed of 25 m/s. Table 4 is the O-D demand matrix (Fig. 4).

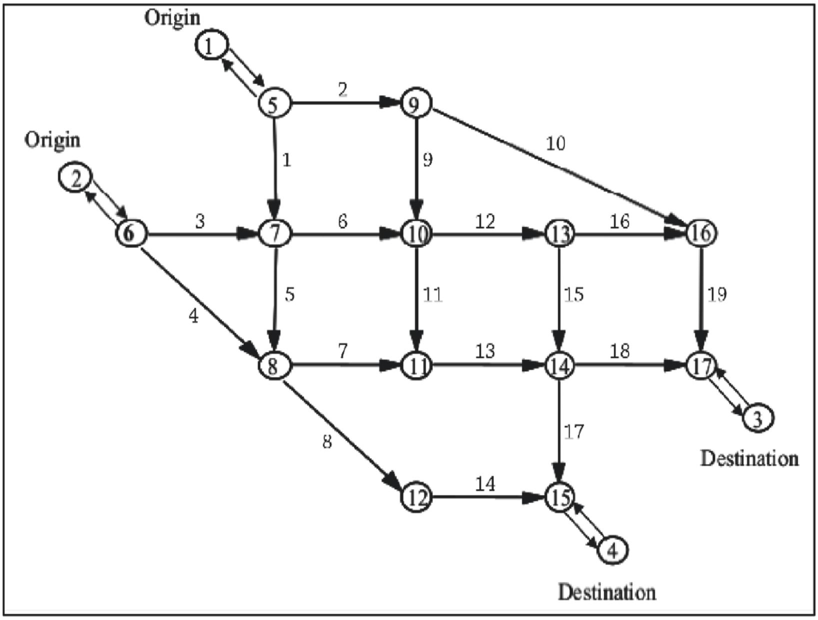

Fig. 4. Network diagram

Table 3. Link information

Link label	Origin	Destination	Length (m)	No. of lanes	Free flow speed (m/s)	t_a^0(sec)
1	5	7	10	4	25	0.40
2	5	9	10	4	25	0.40
3	6	7	10	4	25	0.40
4	6	8	14	4	25	0.56
5	7	8	10	4	25	0.40
6	7	10	10	4	25	0.40
7	8	11	10	4	25	0.40
8	8	12	14	4	25	0.56
9	9	10	10	4	25	0.40
10	9	16	22	4	25	0.90
11	10	11	10	4	25	0.40
12	10	13	10	4	25	0.40
13	11	14	10	4	25	0.40
14	12	15	10	4	25	0.40
15	13	14	10	4	25	0.40
16	13	16	10	4	25	0.40
17	14	15	10	4	25	0.40
18	14	17	10	4	25	0.40
19	16	17	10	4	25	0.40

Table 4. O-D demand matrix

		Destinations	
		15	17
Origins	5	6000	6750
	6	7500	5250

The whole process of AV-dedicated lane deployment is separated into 10 stages, each one has its corresponding experimental market AV penetration rate and limit of the total length of AV-dedicated lanes. As shown in Table 5, Stage 0 is a special case where the market AV penetration rate is 5% while the percent of the total length allowed to be converted to AV-dedicated lanes is 0%. Stage 0 is utilized as a comparison to Stage 1 to illustrate the effectiveness of the added AV lanes in terms of improving the total network travel time. Theoretically, the limit of AV-dedicated lanes when $p_{av} = 85\%$ is 90%.

However, the action of converting a mixed-flow lane of a link to an AV-dedicated lane stops once all mixed-flow links have only one lane, which aims to ensure a minimum level of connectivity of the network to CV users.

Table 5. Market penetration rate and the limit on the length of AV-dedicated lanes for each deployment stage

Deployment stage	Market AV penetration rate (%)	Limit on the total length of AV-dedicated lanes (% of the total length of all the lanes)
0	$p_{av} = 5\%$	0%
1	$p_{av} = 5\%$	10%
2	$p_{av} = 15\%$	20%
3	$p_{av} = 25\%$	30%
4	$p_{av} = 35\%$	40%
5	$p_{av} = 45\%$	50%
6	$p_{av} = 55\%$	60%
7	$p_{av} = 65\%$	70%
8	$p_{av} = 75\%$	80%
9	$p_{av} = 85\%$	90%

Results Analysis. This numerical experiment is based on the network condition illustrated above and this study uses a forced-increasing limit of the total length of AV-dedicated lanes based on the assumption that the market penetration rate of AV will keep growing. Thus, the results show how a freeway network should react to the developing AV market and what can be done to help to promote the increase of the share of AVs on the whole market.

Figure 5 shows that the total network travel time decreases fast between deployment stage 1–4 which indicates that converting the specified length of mixed-flow lanes to AV-dedicated lanes can effectively improve the performance of the overall network, shown here as the dramatically decreased network total travel time. As aforementioned, stage 0 is used as a comparison to stage 1, indicating that when p_{av} is low, for example, 5%, the impact of newly converted AV-dedicated lanes won't have much influence on the network, causing a 0.002% decrease.

However, when the market AV penetration rate is greater than 45%, the network can no longer benefit as much as when p_{av} is relatively smaller from the forced-increasing AV-dedicated lanes. When at stage 7, 7 links have only 1 mixed-flow lane, meaning that they are not available for adding new AV-dedicated lanes. This shows that when $p_{av} > 65\%$, the network can no longer continue to benefit from the newly converted AV-dedicated lanes. Stage 9 is special because there were only 6 lanes left in stage 8 that can be converted to AV-dedicated lanes, thus stage 9 does not have any new AV-dedicated lane.

The travel times decrease after stage 7. This is the result of decreased human-driven vehicle demands. This decrease slows down when no new AV-dedicated lane can be added to the network (stage 8) while the AV-market penetration rate is still increasing resulting in more AV demands between O-D pairs.

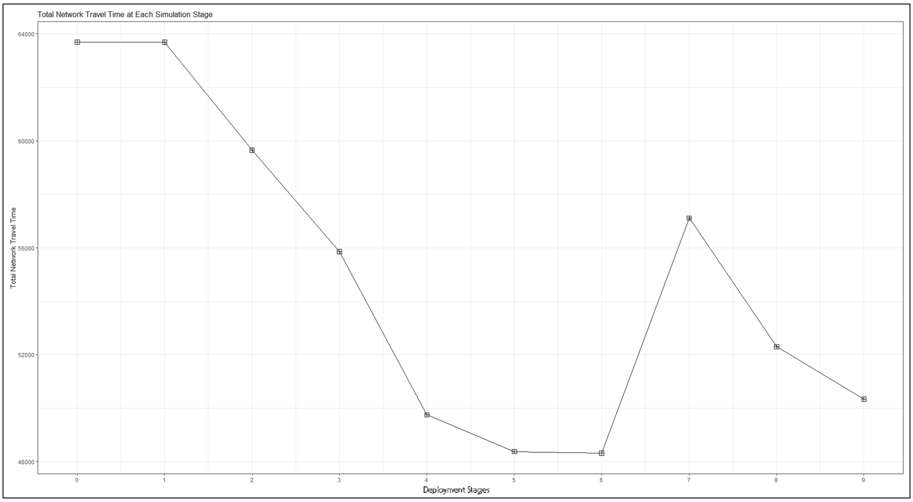

Fig. 5. Total network travel time at each deployment stage

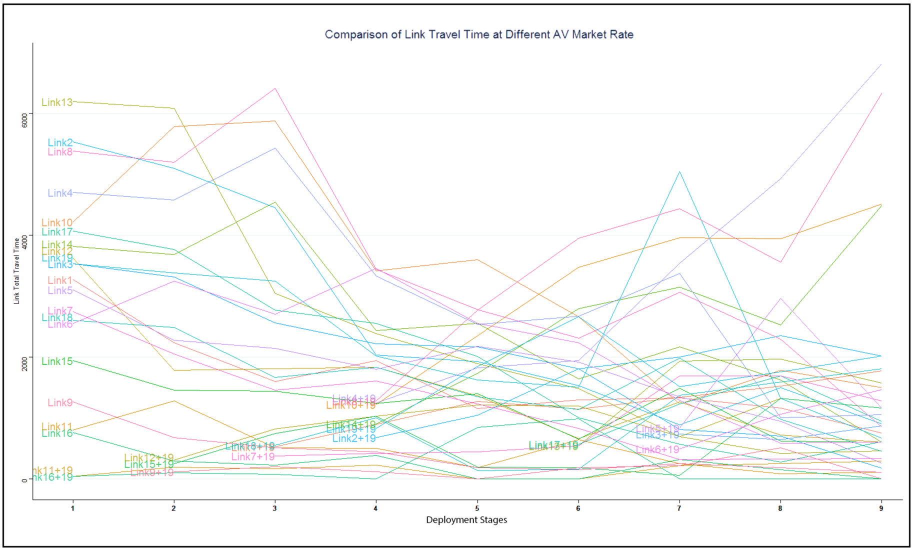

Fig. 6. Link travel time changes at the different deployment stage

As shown in Fig. 6, the link travel time of link 8, link 19, and link 4 + 19 increase significantly at stage 7, which certifies the previously discussed phenomenon of the sudden

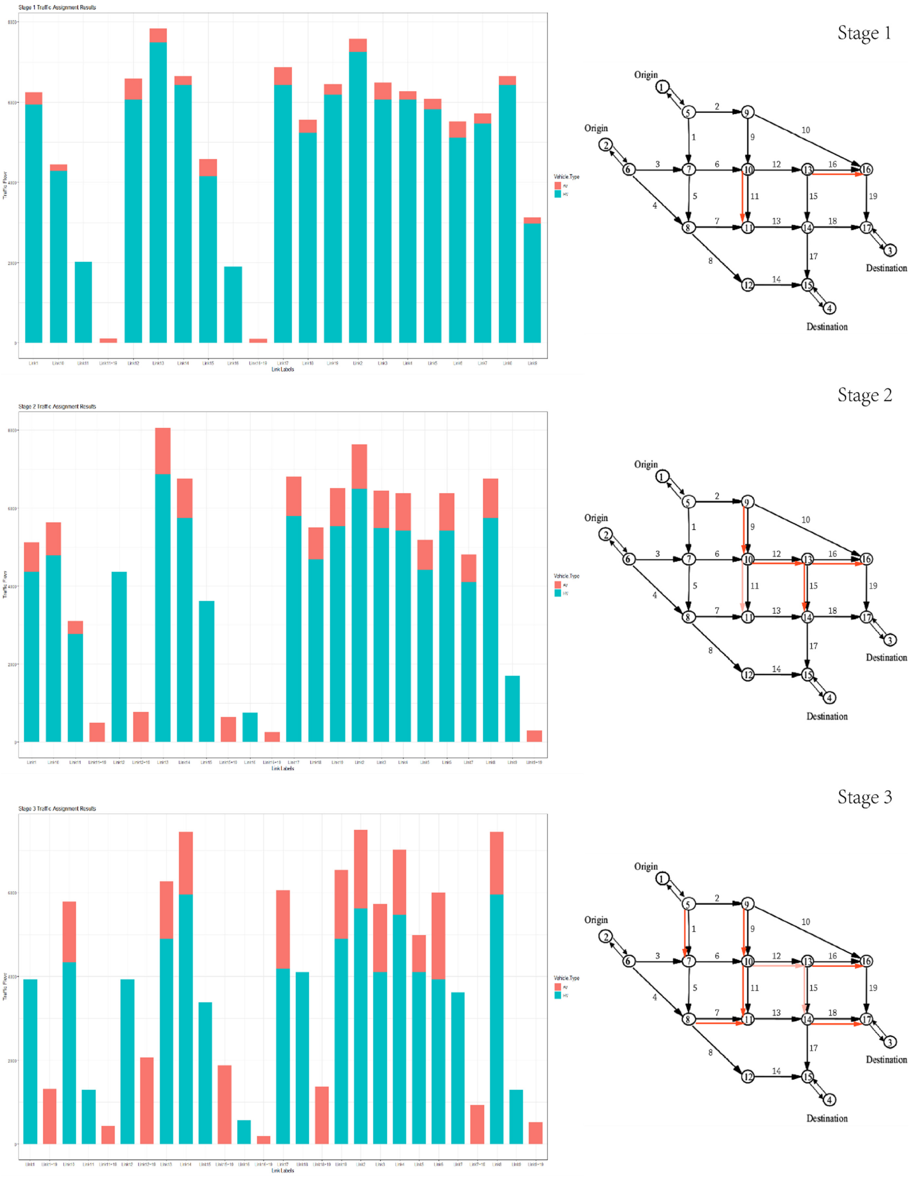

Fig. 7. AV-lanes deployment and traffic assignment results of Stage 1–9

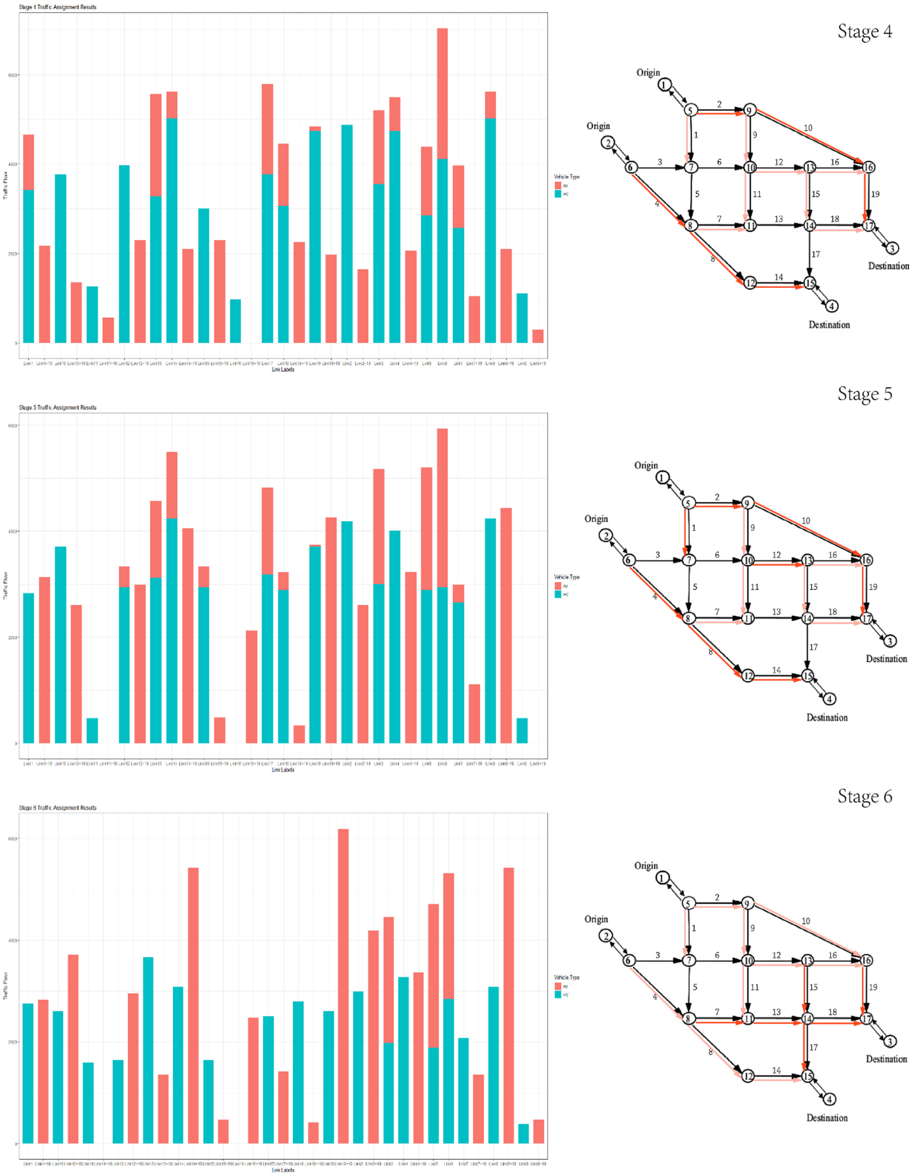

Fig. 7. continued

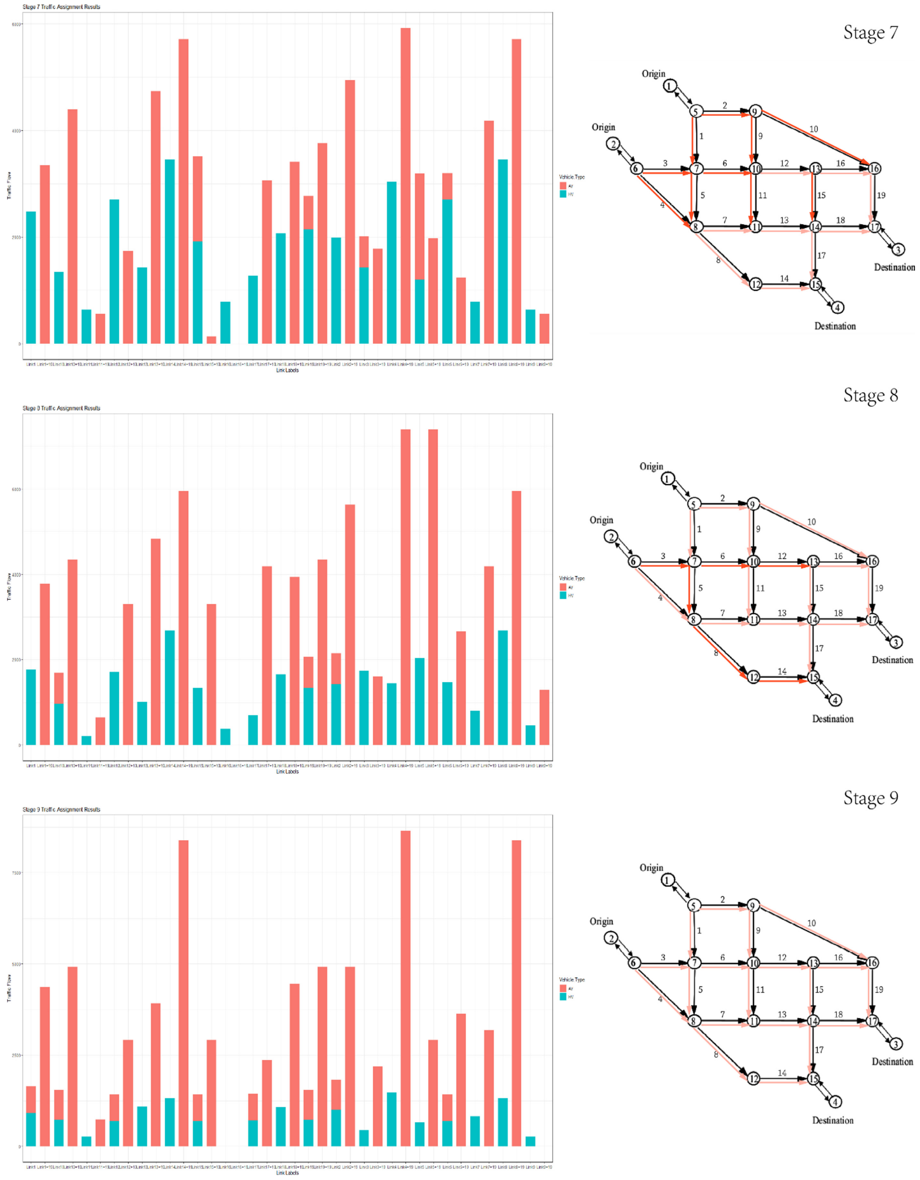

Fig. 7. continued

increase of total network travel time at stage 7, that limited available AV-dedicated lanes candidates and obligated AV-dedicated lane total length weaken the benefits produced by adding the AV dedicated lanes to the network. The travel time of Link 8 + 19 and link 14 + 19 initially decreases in stage 8 but later increases at stage 9. This occurs because the links with newly added AV-lanes at stage 8 are assigned with more AV flows, however, no new AV lane is added at stage 9 but the demand for AV keeps increasing by 10%, link 8 + 19 and link 14 + 19 carries a large portion of the 10% growth of AV demands at stage 9 resulting in its sudden increase of link travel times.

Figure 7 displays the AV-dedicated lanes deployment and UE traffic assignment results at every stage. There exists a concept that the AV-lanes are first allocated to the links in the middle of the network that is being shared by many paths and several O-D pairs, then to the links at two ends (near O-D pairs) and the links on the edges. This shows an underlying sequence of the deployment of the AV-lanes that the links that are being used by more paths are more likely to be first chosen as the candidate of new AV-lanes. Contrary, the links on the edge of the network are assigned with more traffic flows, both CVs and AVs.

Link 16 and its paired link Link16 + 19 are not being utilized as much as other links after stage 7 given the fact that link 16 is one of the links being assigned with AV-lanes within the first 3 stages. While the added AV-lanes have positive effects on the network during stage 1–4. This might be a result of the surrogate measure, instantaneous travel time changes. At stage 1–3 all the instantaneous travel time change measures are positive. The chosen links as candidates for new AV-lanes are those with comparatively smaller traffic flows. that the ones chosen to be added AV-lanes on at first might be the ones are affected negatively the least among all links. This might cause other problems when the model is used on more complex networks. However, this could also be a sign of potential urban design changes. The experimental network is under a high-speed highway scenario where the link free flow speed is homogenous. The links that are being chosen first as the AV-lanes candidates while being utilized the least when AV market penetration rate is high suggest possibilities to convert some of the regions of these links locate in to new zones with different facilities and functions rather than highway surrounded places and possibilities of a less vehicle-oriented, more walkable area. These areas could be utilized as the flag bearers of urban design changes.

5 Conclusion

This paper proposes a computationally effective mathematical procedure to deploy AV-dedicated lanes considering different AV market penetration rates. The idea of the corresponding limit of the total length of AV-dedicated lanes ensures the infrastructure construction moves ahead of the market performance of AVs, by improving the objective driving conditions to promote people's willingness and enthusiasm about AVs. The deployment results at different stages show where, when, and how many mix-flow lanes should be converted to AV-dedicated lanes at its corresponding AV market penetration rate. MSA is used to solve the UE traffic assignment problem with two variables, the CV flow and AV flow. A new measure to find optimal AV-lanes deployment location is formulated by calculating and comparing the instantaneous total paired-links travel time changes, iteratively. The analysis of the deployment results shows that the network can benefit from the new AV-lanes when the AV market penetration rate is lower than 55% and the total network travel time might increase once the AV market penetration rate is higher than 65%. Which indicates that 1) the construction of AV lanes at the early stage of the AV market development can benefit not only the market itself but the overall performance of the network; 2) policy makers should be more cautious about the deployment location of AV-lanes when AV market penetration is relatively high; 3) the "ahead construction" of AV-lanes and its related infrastructures might bring new opportunities for city planning and urban design.

The model proposed in this study presents some limitations that require further investigation. Firstly, the network uses homogenous free flow speed and lacks variation in link length, and no intersection behavior is included in the model. The network has a limited number of O-D pairs. It can only represent a highway scenario and its realness is not sufficient. Further investigations must be performed to understand intersection behavior and complex link interactions. To evaluate such characteristics of the algorithm, a dynamic network must be adopted, such as a core urban network that offers additional O-D pairs and link interactions. Secondly, the instantaneous total travel time change measure is a surrogate measure on which the tradeoff of computational effectiveness and realness is achieved. Higher accuracy can be obtained if more link interactions are captured. Thirdly, MSA is used to solve the UE traffic assignment problem which can only provide an approximate-optimal solution. Although the results are acceptable, the differences between the approximate-optimal solution and the real solution might result in problems in more complex assignment works.

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