# Can Dedicated Lanes for Automated Vehicles on Urban Roads Improve Traffic Efficiency?

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## Abstract

Connected and automated vehicles (CAVs) will behave fundamentally differently than human drivers. In mixed traffic, this could lead to inefficiencies and safety-critical situations since neither human drivers nor CAVs will be able to fully anticipate or predict surrounding traffic dynamics. Thus, some researchers proposed to separate CAVs from conventional vehicles by dedicating exclusive lanes to them. However, the separation of road infrastructure can negatively impact the system's capacity. While the effects of CAV lanes were addressed for freeways, their deployment in urban settings is not yet fully understood. This paper systematically analyzes the effects of CAV-lanes in an urban setting accounting for the corresponding complexities. We employ microscopic traffic simulation to model traffic flow dynamics in a detailed manner and to be able to consider a wide array of supply-related characteristics. These concern intersection geometry, public transport operation, traffic signal control, and traffic management. Our study contributes to the existing literature by revealing the potential of CAV lanes in an urban setting while accounting for the behavioral and topological complexities. The results of this study can support decision-makers in the design of future urban transportation systems and to prepare cities for the upcoming era of automation in traffic.

**Keywords:** automated vehicles, connected vehicles, managed lanes, capacity

## 1 Introduction

The development of automated driving functions as well as advances in communication technology will determine the future driving behavior of vehicles. Ongoing research and development activities explore the operation of connected and automated vehicles (CAVs) and their impacts on traffic flow dynamics on freeways and in urban areas, e.g. [Til18]. It is expected that the driving behavior of CAVs will be fundamentally different from that of human drivers. In mixed traffic, neither human drivers nor CAVs will be able to fully anticipate or predict surrounding traffic dynamics which could lead to safety-critical situations. CAVs could potentially avoid such situations by following a conservative driving style which can result in inefficient traffic flow. Also, to reduce possible negative impacts on traffic safety, some researchers proposed to separate CAVs from conventional vehicles by dedicating exclusive lanes to them, e.g. [Zha20]. However, such separation of road infrastructure can again negatively affect the system's capacity.

In recent years, numerous studies addressed the design of dedicated lanes in networks, not only in the context of CAVs. In fact, these studies mostly focused on freeway road facilities, e.g. [Ghi17; Ye18]. However, the structure of urban networks differs quite substantially from freeway settings. A substantial share of capacities is provided by arterials, i.e. multi-lane corridors interrupted by signalized intersections. This consequently affects the occurring traffic dynamics, especially when frequent stopping maneuvers (e.g. caused by mobility-on-demand services) may further reduce traffic flow, e.g. [Stu22]. Interestingly, little attention has been paid to the effects of dedicated lanes in such urban settings. Related studies either focused on the big picture by applying analytical or macroscopic traffic flow models, thereby omitting detailed driving behavior and intersection complexities, e.g. [Mov20; Ami20], or were rather limited to very specific scenarios when applying microscopic models, e.g. [Sha21; Moh19]. To our best knowledge, no study systematically employs detailed microscopic simulation to investigate the potential benefits of CAV lanes in complex urban settings under mixed traffic conditions.

In this paper, we investigate the effects of CAV lanes for urban settings at the local level based on microscopic traffic flow simulation to fill this gap. Thereby, we focus on the essential element of urban networks, a link, and its downstream and upstream intersections. We vary the underlying characteristics referring to geometric intersection design, the number of lanes, road length, traffic signal control settings, public transport operation, and speed limits. The results of the study indicate under which circumstances the deployment of CAV lanes can be beneficial. This is an important input for higher-level methods to design CAV lanes at the network level. Ultimately, the efficient design of CAV lanes in urban networks can be an opportunity to utilize existing road space more efficiently and safely.

## 2 Methodology

First, we describe microscopic traffic simulation which is the core method of the presented analysis. Then, we depict the base network for which the scenarios are evaluated. Finally, we explain the workflow of the scenario analysis.

### 2.1 Traffic Simulation Models

Heterogeneity in the driving behavior of human driven-vehicles (HDVs) and CAVs can result in complex traffic flow dynamics, especially in urban areas. Existing analytical and macroscopic modeling approaches consider only aggregated scales and simplified topologies. While they were successfully applied to estimate related capacity gains, they lack the possibility to account for key aspects when analyzing mixed traffic in complex urban networks. Therefore, we use the microscopic traffic simulation SUMO [Lop18] that has been successfully applied for studying the effects of CAVs on traffic flow in the past, e.g. [Li19]. We apply standard models for the behavior of HDVs, and the ones proposed in [Ols20] for modeling CAV behavior, as such were developed based on field tests and thus calibrated with empirical data.

### 2.2 Base Network

The base network is depicted in Figure 1. It consists of one intersection with the main signal $S_m$ and four approaches. The arrows describe the direction of travel for each link.

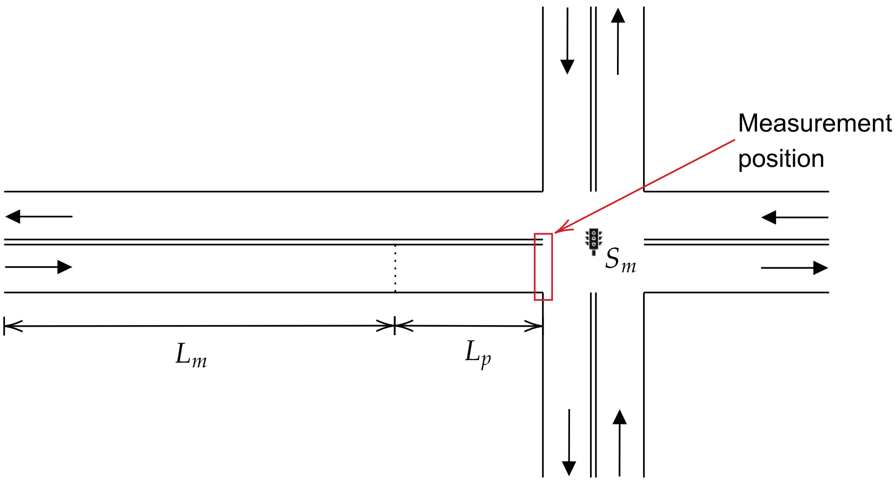


**Figure 1:** Layout of the base network.

The analysis focuses on link $L$ which is divided into a main segment $L_m$ and a pre-sorting segment $L_p$. The control logic refers to the main signal $S_m$. The vehicle throughput is measured at the downstream end of the edge right before the intersection, as highlighted by the red rectangle in the figure.

### 2.3 Scenario Analysis

The main goal is to systematically analyze the effects of a dedicated CAV lane on traffic efficiency in realistic urban settings. Therefore, we focus on the maximum vehicle throughput as performance indicator. To conduct our analysis, we follow a methodology where we gradually increase the scenario complexity. Figure 2 visualizes the overall workflow.

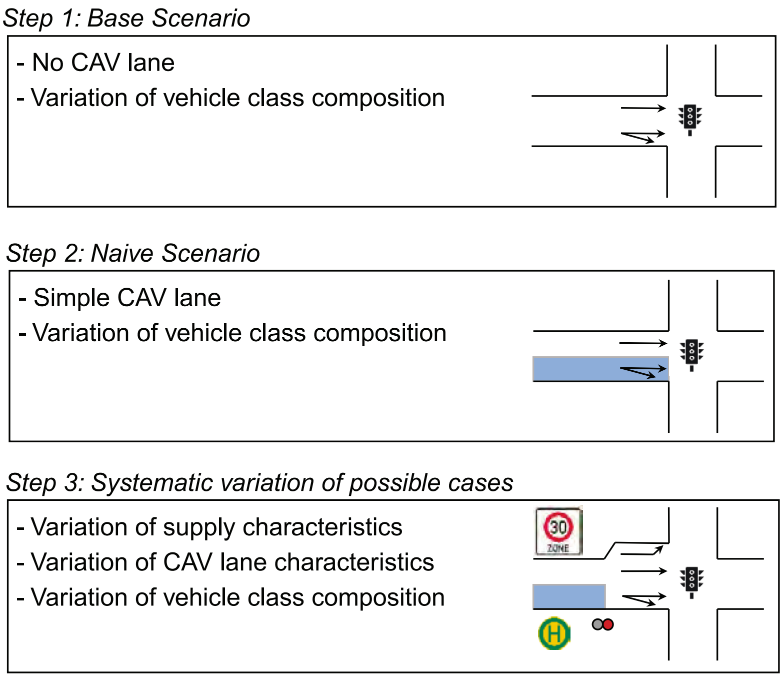


**Figure 2:** Workflow.

In the first step, we evaluate a simple base scenario to demonstrate the general effects of CAVs on the throughput. Then, we naively dedicate one lane to CAVs and analyze the corresponding effects. On this dedicated lane, only CAVs are allowed to drive, whereas all vehicle classes can use the remaining lane. In the third step, we study a large array of supply-related aspects to identify those realistic urban scenario settings for which the deployment of dedicated CAV lanes maximizes the capacity. This also includes additional traffic management schemes, such as the installation of a pre-signal to allow for a more safe and efficient sorting in $L_p$, or changing the maximum speed limits.

This gradual increase of intricacy enables us (i) to account for the complexity of urban infrastructure, (ii) to demonstrate the effects of such and their interaction with CAV lanes, and (iii) to show the potential of additional traffic management measures to further improve efficiency. The varied scenario characteristics are shown in Table 1. The characteristics regarding intersection geometry, public transport operation, intersection control, and traffic management are derived from experience and logical thought. The fixed-time control is based on a 90 s cycle time with reasonable green and amber times. We acknowledge that the respective values in Table 1 are not an exhaustive list but assume that the choice covers a meaningful range.

We consider two different CAV classes, namely the "normal" and "all-knowing" model according to [Ols20]. The total penetration rate in the simulations varies between 0 % and 100 % in steps of 25 %. For some penetration rates, we vary the CAV class composition by

**Table 1:** Analyzed supply and traffic management characteristics.

| **Category** | **Characteristic** | **Values** |
|---|---|---|
| Intersection geometry | Number of lanes | 2, 3 |
| | Road length | 250 m, 500 m, 750 m |
| | Turning options | Right-turning, right- and left-turning |
| | Turning lanes | Yes, no |
| PT Operation | Dedicated bus lane | Yes, no |
| | Headway | 2.5 min, 10 min |
| Intersection control | Type | Fixed-time, actuated |
| Traffic management | CAV lane | Left, middle, right |
| | Pre-signal | Yes, no |
| | Speed limits | 30 km/h, 50 km/h |

setting the respective shares to either 0 %, 50 %, or 100 %. This leads to a total of 11 vehicle class compositions including a reference case with 100 % HDVs (see Table 2).

A simulation scenario is defined by specific values of the supply and traffic management characteristics as well as a vehicle class composition. Combining all possible values leads to approx. 12,500 scenarios which are then evaluated with SUMO. Each scenario is simulated for a reasonable period, and with a trapezoidal loading and unloading curve to mimic a rush hour. We ensure that the loading let the system reach its capacity. Last, all simulation runs are conducted for 10 random seeds.

**Table 2:** Vehicle class compositions.

| **Index [-]** | **HDVs [%]** | **Normal CAVs [%]** | **All-knowing CAVs [%]** |
|---|---|---|---|
| 0 | 100 | 0 | 0 |
| 1 | 75 | 25 | 0 |
| 2 | 75 | 12.5 | 12.5 |
| 3 | 75 | 0 | 25 |
| 4 | 50 | 50 | 0 |
| 5 | 50 | 25 | 25 |
| 6 | 50 | 0 | 50 |
| 7 | 25 | 75 | 0 |
| 8 | 25 | 37.5 | 37.5 |
| 9 | 25 | 0 | 75 |
| 10 | 0 | 0 | 100 |

## 3 Results and Discussion

Figure 3 illustrates those results from scenarios where left-turning is allowed, the traffic signal follows a fixed-time control, and no public transport operation is active. For clarity, we only plot the results for the vehicle class compositions 1, 4, 7, and 10 (see Table 2). All remaining parameters are varied. The three box plots represent lane capacities from scenarios in which no (lightgrey), the right-most (grey), or the leftmost (darkgrey) lane is dedicated to CAVs. The red horizontal line represents the median lane capacity from the reference case with no CAVs. The figure illustrates the wide range of resulting capacities across the different

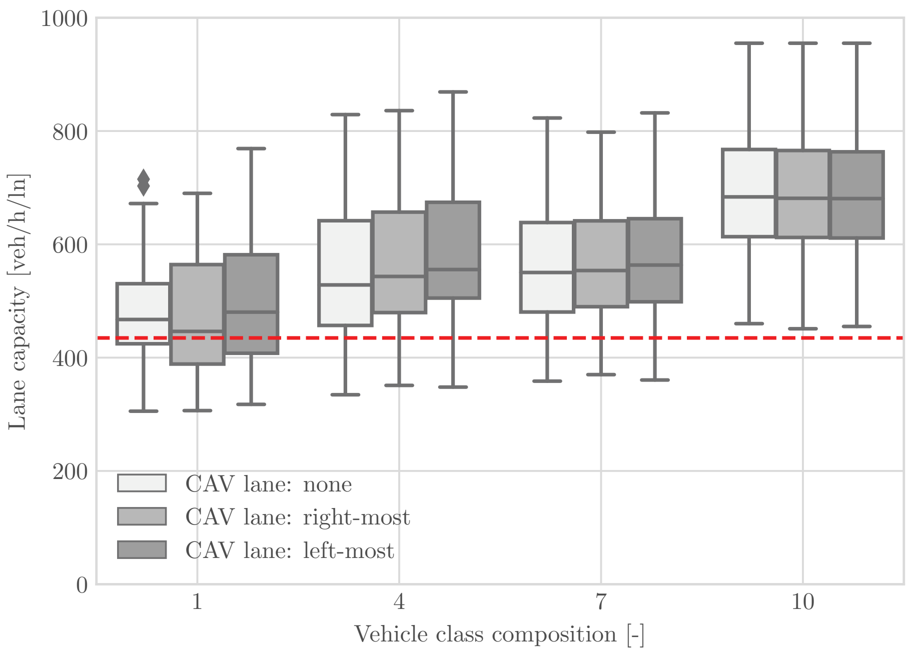


**Figure 3:** Impact of intersection topology and dedicated CAV lanes.

scenarios. Generally, they increase along with the penetration rate of CAVs as indicated by the index of the vehicle class composition. This is due to the corresponding penetration rate of CAVs and the resulting lower average headways in traffic flow. Additionally, the results show that dedicating the leftmost lane to CAVs is preferable in most cases, as the median capacities mostly lie above those of the other configurations. The underlying reason is that in case of spillbacks due to hindered left-turning maneuvers, CAVs on the dedicated lane can still move to the remaining lanes. However, if the dedicated lane is located on the right-most side, such spillbacks could block HDVs which have less flexibility in lateral movement. This lack of flexibility is reflected in the slightly lower capacities measured for these cases. Furthermore, the figure clearly shows high variability in the measured capacities. This emphasizes that a dedicated CAV lane must be introduced following the supply characteristics at hand and that their effects on capacities require a systematic investigation.

From the remaining scenarios, those with three lanes, fixed-time signal control, and turning lanes for both directions profit the most from the introduction of a dedicated CAV lane.

Moreover, we investigated the effect of utilizing an already existing dedicated lane for public transport vehicles, the effect of pre-signals for pre-sorting, and different speed limits. While a detailed presentation of the results is out of scope, it turns out that the further utilization of dedicated bus lanes expectedly increases the overall throughput, pre-signals do not necessarily improve traffic efficiency, and speed limits do not affect the overall results nor show any interaction with the other analyzed factors.

## 4 Conclusions and Future Work

This paper presented a comprehensive simulation study of the effects of CAV lanes on traffic efficiency in an urban setting. We analyzed a vast array of scenarios with increasing complexity. This included characteristics concerning vehicle composition, intersection geometry, public transport operation, traffic signal control, and traffic management. The presented results illustrate that while under most conditions, the flows are not substantially increased by introducing CAV lanes, they remain on a similar level as in scenarios without such lanes. Furthermore, for penetration rates of 50 % we found scenarios that led to a significant increase in vehicle throughput. Considering the expected positive effects of such lanes on traffic safety and the potentially higher occupancies of CAVs, the deployment of dedicated CAV lanes in urban settings seems to be of advantage.

This study focused only on the core element of an urban network, namely a link between two intersections. Nevertheless, the results can contribute to network-wide analyses of CAV lane systems in complex urban networks. For example, if such a system shall be designed by employing an optimization model where CAV lanes are related to the decision variable, our study can strongly decrease the parameter space by excluding certain cases where a positive impact of CAV lanes on flows is not expected. Another interesting topic of future work is the inclusion of other quantitative performance indicators, e.g. related to passenger flows, traffic safety, and emissions. Of course, in a world with CAVs only, completely new management possibilities exist [e.g. Nie20].

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