Autonomous and Connected Cars: HCM Estimates for Freeways with Various Market Penetration Rates

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Abstract
Major IT companies and vehicle manufacturers have announced their plans for autonomous driving technology. Autonomous light duty vehicles are often referred to as “driverless cars” (DLC). These technologies intend to partly or fully replace driving by combining navigation systems, artificial intelligence, in-vehicle sensors, roadside ITS and traffic monitoring data, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications.

The absence of perception errors and the minimal perception and reaction time of DLC enable them to maintain shorter headways, to apply consistent acceleration and deceleration rates, and to optimize the use of gaps. In theory, freeway operations and level of service (LOS) can be impacted to a substantial but yet unknown degree by the DLC.

The Highway Capacity Manual (HCM) is a static and macroscopic methodology for assessing various traffic flow facilities. Its 2010 edition is not adjusted for the presence of DLC on highways, however, several of its parameters are sensitive to differences in perception and reaction times, headways, etc. An investigation was conducted to assess the likely changes to traffic flow characteristics that may result from the introduction of DLC. The focus of this paper is on expressways, that is, on HCM analyses of basic freeway segment and freeway weaving segment.

DLC is able to increase capacity ($c$), the maximum service flow rate ($MSF_L$), the adjustment factor for unfamiliar driver population ($fP$), passenger-car equivalent ($PCE$), and the proportion of heavy vehicles ($PT$). The combined benefits improve LOS. The results from the case studies show that the impacts of DLC on HCM parameters are tiny if the DLC have a very small market share. Two types of DLC are considered in this paper: Autonomous DLC, and Connected DLC with V2V and V2I. On a basic freeway segment the Autonomous DLC improves LOS from D to C when its share in traffic reaches 7%. The same case study shows that the Connected DLC improves LOS from D to C when its share in traffic reaches 3%.

Keywords: driverless, autonomous, connective vehicle, freeway operations, HCM, LOS
1 Introduction

Driverless cars (DLC), also known as autonomous vehicles or self-driving cars, is an emerging technology that has been growing rapidly in the past few years. As Google, Uber, and Apple, along with other auto manufacturers (e.g., Audi, BMW, Mercedes, Tesla) are making progress on the road towards driverless transport, other major automakers such as Nissan, Toyota, and VW are focusing on developing vehicles with certain automated driving functions. However, details of DLC have not been revealed to the public yet. In the early stage of DLC implementation, traffic composition will be mostly manually-driven vehicles with several vehicles with automated driving functions and some DLC. It becomes significant to study the traffic flow performance when DLC with different settings are mixed in traffic.

Several studies on DLC and their impact on traffic operations focus on modeling car-following features based on a variety of assumptions about DLC capabilities. For example, Adaptive Cruise Control (ACC) (Kesting, et al., 2005) was shown to eliminate traffic congestion with 30% share in traffic. The ACC was applied on a classic macroscopic traffic flow mode and proved to greatly improve capacity (Baskar, et al., 2009). Using microscopic simulation, Cooperative ACC (CACC) vehicles are found to be able to relieve congestion even with a low proportion of CACC vehicles in traffic (Arem, 2015).

The Highway Capacity Manual (HCM) has been established as a standard tool for the operational analysis for highways and related facilities (HCM, 2010). It provides deterministic and macroscopic methodologies for estimating measures of traffic operational such as speed, density and delay, which are used as the foundation for economic and environmental analyses. For uninterrupted flow facilities, density is used as an indicator of the level of service (LOS), and modeled as a function of capacity, flow rate, and average speed. These parameters are adjusted by a set of factors describing drivers’ behaviors towards lane and shoulder widths, unfamiliar routes and lane change. However, DLC is not sensitive to these factors due to its navigation, LIDAR and programmed car-following systems (Shi and Prevedouros, 2014) (Kesting, et al., 2005). An evaluation of traffic performance with DLC in traffic can be conducted using the HCM methodology.

DLC features combined together are meant to improve headway, which can also be used to adjust the macroscopic measures defined in HCM. Because so little is known about DLC, the HCM approach adopted herein keeps things simpler and grounded on flow fundamentals for assessing the potential of DLC on LOS. Considering current degrees of automation, DLC can be classified into two types: Autonomous DLC (A-DLC) and Connected DLC (C-DLC). This paper proposes an analytical assessment of the potential capacity enhancing and LOS improving opportunities of DLC based on modified formulations of standard HCM analysis for freeways. Two key variables are defined to quantify the features of DLC:

- \( h_D \) is the car-following headway of DLC, which represents their technical capability.
- \( P_D \) is the proportion of DLC in the traffic stream.

The paper is organized as follows: Section 2 establishes the connections between HCM parameters and DLC features, followed by adjusting those parameters using quantified DLC features in section 3. Section 4 presents case studies on Basic Freeway Segment and Freeway Weaving Segment to demonstrate the potential effect of DLC on LOS. Results are compared between A-DLC and D-DLC under different traffic composition shares. Considering the varieties of DLC features, sensitivity analyses are conducted in each case study. Section 5 presents discussion and brief conclusions.
2 Connections between HCM and DLC Features

This paper focuses on the HCM 2010 Basic Freeway (Chapter 11) and Freeway Weaving segments (Chapter 12), and estimates the effects of DLC with different degrees of automation (A-DLC and C-DLC). Each parameter in the respective chapters was assessed for influences and sensitivity to DLC features because DLC may offer much reduced perception and reaction time, tight car-following, precise lane keeping, correct assessment of gaps and crisp lane changing, no erroneous or unnecessary lane changes, and route familiarity.

HCM defines LOS as a measure of the quality of service from a traveler’s point of view. The measures used to determine LOS for uninterrupted flow facilities are flow rate, speed and density. These variables are the aggregates of microscopic features, i.e. driver behavior. Human factors determine how people drive and their processes of perception, cognition, decision, and action (Nass, 2013) (Parasuraman, et al., 2000). Drivers have different perception-reaction process towards the roadway environment, and which affect macroscopic traffic flow variables. HCM uses different factors to aggregate driver behavior towards roadway conditions (number of lanes, lane and shoulder widths), traffic profiles (PHF), traveler route/lane choice (familiarity to the route and lane change), weather/work zones and even vehicle types (heavy vehicles or passenger cars). The roadway environment influences the perception and reaction time of each individual, which in turn determines the speed choices and space between vehicles.

Compared to the variable driving behavior of an individual, a DLC exhibits a uniform car-following process by requiring a practically zero perception-reaction time for making necessary changes (Ni, et al., 2010). A 0.3 sec. is much too short for a driver to perceive, react and act to a stimulus but it is technically feasible for a DLC (Carbaugh, et al., 1998). A CACC vehicle is able to maintain a 0.5 sec. headway when following another CACC (Arem, 2015), which yields higher average speeds, smoother and potentially optimized for fuel and pollution speed changes, and tighter roadway space utilization (Barth, 2012).

3 Adjustments for DLC Features in HCM Methodology

3.1 Adjust Capacity and MSF

The operational analyses in HCM Chapters 11 and 12 use the free-flow speed (FFS) and the adjusted demand flow rate (v) to calculate density (D). A detailed presentation of the potential effects of DLC on HCM parameters was given in (Shi and Prevedouros, 2014). HCM generates two important outputs: capacity (c) and LOS. Capacity is defined as a function of the average headway:

$$c = \frac{3600}{h}$$ (1)

DLC affects capacity because it changes the average headway. If the headway of DLC is $h_D$ and the share of DLC is $P_D$, then the average headway and capacity of vehicles with DLC at $P_D$ can be adjusted into:

$$h' = h \times (1 - P_D) + h_D \times P_D$$ (2)

$$c' = \frac{3600}{h'\left[1 + P_D \times \left(\frac{2P_D}{\pi} - 1\right)\right]}$$ (3)

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It is worth mentioning that the expression 
\[ \frac{1}{1 + PD \left( \frac{h_D}{\bar{h}} - 1 \right) h} \]
in Eq. 3 has the same format as the heavy vehicle factor \( f_{HV} \). Thus it can be considered as an adjustment factor \( f_D \) for DLC on capacity. The expression \( \frac{h_D}{\bar{h}} \) can be considered as a passenger-car equivalent (PCE) value \( E_D \) for DLC as \( E_T \) is for heavy vehicles.

### Table 1: MSF and capacity for various DLC shares at \( h_D = 0.5 \) sec.

<table>
<thead>
<tr>
<th>MSF/c, ((i=A, \text{Breakpoint}, B, C, D, E))</th>
<th>0.32</th>
<th>0.50</th>
<th>0.52</th>
<th>0.70</th>
<th>0.87</th>
<th>1.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed, mi/h ((i=A, \text{Breakpoint}, B, C, D, E))</td>
<td>70.00</td>
<td>70.00</td>
<td>69.44</td>
<td>65.00</td>
<td>59.43</td>
<td>53.33</td>
</tr>
<tr>
<td>DLC Share</td>
<td>Average headway</td>
<td>A</td>
<td>Breakpoint</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>0%</td>
<td>1.50</td>
<td>770</td>
<td>1200</td>
<td>1250</td>
<td>1690</td>
<td>2080</td>
</tr>
<tr>
<td>0.10%</td>
<td>1.50</td>
<td>771</td>
<td>1201</td>
<td>1251</td>
<td>1691</td>
<td>2081</td>
</tr>
<tr>
<td>1%</td>
<td>1.49</td>
<td>775</td>
<td>1208</td>
<td>1258</td>
<td>1701</td>
<td>2094</td>
</tr>
<tr>
<td>5%</td>
<td>1.45</td>
<td>797</td>
<td>1241</td>
<td>1293</td>
<td>1748</td>
<td>2152</td>
</tr>
<tr>
<td>10%</td>
<td>1.40</td>
<td>825</td>
<td>1286</td>
<td>1339</td>
<td>1811</td>
<td>2229</td>
</tr>
<tr>
<td>50%</td>
<td>1.00</td>
<td>1155</td>
<td>1800</td>
<td>1875</td>
<td>2535</td>
<td>3120</td>
</tr>
<tr>
<td>100%</td>
<td>0.50</td>
<td>2310</td>
<td>3600</td>
<td>3750</td>
<td>5070</td>
<td>6240</td>
</tr>
</tbody>
</table>

HCM uses 1.5 sec as \( \bar{h} \) for regular drivers and the corresponding capacity is 2400 veh/h/ln. Because \( h_D < \bar{h} \), capacity will be expanded when DLC are present in traffic. Based on an estimation demonstrated in the rightmost column of Table 1, the average headway drops to 1 sec. at \( PD = 50\% \) when DLC is capable of a \( h_D = 0.5 \) sec. headway. Capacity at this point increases to 3600 veh/h/ln. When DLC reach 100% share, capacity triples to 7200 veh/h/ln. This improvement also changes the values of maximum service rate (MSF) for each LOS. MSF is the service measure used for design analysis in HCM. Recent versions of HCM use a constant ratio of MSF/c for each LOS, as shown in the first row of Table 1. Breakpoint is defined as the turning point at which the speed starts to drop as the flow rate increases. It is treated as a reference point for average speed if the flow rate is above the breakpoint, and it marks the end of FFS and the start of reaching capacity. With DLC mixed in traffic, MSF is adjusted as

\[ MSF' = c' \times \frac{v}{c} \]

Capacity increases as the proportion of DLC grows in the traffic, and so does MSF. The trend lines are plotted in Figure 1.
LOS is described in the speed-flow curve. The shape of the curve might also be changed by DLC. DLC are able to maintain a higher speed even at higher traffic density conditions, which means speed is not reduced due to the shorter car-following distances. Thus LOS evolves with the presence of DLC in traffic. Figure 2 shows the evolution of the speed-flow curve at 0%, 50%, and 100% DLC share in traffic.

**Figure 1:** MSF trend with 0.5-sec-DLC in traffic

**Figure 2:** Definition of LOS on the speed-flow curves for various DLC shares.
It should be mentioned that the actual adoption of DLC is likely to be very slow and progressive due to their complexity, high expected price, and other factors. We note that it took hybrid vehicles over ten years to reach 2% in the traffic mix of most US cities. DLC adoption may be smaller than that of the hybrid vehicles, so this paper focuses on the first few percentage points of share of DLC with different degrees of automation. However, the 50% and 100% estimates provide a depiction of a potential far in the future.

3.2 Adjust Demand Flow Rate

Considering the larger gaps in car following kept by trucks and unfamiliar drivers, HCM models this negative effect on capacity with two parameters \( f_{HV} \) and \( f_p \). These cause the flow rate to increase, which increases the density and worsens the LOS.

The \( PCE \) of trucks \( E_T \) can be expressed using the Headway Ratio Method proposed by Greenshields (Benekohal & Zhao, 1995):

\[
E_T = \frac{h_T}{h}
\]

where \( h_T \) is the average headway of trucks. Assuming \( P_{D,T} \) is the traffic composition share of driverless trucks (DL-T) with a headway of \( h_{D,T} \). The modified \( PCE \) and adjustment for trucks are

\[
E'_T = E_T \times (1 - P_{D,T}) + E_{D,T} \times P_{D,T}
\]

\[
E_{D,T} = \frac{h_{D,T}}{h}
\]

\[
f'_{HV} = \frac{1}{1 + P_T \times E'_T - 1} = \frac{1}{1 + P_T \times \left( E_T \times (1 - P_{D,T}) + E_{D,T} \times P_{D,T} \times E_{D,T} \right)}
\]

Eqs. 6,7 suggest how automated trucks improve traffic efficiency: the heavy vehicle factor increases for automated trucks because \( E_{D,T} \) is smaller than \( E_T \); this reduces the flow rate and the density.

Unlike regular commuters, drivers who are unfamiliar with a route tend to maintain longer headways for making decisions on lane choice. Mapping system and sensors provide DLC with detailed routing information and smarter lane choices, therefore their driving behavior could be the same or better than that of familiar drivers. A number ranging from 0.85 to 1 is adopted for \( f_p \) for the operational analysis, and the value cannot be derived from equation. For regular commuters HCM uses 1 as a reference point for \( f_p \); for unfamiliar commuters a value that is smaller than 1 will be used to reflect the lost efficiency by unfamiliar population. Incorporating the Headway Ratio Method, the equation for \( f_p \) is written as:

\[
f_p = 1 \times (1 - P_D) + \frac{h}{h_D} \times P_D = 1 \times (1 - P_D) + \frac{1}{E_D} \times P_D
\]
\( \frac{1}{E_D} \) in Eq. 8 can be seen as an expression of traffic efficiency by DLC relative to drivers. Similarly, Eqs. 3, 8 can be rewritten into \( 1 + P_D \times \left( \frac{1}{E_D} - 1 \right) \). The factor \( f_p' \) increases as DLC share increases, which reduces the flow rate and the density.

4 Case Studies of Freeway Segments

The modified HCM parameters are used in the following case studies. The case studies were selected from HCM Example Problems of each chapter, because we wanted to ensure that with \( P_D = 0\% \), the results with our modified HCM equations are identical to the results in the HCM. The effects of DLC on the service measures and their sensitivity to DLC are presented and compared.

4.1 A Case Study of a Six Lane Basic Freeway Segment

A six-lane freeway facility of base lane and shoulder widths and regular drivers is chosen from HCM Chapter 11 as the case study, with the following settings:
- Three lanes in one direction, \( N = 3 \)
- Volume (\( V \)) = 5,000 veh/h in one direction
- Proportion of trucks (\( P_T \)) = 10%
- Measured FFS = 70 mi/h
- PHF = 0.95

The resultant density of the base case study is 28.2 pc/mi/ln, which corresponds to LOS D. Adjustments for DLC are applied on the base case study to evaluate its effects on the parameters.

Our modifications included DLC shares from a very low proportion in the first stage of the adoption of DLC to a high proportion in the future, \( P_D = 0.1\%, 1\%, 5\%, 10\%, 20\%, 30\%, 50\%, 60\%, 90\%, 100\% \). Two headway settings were applied: 1.0 sec for A-DLC which represents the vehicles with automated driving functions; 0.5 sec for C-DLC which represents a stage when V2V or V2I capability is enabled (Arem, 2015). The more conservative setting for the A-DLC reflects the absence of communications with other DLC for traffic information gathering, thus a more forgiving setting was chosen. Heavy vehicles need a larger headway and spacing during car following; a headway of 1.2 sec. was used for DLC-trucks.

The effects of DLC on parameters \( E_T, f_{HV}, f_p \) at low proportions (\( P_D = 0\%, 0.1\%, 1\%, \) and 5\%) are summarized in Table 2. At the introductory stage, DLC can be considered as a new travel mode with a shorter car following and more traffic knowledge than regular drivers, with a higher \( f_p \) and a smaller \( PE \) for trucks. Even under low DLC shares, the larger \( E_T \) is observable as more DL-T are introduced in traffic. The factors can be positively affected by DLC.

As the number of DLC grows, the adjusted flow rate decreases which decreases density. With low DLC share, the change in the density is small. With a higher DLC share, density decreases and the LOS improves especially when DLC are tuned aggressively.

For C-DLC with \( h = 0.5 \) sec., LOS improves from D to C when the share of C-DLC reaches \( P_D = 3\% \), from C to B when \( P_D = 15\% \), and from B to A when \( P_D = 41\% \). With a longer headway setting at \( h = 1.0 \) sec for A-DLC, LOS changes from D to C when A-DLC reaches \( P_D = 7\% \), and from C to B when \( P_D = 41\% \). For this particular case study, LOS cannot reach LOS A by A-DLC even with \( P_D = 100\% \).

While LOS is being downgraded, its criteria for each level might also be changed. The growing trend presented in Table 3 resembles the shapes shown in Figure 2: Definition of LOS on the speed-flow curves for various DLC shares. The criterion for LOS will be changing according to the presence.
of increasing numbers of highly automated DLC in the future. Under low rate of DLC, slight change on LOS criteria is manifested in Table 3. And the change is hard to observe in traffic with only a small portion of A-DLC of longer headway settings.

Table 2: $E_T, f_{HV}, f_P, v_P$, Speed, and Density for various DLC shares and headways

<table>
<thead>
<tr>
<th>PD</th>
<th>$E_T$</th>
<th>$f_{HV}$</th>
<th>$f_P$</th>
<th>$v_P$</th>
<th>Speed</th>
<th>Density</th>
<th>LOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-DLC ($h_D$ = 1 sec)</td>
<td>0%</td>
<td>1.500</td>
<td>0.952</td>
<td>1.000</td>
<td>1842</td>
<td>65.217</td>
<td>28.2</td>
</tr>
<tr>
<td></td>
<td>0.1%</td>
<td>1.499</td>
<td>0.952</td>
<td>1.001</td>
<td>1841</td>
<td>65.239</td>
<td>28.2</td>
</tr>
<tr>
<td></td>
<td>1%</td>
<td>1.493</td>
<td>0.953</td>
<td>1.005</td>
<td>1832</td>
<td>65.434</td>
<td>28.0</td>
</tr>
<tr>
<td></td>
<td>5%</td>
<td>1.465</td>
<td>0.956</td>
<td>1.025</td>
<td>1791</td>
<td>66.241</td>
<td>27.0</td>
</tr>
<tr>
<td>C-DLC ($h_D$ = 0.5 sec)</td>
<td>0%</td>
<td>1.500</td>
<td>0.952</td>
<td>1.000</td>
<td>1842</td>
<td>65.217</td>
<td>28.2</td>
</tr>
<tr>
<td></td>
<td>0.1%</td>
<td>1.499</td>
<td>0.952</td>
<td>1.002</td>
<td>1838</td>
<td>65.286</td>
<td>28.2</td>
</tr>
<tr>
<td></td>
<td>1%</td>
<td>1.490</td>
<td>0.953</td>
<td>1.020</td>
<td>1805</td>
<td>65.869</td>
<td>27.4</td>
</tr>
<tr>
<td></td>
<td>5%</td>
<td>1.450</td>
<td>0.956</td>
<td>1.100</td>
<td>1669</td>
<td>67.878</td>
<td>24.6</td>
</tr>
</tbody>
</table>

Table 3: LOS criteria for various DLC shares and headways

<table>
<thead>
<tr>
<th>PD</th>
<th>LOS</th>
<th>Breakpoint</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-DLC ($h_D$ = 1 sec)</td>
<td>0%</td>
<td>11.00</td>
<td>17.00</td>
<td>18.00</td>
<td>26.00</td>
<td>35.00</td>
</tr>
<tr>
<td></td>
<td>0.1%</td>
<td>11.00</td>
<td>17.15</td>
<td>18.01</td>
<td>26.01</td>
<td>35.01</td>
</tr>
<tr>
<td></td>
<td>1%</td>
<td>11.04</td>
<td>17.20</td>
<td>18.06</td>
<td>26.09</td>
<td>35.12</td>
</tr>
<tr>
<td></td>
<td>5%</td>
<td>11.19</td>
<td>17.43</td>
<td>18.31</td>
<td>26.44</td>
<td>35.59</td>
</tr>
<tr>
<td>C-DLC ($h_D$ = 0.5 sec)</td>
<td>0%</td>
<td>11.00</td>
<td>17.00</td>
<td>18.00</td>
<td>26.00</td>
<td>35.00</td>
</tr>
<tr>
<td></td>
<td>0.1%</td>
<td>11.01</td>
<td>17.15</td>
<td>18.02</td>
<td>26.02</td>
<td>35.02</td>
</tr>
<tr>
<td></td>
<td>1%</td>
<td>11.07</td>
<td>17.26</td>
<td>18.12</td>
<td>26.17</td>
<td>35.23</td>
</tr>
<tr>
<td></td>
<td>5%</td>
<td>11.38</td>
<td>17.73</td>
<td>18.62</td>
<td>26.90</td>
<td>36.21</td>
</tr>
</tbody>
</table>

For a given case HCM calculates only one single value for variables and LOS. In order to take into account the variety of DLC in headway settings, proportion in traffic and the overall demand (volume) on the subject freeway facility, Monte Carlo simulations (MCS) were conducted for further impact study of DLC. Also sensitivity analysis is performed to evaluate the impact of DLC on LOS under different traffic demands, DLC headways, and proportions.

The same base case study was used and then, 100 randomly distributed demands ranging from 1500 veh/h to 6500 veh/h were generated by MCS to reproduce the fluctuation of hourly demand. DLC with V2V or V2I communication functions were mixed in the traffic stream. For comparison purposes, the proportions of A-DLC were the same as the traffic compositions mentioned previously. The simulation results from Matlab are displayed in Figure 3 along with the various demand values in the inset graph. The results suggest that the more congested a road is, the more improvement it will receive with DLC. The three lines (from bottom to top) represent the trend of LOS from A to C. Under low DLC shares, when $P_D$ is over 1%, density starts to drop and LOS improves from D to C. Figure 4 also presents another expected outcome: if the initial traffic condition is good (LOS B), even with
100% DLC the improvement will be very small. When $P_D$ is over 15%, densities drop below the LOS B green line. Around a DLC share of 50% all curves form into parallel lines below LOS A, because with more DLC in traffic the average speed tends to be closer to the FFS.

Figure 3: Sensitivity of LOS to traffic demand and DLC share

Figure 4 presents the sensitivity of LOS to DLC headways. The inset graph shows the 100 randomly distributed headways ranging from 0.5 to 1.5 sec. were generated by MCS to reproduce the variety of DLC headways. Demand remains the same as the demand in the base case study. Two lines represent the plots of the aforementioned DLC types: the pink line represents ADLC with assumed 1.0 sec. headway; and the magenta line on the bottom represents CDLC with 0.5 sec headway. The top line represents the LOS when DLC are tuned to maintain the headway that is closer to but less than

Figure 4: Sensitivity of LOS to DLC headway and share
regular drivers, thus it remains as a level line with a slight incline. Under low $P_D$, as the $h_D$ becomes shorter the trend line is steeper. When $P_D$ is above 50%, parallel lines are formed. The findings show that DLC have no effect on LOS with only a few of them in traffic, such as the DLC being tested in the present time. When DLC reach higher $P_D$, DLC will play a major role of improving LOS and relieving congestion. The MCS presented in Figure 5 demonstrates the sensitivity of LOS to DLC for low shares in traffic, and with possible headway capabilities in various traffic demands. The line with asterisks represents the mean value of the density of each percentage, which indicates that DLC are able to reduce density especially in congested traffic.

Even though the driverless technology might have different requirements for different vehicle types, the fact that it improves the quality of basic freeway service stays the same.

![Figure 5: Sensitivity of LOS to demand, DLC headways and low shares](image)

### 4.2 A Case Study of a Four Lane Freeway Weaving Segment

The base case study selected from the HCM Chapter 12 is a four-lane weaving segment with:
Two lanes in one direction
Volume \( (v) = 4,841 \text{ veh/h in one direction} \) \( (V_{FF}=1,815 \text{ veh/h}, V_{RF}=1,037 \text{ veh/h}, V_{FR}=692 \text{ veh/h}, V_{RR}=1,297 \text{ veh/h}) \)
Proportion of trucks \( (P_T) = 10\% \)
Measured \( FFS = 65 \text{ mi/h} \)
\( c_{IFL}=2,350 \text{ pc/h/ln} \)
Regular drivers
\( PHF=0.91 \)

The density is estimated as 26.3 pc/mi/h as a LOS C from the base case. Unlike a basic freeway segment, a weaving segment has a lower capacity per lane due to the lane-changing maneuvers. A gap acceptance study found that passenger cars tend to slow down before the drivers make their decisions of changing lane, which creates larger gaps ranging from 2.60 to 5.07 sec. (Kusuma, et al., 2013). Gap acceptance behavior is important to freeway capacity analysis. DLC are able to accept shorter gaps for lane-changing, and therefore reduce the lane-changing rates defined in HCM. The order of evaluating parameters starts with adjusting flow rates, capacity, and lane-changing rates. Weaving turbulence is described by lane-changing rates parameters. The minimal weaving turbulence is defined as \( LC_{MIN} \), which is determined by the configuration of the weaving segment and weaving demand flow rates. The weaving turbulence increases as the lane-changing rate increases, which cause non-weaving speeds to decrease.

Our modifications on the weaving segment analysis included DLC shares of 0.1%, 1%, 5%, 10%, 20%, 30%, 50%, 60%, 90%, 100%. One hundred traffic demands ranging from 1500 to 6000 veh/h were generated with MCS. Sample results of major parameters of weaving segments under different demands and shares of DLC are summarized in Table 4.

**Table 4:** Flow rate, lane-changing rates, capacity, speed, and density for various DLC shares and headways

<table>
<thead>
<tr>
<th></th>
<th>PD 0%</th>
<th>PD 0.1%</th>
<th>PD 1%</th>
<th>PD 5%</th>
<th>PD 10%</th>
<th>PD 20%</th>
<th>PD 50%</th>
<th>PD 100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>( v )</td>
<td>5586</td>
<td>5583</td>
<td>5554</td>
<td>5431</td>
<td>5284</td>
<td>5010</td>
<td>4319</td>
<td>3475</td>
</tr>
<tr>
<td>( LC_{MIN} )</td>
<td>798</td>
<td>798</td>
<td>794</td>
<td>776</td>
<td>755</td>
<td>716</td>
<td>617</td>
<td>497</td>
</tr>
<tr>
<td>( C_W )</td>
<td>8038</td>
<td>8042</td>
<td>8083</td>
<td>8266</td>
<td>8496</td>
<td>8960</td>
<td>10393</td>
<td>12917</td>
</tr>
<tr>
<td>( LC_{ALL} )</td>
<td>1927</td>
<td>1926</td>
<td>1918</td>
<td>1884</td>
<td>1843</td>
<td>1768</td>
<td>1578</td>
<td>1346</td>
</tr>
<tr>
<td>( D )</td>
<td>26.3</td>
<td>26.3</td>
<td>26.1</td>
<td>25.4</td>
<td>24.6</td>
<td>23.1</td>
<td>19.5</td>
<td>15.3</td>
</tr>
</tbody>
</table>

As in the previous case study, two headway settings were considered: 0.5 sec. for C-DLC and 1.0 sec. for A-DLC. Estimates indicate that density is reduced by 25% when \( PD=13\% \), the point where LOS improves from C to B. When \( PD=62\% \), density reduces by 62% (a numerical coincidence) LOS improves to A. However, LOS could not reach A even at a 100% penetration rate with a DLC headway of 1.0 sec. DLC can increase the values of \( f_{HV} \) and \( f_p \), which also results in an increasing capacity. HCM models the lane-changing behaviors using number of lane changes: \( LC_{MIN} \) and \( LC_{ALL} \).
\(L_{\text{MIN}}\) is determined by traffic demand and configuration of the weaving segment, thus it decreases as \(P_D\) increases. The total number of lane changes is affected by flow rates. DLC can make faster lane-changing maneuvers. Both parameters will shrink as the number of DLC grows. The average speed is estimated by the weighted average of weaving speeds and non-weaving speeds, which are determined by demand and lane-changing rates. Therefore DLC will tend to increase the average speed.

For weaving segments, DLC is able to reduce the weaving turbulence due to its shorter headways for car-following and lane-changing. However, the improvements are observable when DLC reach at least 1\% of the traffic composition and have 0.5 sec headway, as the dotted line in Figure 7 indicates. When \(h_D = 1.0\) sec., as the lighter dotted line indicates, at least 5\% DLC are needed to make the density drop observably. Thus, there are two ways of improving traffic flow by adopting DLC: Either by improving their technological capability with short headways or by increasing the traffic compositions of DLC in traffic, as long as DLC are tuned with headways that are shorter than the average driver’s.

MCS simulations in Figures 6 and 7 manifest results similar to those discussed in section 4.1: As the demand increases the reduction in density brought by DLC increases. Lower DLC headway yields a lower density and a better LOS.

5 Conclusions

This paper provides sample quantifications of the possible impact of DLC on freeway traffic flow for a basic segment and a weaving segment. Our analyses include the possible implementation of driverless technology on passenger cars and trucks, and also its degrees of automation. The analyses are modified and parameters adjusted based on HCM 2010 methodologies. Considering the uncertainty of future implementation, Monte Carlo simulations are used to provide scenarios when: (1) DLC with one certain headway setting to be mixed in different traffic demands; (2) DLC with varied headway settings are mixed in the same traffic demand DLC are designed to provide a safer and more efficient driving experience than human drivers do. In order to achieve this, technologies such as mapping and geolocation systems, cruise control, and automated lane-changing systems are designed.
to conduct all driving maneuvers without being affected by the uncertainties of the human decision-making process.

Two types of DLC were considered in this paper: Autonomous DLC, and Connected DLC. The latter incorporates V2V and V2I communications and may operate with even shorter headways due to the direct information exchange among vehicles and infrastructure. The Autonomous DLC may be set to maintain relatively longer headway due to safety and liability concerns. The impacts of DLC on the HCM parameters of freeway traffic flow are estimated under two assumptions: (i) Headway settings: 0.5 sec for the Connected DLC and 1.0 sec for the Autonomous DLC; (ii) Market penetration rates:
0.1%, 1%, 5% of DLC are assumed for the early stages of implementation, and a 100% rate is considered as a theoretical reference for realizing the maximum potential of this technology.

The primary findings of this analysis are as follows:

- If the DLC headway is comparable to that of the average driver, then the LOS on basic freeway segments will improve very little even with $P_D=100\%$. Some improvement should be expected at weaving areas due to crisper and safer lane-changing by the DLC.
- DLC will provide low or no improvement in LOS in low density conditions.
- DLC may provide substantial improvement in LOS in high density conditions.
- DLC shares below 2% are unlikely to produce detectable improvements in the quality of traffic flow. Given that gasoline-electric hybrid cars took at least a decade to reach a 2% share in the traffic composition of several major cities in the U.S., and that DLC are likely to be much costlier than hybrids, DLC benefits in freeway operations may take decades to materialize.
- More improvement on LOS can be achieved by growing the DLC share in traffic ($P_D$).
- More improvement on LOS can be achieved by shortening the DLC car following headway ($h_D$).

Additional potential traffic flow advantages of DLC include the following:

- V2V and V2I communications between vehicles and infrastructure may provide more efficient traffic flow, particularly at the weaving flows of freeway merges and diverges.
- DLC may help to attenuate traffic flow perturbations with more advance settings such as adaptive headways.

References


