Effects of Connected and Autonomous Vehicles on Contraflow Operations for Emergency Evacuation: A Microsimulation Study

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INTRODUCTION
In recent times, integration of advanced wireless communication and sensing technologies into traffic management systems have occurred with the goal of enhancing mobility, sustainability, safety, and reliability of these systems. Autonomous vehicles have been prototyped with substantial advances wireless communication technologies to create an internet of vehicles where individual vehicles can communicate with other vehicles (through vehicle-to-vehicle [V2V] communications) and infrastructure (through vehicle-to-infrastructure [V2I] communications (1)). The intent of this research is to study the effects of connected and autonomous vehicles (CAV) in emergency evacuation situations, where better operations can make a world of difference for an efficient and safe evacuation.

One of the most common and effective emergency evacuation alternatives deployed by state agencies along interstates is contraflow operations. In this research study, the contraflow operations utilizes the eastbound lanes of the I-10 in the state of Florida between SR 23 and I-75 to allow the evacuating traffic to travel westbound, allowing westbound traffic to cross over to the eastbound lanes. The alternatives tested in this study are determined by different market penetration rates (MPRs) of CAV with respect to non-CAV vehicles. The analysis evaluated the following MPRs of CAV for I-10: 0% CAV, 20% CAV, 30% CAV, and 50% CAV.

Previous studies related to evacuation focused on developing evacuation network model to forecast traffic flow conditions (2, 3) and operating procedures for contraflow lanes (4, 5). Several studies also focused on intelligent transportation system techniques such as contraflow network reconfiguration approaches incorporating road capacity constraints (6, 7). However, there is a lack of comprehensive research on using connected and/or autonomous vehicle technologies during an emergency evacuation. There is indeed a need to understand the effects of CAV vehicles on unique emergency evacuation situations when heavy traffic, slower human reaction times, and tense situations can interrupt traffic flow patterns. This research study aims to investigate if CAVs can improve operations in such scenarios.

METHODOLOGY
Florida Department of Transportation (FDOT) model forecasts from the Statewide Regional Evacuation Study Program (SRESP) were used as a basis to develop the hourly volumes for this research study (10). The countywide evacuation total volumes from the SRESP were then converted to hourly volumes based on the K-factors obtained from FDOT traffic count stations along I-10. VISSIM analysis was conducted for a six-hour evacuation period. At least 10 different seeds were used to ensure the stochastic nature of the models for simulation.

The calibration process involved modifying default model parameters so that the model outputs reasonably replicate existing year (2015) conditions. Traffic volumes and speeds were aggregated to 15-minute intervals for an hour for both simulated and actual conditions. Geoffrey E. Havers (GEH) statistic was used to compare field volumes with those obtained from the simulation model. GEH is defined as:

\[ GEH = \sqrt{\frac{2(E-V)^2}{E+V}} \]  

Where, \( E = \) model estimated volume and \( V = \) field observed volume

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To achieve validation, simulated and measured link volumes for more than 85% of links needs to have a GEH < 5, and modeled average link speeds to be within the ±5 mph of field-measured speeds (11, 12). For volume validation, the calculated GEH was 2.63 for 89.7% of eastbound links and 2.95 for 93.5% of the westbound links. GEH statistics between model speeds and field speeds in the peak hour was within a difference of less than 2.15 mph for 86% of the observations for eastbound and 2.24 mph for 94% of the observations for the westbound directions. Therefore, the volumes and speeds in the VISSIM models are a good representation of the existing conditions that were measured in the field.

Three freeway driving behavior types were used in the existing conditions models based on field data for the mainline, merge, and diverge areas. Parameters for each type of the driving behaviors were varied to allow for increased driving headway aggressiveness, improved lane change (ramp merge cooperation) behavior, and safety distance behavior.

For this study, a customized external driver model was created to define a CAV behavior using C++ programming language. This model utilizes the Cooperative Adaptive Cruise Control (CACC) autonomous feature, which is a third level of automation based on the USDOT definition. In the platooning, the optimal driving maneuvers to maintain the desirable headways are generated based on the driving information collected by each pair of leading-to-following vehicles. To model machine driving behavior, previous researches used Intelligent Driver Model (IDM) or modified IDM to model ACC or CACC (8, 9, 13, 14). The IDM model defines the desired acceleration ($\dot{v}_{IDM}$) as following:

$$\dot{v}_{IDM}(t + t_a) = \max \left\{ b_m, a_m \left[ 1 - \left( \frac{v}{v_0} \right)^\delta - \left( \frac{s^*}{s} \right)^2 \right] \right\}$$

(2)

where, $t_a =$ perception-reaction time, $b_m =$ maximum deceleration, $a_m =$ maximum acceleration, $v =$ speed of the following vehicle, $v_0 =$ desired speed, $\delta =$ acceleration exponent, $s =$ gap distance between two vehicles, $s_0 =$ minimum gap distance at standstill, $T =$ safe time headway, $b =$ desired deceleration, $s^* =$ desired gap distance and $\Delta v =$ speed difference between leading and following vehicles.

In order to maintain the grouping for platooning, three types of joining methods were implemented in the autonomous longitudinal vehicle control algorithm. The joining types are: rear joining, front joining and middle joining. For the CACC model, the following set of equations describes the leading and following vehicles desired distance (15).

$$u_2(t) = c_0 \dot{x}_1(t) + c_1 \{ \dot{x}_1(t) - \dot{x}_2(t) \} + c_2 \{ r(t) - r_d(t) \}$$

(3)

$$u_2(t) \leq a_{max}$$

$$u_2(t) \geq d_2$$

Where, $r_d(t) =$ desired distance between vehicles, $r(t) =$ current distance between vehicles, $\dot{x}_1(t) =$ acceleration of the leading vehicle, $\dot{x}_1(t) =$ speed of the leading vehicle, $\dot{x}_2(t) =$ speed of the following vehicle, $a_{max} =$ maximum allowed acceleration, $d_2 =$ maximum allowed deceleration, and $c_0 =1, c_1 > 0, c_2 > 0$. 

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FINDINGS
The daily volumes for the contraflow operations assumed that the average conditions from the six hours model occur for eight hours and the remaining 16 hours operate at 2,000 vph on the two westbound regular lanes. Study results are shown in Table 1 and Table 2.

Table 1 Theoretical Capacity vs. Simulated Volumes

<table>
<thead>
<tr>
<th>MPR</th>
<th>Theoretical Capacity (vehicles)</th>
<th>Modeled/Simulated Volumes (vehicles)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hourly</td>
<td>Daily</td>
</tr>
<tr>
<td>0% CAV</td>
<td>6,000</td>
<td>112,000</td>
</tr>
<tr>
<td>20% CAV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30% CAV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% CAV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Corridor-wide Measures of Effectiveness Results

<table>
<thead>
<tr>
<th>Measures of effectiveness</th>
<th>0% CAV</th>
<th>20% CAV</th>
<th>30% CAV</th>
<th>50% CAV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average value</td>
<td>Average value</td>
<td>% Change from the 0% CAV (p-value)</td>
<td>Average value</td>
</tr>
<tr>
<td>Delay (sec)</td>
<td>347.70</td>
<td>273.20</td>
<td>-21.43% (0.0011)</td>
<td>208.40</td>
</tr>
<tr>
<td>Latent demand (vehicles)</td>
<td>4061</td>
<td>3947</td>
<td>-2.81% (0.1340) #</td>
<td>3805</td>
</tr>
<tr>
<td>Travel time (sec)</td>
<td>592.10</td>
<td>589.60</td>
<td>-0.42% (0.1234) #</td>
<td>584.90</td>
</tr>
<tr>
<td>(between interchanges)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Travel time (sec)</td>
<td>5617.70</td>
<td>5597.20</td>
<td>-0.36% (0.9760) #</td>
<td>5523.90</td>
</tr>
<tr>
<td>(Begin to end regular lanes)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Travel time (sec)</td>
<td>5763.10</td>
<td>5533.40</td>
<td>-3.99% (0.2745) #</td>
<td>5411.80</td>
</tr>
<tr>
<td>(Begin to end contraflow lanes)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed (mph) (regular lanes)</td>
<td>55.18</td>
<td>57.82</td>
<td>4.78% (0.0186)</td>
<td>58.97</td>
</tr>
<tr>
<td>Speed (mph)</td>
<td>63.13</td>
<td>64.96</td>
<td>2.90% (&lt;0.0001)</td>
<td>65.63</td>
</tr>
<tr>
<td>(contraflow lanes)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Queue delay (sec)</td>
<td>12.09</td>
<td>7.92</td>
<td>-34.50% (&lt;0.0001)</td>
<td>6.40</td>
</tr>
</tbody>
</table>

# Not significant at 5% significance level
The results in Table 1 show that there is 30.7% increase of hourly throughput for the traffic mix with 50% CAV compared to traffic with 0% CAV vehicles. Also, the daily throughputs are lower than the theoretical capacity of the roadway for the 0%, 20% and 30% CAV MPRs. Several measures of effectiveness were extracted from the VISSIM runs for all the models with different MPRs. Two sample t-test was performed for each of the measures at 95% confidence interval to identify the significance of the CAV vehicles on the operations of the evacuation. Table 2 provides the summary of the p-value statistics between the 0% CAV vs. different CAV MPRs.

According to the Table 2 results, there were no significant improvements in the results of the latent demand and travel times between the 0% CAV and the 20% CAV MPRs. Although the overall delay, speeds and queue delay showed significant improvements (based on the p-value) for the 20% CAV compared to the 0% CAV MPR. However, the 30% and 50% CAV MPRs showed improvements for all the measures of effectiveness parameters over the 0% CAV MPR. Compared to the 0% CAV, for the 50% CAV MPR, there was about 83.85% reduction in overall delay, 10.24% reduction in latent demand, 3.69% reduction in travel time for the regular lanes, 7.29% reduction in travel time for the eastbound contraflow lanes, 13.01% increase in evacuation speed for the regular lanes, 7.37% increase in evacuation speed for the contraflow lanes, and 52.5% reduction in queue delay. The results show that the inclusion of CAV vehicles in a traffic mix for evacuation can reduce the overall delays as there will be less burden on unfamiliar drivers with limited time to evacuate, resulting in smoother flow if they are equipped with CAV vehicles. The overall reduction in travel times for the contraflow lanes also proves that for such unusual operations, CAV vehicles can provide a smoother flow, as the primary objective of a CAV vehicle is to maintain a platoon while achieving a desirable speed and headway, which eventually results in a consistent flow and faster travel.

Speeds between the interchange segments were collected for all the simulation runs for the 6-hour simulation period. Figure 1 shows plots with westbound average speeds and travel times along the corridor between the interchanges for the regular and contraflow lanes. The plots show that vehicles were able to maintain a steady speed close to 60 mph for most of the corridor for all of the CAV alternatives, where CAV vehicles were able to maintain the platoon and steady travel speeds. However, the model with 0% CAV exhibited lowed speeds compared to the CAV models. Also, the average travel times were lower for the CAV alternatives compared to the non-CAV one.
Figure 1 Speed and travel time comparison among different CAV MPRs for westbound I-10 evacuation (a) regular lanes, (b) contraflow lanes.

CONCLUSION
The purpose of this study was to evaluate the effect of connected and autonomous vehicle (CAV) systems for evacuation purposes along I-10 during an emergency evacuation event. I-10 is a major east-west evacuation route for the northern portion of the State of Florida. The alternatives tested in this study are determined by different MPRs of CAVs with respect to non-CAV vehicles. The research study evaluated the effects of CAVs on contraflow evacuation with the following MPRs of CAV for I-10 between SR 23 and I-75: 0% CAV, 20% CAV, 30% CAV and 50% CAV.

Results of the analysis showed that all the alternatives with CAV vehicles showed better performances in terms of average speed, overall delay, travel time and queue delay for the regular westbound lanes as well as the eastbound lanes for the contraflow operations. Daily throughputs of the networks with the CAV alternatives were also higher than the 0% CAV alternative. The VISSIM models simulated higher number of vehicles arriving per hour for the CAV alternatives compared to the non-CAV one. Non-CAV vehicles showed increased weaving due to slightly aggressive driving behavior. However, the CAV vehicles exhibited better platooning behavior resulting in decreased friction.
Some previous studies provided theoretical projections to show that CAV vehicles can improve delay or throughputs for a freeway. However, this study showed new findings by simulating a contraflow evacuation operation and with varying mix of CAVs. The study clearly identified the positive effects of CAVs on traffic operations in a unique scenario such as an emergency evacuation.

Future researches can incorporate multiple autonomous technologies so that the effects of fully autonomous vehicles can be understood. The external driver can be improved to incorporate a lane changing behavior in the external driver model.

REFERENCES


