Management of Connected and Automated Vehicle Disengagements in the proximity of Work Zones

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Introduction

Work zones (WZ) incur profound impacts in the safety, mobility and environmental realms. Researchers and transportation agencies have exerted significant efforts in mitigating their adverse impacts (i.e. high crash frequency and severity, congestion, increased energy consumption and emissions). To this end, Intelligent Transportation Systems (ITS) have been used to deploy speed managements techniques in the proximity of WZs (Bham and Mohammadi, 2011; Khondaker and Kattan, 2015; Maze et al., 2000) and traffic diversion to alternative routes (Edara et al., 2013). Focus has been also placed on WZ traffic analysis (Zhang et al., 2012), WZ safety analysis and modelling (Yang et al., 2015), and impact assessment (Ullman et al., 2011).

The advent of connected vehicle (CV) technologies has brought new opportunities in traffic management around WZs. Vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communication technologies were shown to improve mobility performance around WZs (Abdulsattar et al., 2019; Ramezani and Benekohal, 2015). Moreover, vehicle automation in conjunction with vehicle connectivity has facilitated cooperative driving among connected and automated vehicles (CAV) which can yield travel time, safety and emission benefits at freeway WZs (Zou and Qu, 2018). However, this is the first study that focuses on management of CAV disengagements in the proximity of WZs to the authors' best knowledge.

System-initiated (downward) control transitions are expected to be frequent in the proximity of WZs due to ambiguous lane markings and complex traffic situations (Favarò et al., 2018). We name the areas that the latter control transitions will be taking place as "Transition Areas" (TA) (Wijbenga et al., 2019). This study investigates the effects of Day 1 Cooperative ITS (C-ITS) applications and Cooperative Driving (CD) on management of vehicle disengagements and work zone performance with the use of microscopic traffic simulator SUMO (Lopez et al., 2018).

Methodology

Simulation experiments are conducted on a hypothetical two-lane highway WZ using simplified demand scenarios (Maerivoet et al., 2019). Mixed traffic conditions that encompass legacy vehicles (LVs), CVs, and CAVs are considered. CVs are explicitly capable of exchanging Day 1 C-ITS messages, while CAVs have more advanced communication capabilities (i.e. collective perception, manoeuver coordination). LVs are manually driven and have no connectivity capabilities. Simulation analysis is performed for three different traffic demand levels and penetration rates of automation and connectivity (Mintsis et al., 2019a).

Longitudinal CV and CAV motion is replicated based on thoroughly tested ACC and CACC car-following algorithms (Milanés et al., 2014; Milanés and Shladover, 2014; Porfyri et al., 2018). Lateral motion of CAVs is emulated by parametrizing the default SUMO lane change model (Erdmann, 2014) with the use of actual lane change data (prototype vehicle) provided by Hyundai Motor Europe Technical Center GmbH (HMETC) (Mintsis et al., 2019a). A novel transition of control (ToC) model was developed to mimic system-initiated (downward) ToCs and minimum risk manoeuvers (MRM) (in case of unsuccessful ToCs) (Lücken et al., 2019). Detailed information with the respect to the parametrization of the latter models in the context of this study can be found in (Mintsis et al., 2019a).

Two different traffic management scenarios were developed and simulated to examine vehicle disengagements and improve WZ performance. The first scenario explicitly encompasses Day 1 C-ITS applications. A roadside unit (RSU) is installed 300 m upstream of the WZ. Approaching CVs receive DENM messages and execute successful ToCs (drivers of CVs are assumed to continuously monitor the primary driving tasks due to lower automation level of CVs). On the other hand, CAVs are categorized in two distinct groups based on their capabilities to accommodate WZ scenarios. The first group (CAVs_G_A) cannot cope with WZs in automated mode, and thus CAVs_G_A issue take-over requests (TOR) upon DENM reception. If drivers fail to respond to the latter TORs, CAVs execute MRM in lane. The second group (CAVs_G_B) can pass WZs in automated mode if CAVs_G_B travel on the non-blocked lane or can merge unimpeded (from surrounding traffic) to non-blocked lane. Otherwise, they dynamically issue TORs in the close proximity of the work zone (according to their speed and distance from the WZ).

In the Cooperative Driving scenario, two RSUs are existent 300 m and 900 m upstream of the WZ. CV and CAV_G_A behavior is similar as in the Day 1 C-ITS scenario. However, CAVs_G_A are now guided towards safe spots (in front of the WZ) in case of MRMs. CAVs_G_B receive lane change or keep advice depending on the driving lane upon entrance to traffic management area (within communication range). Additionally, their lane change behavior is assumed more aggressive within traffic management area due to enhanced perception from the TMC side (i.e. collective perception, data fusion). Finally cooperative lane changing is feasible among CAVs_G_B based on a distributed approach presented in (Mintsis et al., 2019b).

Results

As aforementioned, Day 1 C-ITS and Cooperative Driving scenarios are simulated for three different traffic demand levels (LOS B, C, and D) and three different vehicle mixes (Mix 1, 2, and 3) as described in (Mintsis et al., 2019a). Furthermore, 10 simulation runs pertaining to different random seeds for each combination of demand level and vehicle mix are executed. In the following, the simulation results are analyzed in the aspects of traffic efficiency, safety, and environmental impacts.

Fig. 1 indicates that MRMs occurring in lane during the Day 1 C-ITS scenario generate traffic breakdown that affects the road section upstream of the work zone for the whole simulation timeline (left plot). On the contrary, CAV_G_A guidance to safe spot on the blocked lane during the Cooperative Driving scenario prevents the propagation of traffic disruption upstream towards the network entry (right plot). Moreover, it can be observed that infrastructure-assisted traffic management and cooperative driving ensure an improved level of service (increased speeds) by preventing inefficient traffic operations in the proximity of the work zone (smoother merging in the non-blocked lanes).

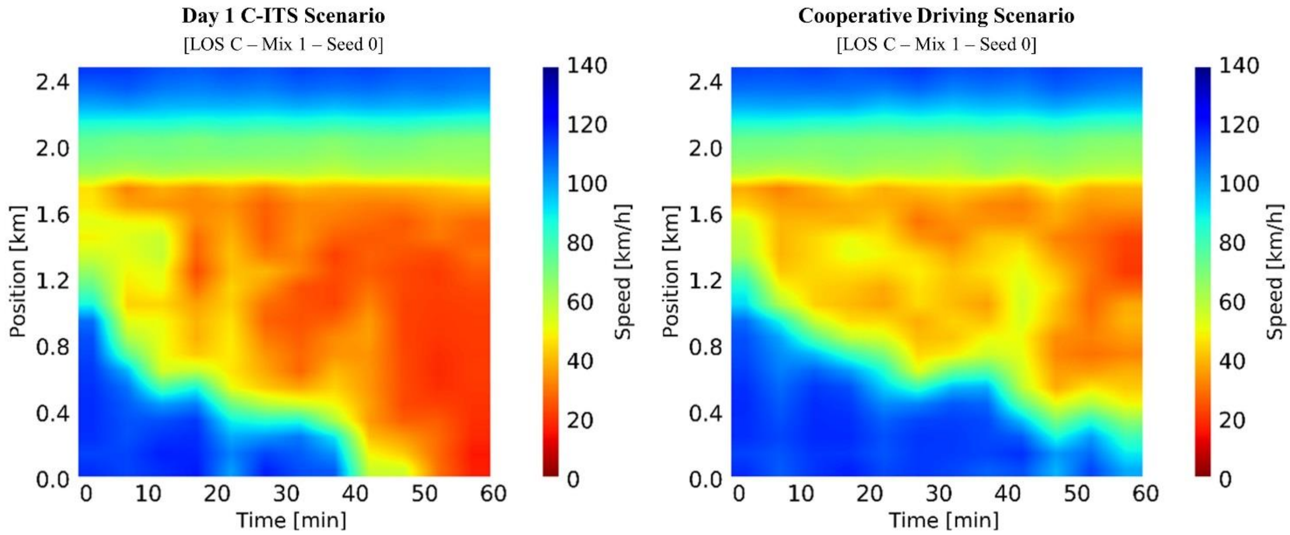
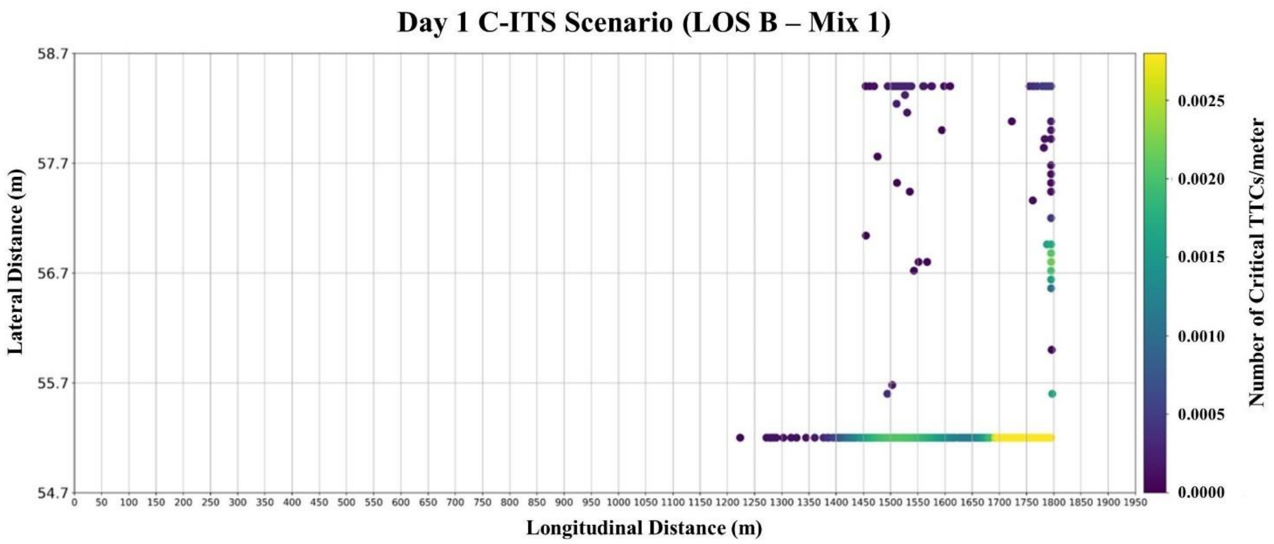


Fig. 1. Exemplary speed tempo-spatial diagrams for simulation run: LOS C – Mix 1 – Seed 0. The left column corresponds to Day 1 C-ITS scenario; the right column to Cooperative Driving scenario.

Fig. 2 depicts the spatial distribution of safety critical events. The time-to-collision (TTC) density plots feature the aggregated number of critical TTCs of 10 seeds (per LOS/Mix) marked as bins along the highway network. Each plotted bin means that at least one TTC occurred at this position. The color of a bin then indicates the amount of TTCs at this marked position. It is shown that infrastructure-assisted traffic management and cooperative driving reduce collision risk. Provision of lane change/keep advice to CAVs_G_B and homogenized lane change behavior within the traffic management area improve safety levels due to mitigation of safety critical car following and lane changing situations.



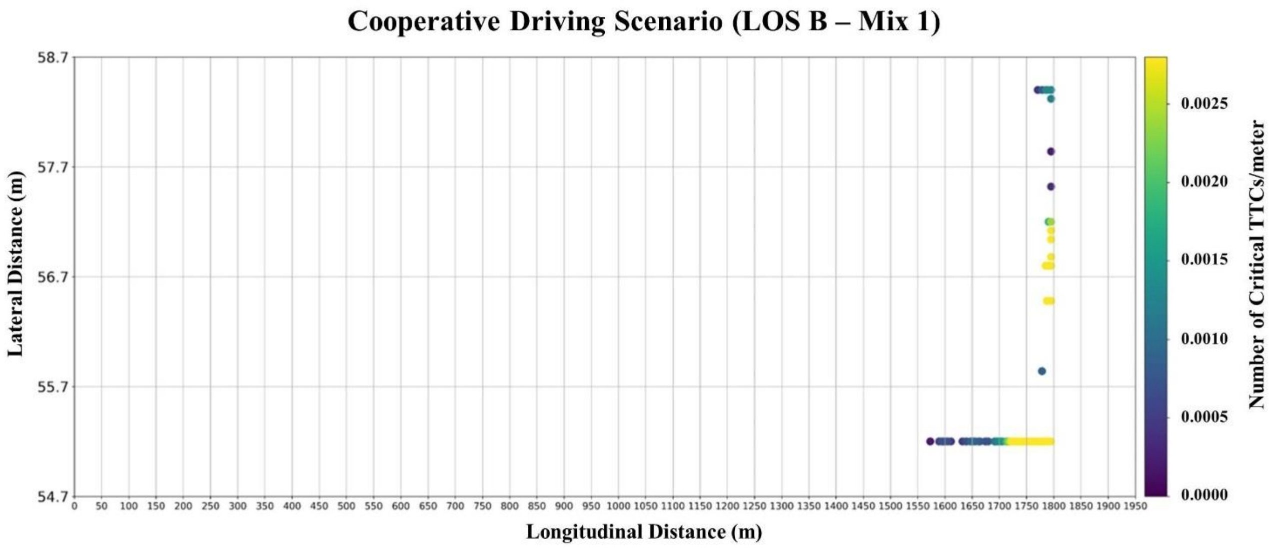


Fig. 2. Spatial distribution of critical TTCs (< 3sec) for parameter combination: LOS B – Mix 1. Upper plot depicts Day 1 C-ITS scenario results; lower plot depicts Cooperative Driving scenario results.

Finally, Fig. 3 demonstrates that in Cooperative Driving scenarios improved performance in terms of environmental benefits (especially for congested conditions) is achieved compared to Day 1 C-ITS scenarios. This finding coincides with reported traffic efficiency results presented in Fig. 1.

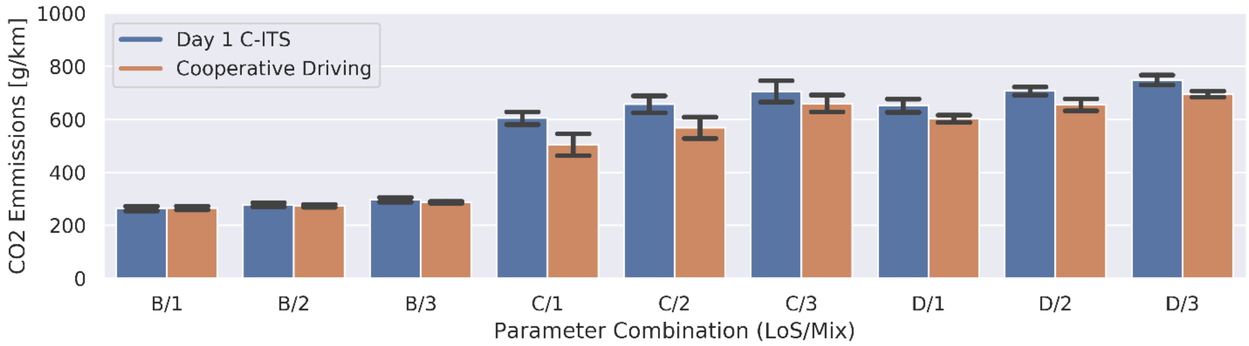


Fig. 3. Average CO_2 emissions per driven kilometre for the examined parameter combinations (varying the LOS and vehicle mix). Different bar colours correspond to Day 1 C-ITS and Cooperative Driving simulations.

Conclusion

This study showed that C-ITS applications beyond Day 1 in conjunction with cooperative driving could more efficiently manage vehicle disengagements and improve WZ performance compared to Day 1 C-ITS applications. Future research efforts will focus on the comparison of examined scenarios (Day 1 C-ITS and Cooperative Driving) with sensor-based and manual driving.

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