Towards Synergistic Effects of C-ITS Services: Assessing the Joint Impact of GLOSA and CACC on Traffic Efficiency and Sustainability

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Abstract: This paper investigates the combined effects of Cooperative Adaptive Cruise Control (CACC) and Green Light Optimal Speed Advisory (GLOSA) on traffic efficiency and sustainability using microscopic traffic simulations. Addressing a gap in the literature, the research focuses on the simultaneous use of these Cooperative Intelligent Transport System (C-ITS) services rather than their individual effects. Simulations were conducted at three test sites with varying traffic characteristics and different penetration rates of C-ITS technologies. The results demonstrate that CACC significantly improves traffic flow and reduces CO_2 emissions starting at a 16% penetration rate. However, the effects of GLOSA were marginal and statistically insignificant within the chosen simulation setup. The combined use of CACC and GLOSA provided slight improvements over CACC alone, though these differences were not statistically significant. The findings highlight the substantial benefits of CACC in enhancing traffic flow and reducing emissions, particularly at higher penetration rates. The study underscores the importance of widespread adoption of CACC and calls for further research to explore additional service combinations to optimise the potential of C-ITS for sustainable transportation.

1 INTRODUCTION

Conventional traffic management systems are increasingly reaching their capacity limits due to the continuous rise in urban traffic volumes worldwide (Eurostat, 2023). The increase in traffic volume has resulted in longer journey times, a greater frequency of stop-and-go movements, and an overall rise in energy consumption. These factors not only affect the efficiency and sustainability of urban transportation but also have a detrimental impact on the quality of life of residents in these areas (Walch et al., 2024). In response to these challenges, technologies that enhance traffic management through the use of connectivity and automation, commonly known as Cooperative Intelligent Transport Systems (C-ITS), are gaining prominence (European Commission, 2016).

Among these technologies, Cooperative Adaptive Cruise Control (CACC) and Green Light Optimal Speed Advisory (GLOSA) aim to support enhancing traffic efficiency and sustainability. CACC stabilises traffic flow by enabling vehicles to coordinate speeds and promptly respond to traffic changes, enhancing driver comfort. GLOSA, on the other hand, optimises intersection passage by advising drivers on speeds to avoid unnecessary stops during traffic signal cycles. Both technologies aim to improve traffic efficiency while reducing emissions and fuel consumption by promoting smoother driving.

While numerous studies have demonstrated the effectiveness of individual C-ITS services (see Section 2), research on their combined application is limited. Walch et al. (2025) conducted a comprehensive literature review of 104 papers, highlighting this gap in research and emphasizing the need for further studies. Therefore, this study seeks to bridge that gap by investigating the impacts of GLOSA and CACC, both individually and in combination, to determine whether their joint implementation yields complementary, reinforcing, or conflicting effects. Additionally, it aims to assess the advantages of simultaneous use compared to isolated applications.

The paper is structured as follows: Section 2 presents related work on the individual impacts of

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GLOSA and CACC. Section 3 illustrates the applied methodology while section 4 discusses the results of the simulation studies and investigates the effect of combining CACC and GLOSA.

2 RELATED WORK

The potential effects of GLOSA and CACC have been the subject of numerous studies in the scientific literature.

GLOSA systems enhance traffic flow by optimising vehicle speed to reduce unnecessary stops. Katsaros et al. (2011) found that GLOSA can reduce waiting times by up to 80% at a 50% penetration rate, where the penetration rate corresponds to the proportion of vehicles equipped with and using the relevant C-ITS service. Multi-segment GLOSA, which optimises flow across multiple traffic lights, has demonstrated greater efficiency but poses more significant implementation challenges (Khayyat et al., 2024). Environmentally, GLOSA can decrease CO_2 emissions by 9.9% at 100% penetration, alongside reductions in travel time (5.7%) and waiting time (18.2%) (Lebre et al., 2015). Noise pollution can also be mitigated through reduced acceleration events (Umweltbundesamt, 2024a).

CACC has been shown to improve traffic efficiency and reduce environmental impact. Rios-Torres and Malikopoulos (2017) demonstrated that highway merging scenarios exhibit travel time reductions of 7–13%, coupled with up to 53% lower emissions. HomChaudhuri et al. (2017) showed that these systems mitigate braking shockwaves and nearly eliminate red light idling. Even at low penetration rates, CACC achieves traffic flow stabilisation and emission reductions (Wang et al., 2015). The environmental benefits are also evident at low rate levels, with NO_x emission reductions beginning at a 20% penetration rate.

Kamal et al. (2015) investigated the impact of an eco-driving system consisting of CACC and GLOSA, and observed a 2% reduction in fuel consumption and a 2.8% decrease in travel time with 10% vehicle penetration. The system of Asadi and Vahidi (2011), combining ACC with traffic light data resulted in CO_2 savings of up to 56%. Xin et al. (2018) expanded the capabilities of ACC by integrating V2X technology to anticipate the onset of red lights leading to reduced travel times (4.9%) and fuel consumption (25.5%). Liu and El Kamel (2016) demonstrated that the integration of V2X into CACC systems resulted in an improvement in traffic flow at intersections. To assess the combined impacts of C-ITS services, Walch et al. (2024) proposed a qualitative impact evaluation model using causal loop diagrams, demonstrating its utility in analysing service combinations such as Road Hazard Warning, Road Works Warning, Traffic Jam Ahead Warning and Shockwave Dampening.

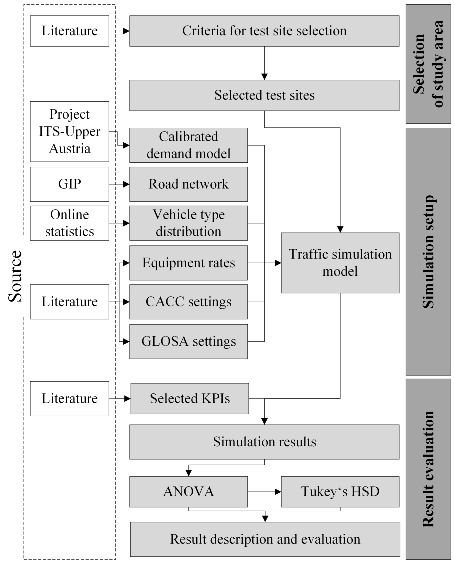

Figure 1: Methodology.

3 METHODOLOGY

This section builds upon the related work discussed in Section 2 to present a framework for the simulative assessment of the combined C-ITS services. Figure 1 illustrates the methodology employed in this study, while the subsequent sections delve into the individual components in depth.

3.1 Selection of Study Area

The following sections outline the site selection criteria and describe the chosen test sites.

3.1.1 Criteria for Test Site Selection

The selection of suitable test sites is essential for effectively evaluating Intelligent Transport Systems (ITS). To ensure a comprehensive evaluation, several criteria were considered during the site selection process. GLOSA, for instance, requires at least one traffic light-controlled intersection, with test sites featuring multiple traffic signals being particularly valuable. Additionally, test sites must include sufficiently long road segments to influence vehicle speed. Moreover, different regional types, including urban and suburban sections, were considered a key factor in site selection. Sites with available historical traffic data were prioritized for simulation calibration and validation, improving result accuracy.

In this study, the Travel Time Index (TTI) (INRIX, 2024) was used to identify relevant road sections. TTI measures the ratio of the average travel time along a route to the free-flow time, defined as the 15th percentile of observed travel times. By analyzing TTI data, road segments with delays caused by high traffic volumes were identified.

3.1.2 Description of Selected Test Sites

Three Austrian test sites were selected for the simulation studies based on the criteria described.

The B1 test site spans approx. 12 km, starting at the highway interchange and extending past Linz Airport. It is characterized by a predominantly straight, two-lane road with 20 traffic signals placed between 400 and 1,000 meters apart, and a speed limit of 70 km/h. The B3 test site, located near Mauthausen, covers a 3 km stretch connecting northeastern Upper Austria to Linz. This single-lane road features two traffic signals that significantly impact traffic flow during peak hours, with speed limits varying from 50 km/h at intersections to 100 km/h on other sections. The B139 test site extends 1.5 km from the Römerbergtunnel as a western bypass of Linz city center. This inner-city route, with a speed limit of 50 km/h, includes several curves and eight traffic signals, leading to frequent braking and acceleration.

3.2 Simulation Setup

The following section outlines the process of creating and calibrating the simulation model used to assess the impact of GLOSA, CACC and their service combination (SC).

3.2.1 SUMO Traffic Simulation Model

This study employs an adapted version of the SUMO traffic simulation model from the ITS-Upper Austria project (Presinger, 2021), incorporating a recalibrated demand model based on traffic data collected over a year. Thereby, data from induction loops and radar sensors were utilised for calibration. Due to the unequal distribution of traffic volume on the individual days of the week, only data from Tuesday to Thursday were considered, and data from public holidays and school holidays were excluded. Furthermore, origin-destination (OD) matrices for the state of Upper Austria were employed in conjunction with the sensor data. The demand model was calibrated using SUMO's routeSampler.py tool. The R^2 (Backhaus et al., 2018) values for model calibration are presented in Table 1, with sites B1 and B3 demonstrating high quality and B139 exhibiting moderate quality.

Table 1: Traffic Simulation - R^2 values.

Test Site	R^2
B1	0.9222
B3	0.9401
B139	0.6627

3.2.2 Definition of Vehicle Type Distribution

The demand model initially only considered passenger cars, but was updated with emission class data derived from statistical distributions of drive technologies (Statistik Austria, 2024; Umweltbundesamt, 2024b).

3.2.3 Definition of Penetration Rates

A key parameter in assessing the impact of C-ITS is the penetration rate. This allows investigating how the impact intensifies as the number of users increases. The rates chosen in this study are based on Rogers' diffusion of innovations theory (Rogers, 2003) which divides society into five groups of adopters: innovators (2.5%), early adopters (13.5%), early majority (34%), late majority (34%), and laggards (16%).

3.2.4 GLOSA Settings

This study used the GLOSA algorithm implemented in SUMO (SUMO, 2025a). When defining the parameters for GLOSA, it is necessary to give particular consideration to the recommended speed. Research indicates that speeds around 50-60% of the limit do not overly disrupt traffic while still maximising the use of green lights (Eckhoff et al., 2013). Consequently, the minimum speed on all three test routes will be set to 55% of the speed allowed. With regard to the maximum speed, the SUMO default value (110% of speed limit) is assumed for all scenarios.

In addition, the activation distance is critical to GLOSA's efficiency. For a speed of 50 km/h, the optimal activation point is approximately 350 m from the traffic light (Katsaros et al., 2011). Shorter distances hinder speed adjustments, increasing fuel consumption and travel times. In cases of closer traffic light spacing, the activation distance is reduced to 250 meters to avoid communication issues (Katsaros et al., 2011). For the B139 route with many traffic lights, a 250 m activation distance is used, while for the B3 and B1 routes the distance is set at 500 m. The study uses single-segment GLOSA, offering speed recommendations for the next traffic light only.

3.2.5 CACC Settings

This study uses the CACC model implemented in SUMO, based on Milanés and Shladover (2014), Xiao et al. (2017), and Xiao et al. (2018). The model adapts vehicle following behavior based on gap and speed differences, regulated by four modes (speed control mode, gap control mode, gap-closing mode and collision avoidance mode). The study uses the default CACC parameters, ensuring consistency with prior research.

3.3 Result Evaluation

In the following section, the evaluation design employed in this study is described.

3.3.1 Selection of Impact Categories and KPIs

This study uses traffic efficiency and sustainability to assess the impact of CACC and GLOSA, as both technologies aim to optimise traffic flow and reduce environmental impact. The KPIs used include lost time and CO_2 emissions to reflect the ability of the C-ITS service to improve traffic flow and to measure the environmental benefits (SUMO, 2025b).

3.3.2 Statistical Evaluation

The simulations included three C-ITS services (GLOSA, CACC, and SC), three test sites (see Section 3.1.2), five penetration rates (see Section 3.2.3), and ten different seed values. Additionally, simulations were conducted without C-ITS on all test sites to provide a basis for comparison, resulting in a total of 480 simulation runs.

The results for each test route and penetration rate combination were analyzed using an ANOVA to assess whether the use of no C-ITS, GLOSA, CACC, or SC had a statistically significant effect on lost time and CO_2 emissions. If significant, Tukey's HSD Post-Hoc test was conducted for pairwise comparisons to determine which factors exhibited statistically significant differences. This process allows for concrete conclusions regarding the impacts of individual or combined C-ITS services.

4 RESULTS

The following sections present the results of the simulation studies.

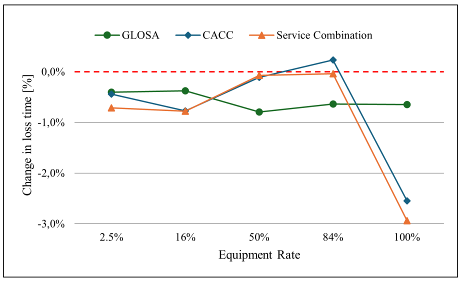

Figure 2: Results B1 - Loss Time.

4.1 Impact on Loss Time

The ANOVA results comparing loss time across the scenarios (i) no C-ITS services, (ii) CACC, (iii) GLOSA, and (iv) SC, are presented in Table 2.

Table 2: ANOVA p-Values - Loss Time.

Test Site	2.5%	16%	50%	84%	100%
B1	-	-	-	-	***
B3	-	***	***	***	***
B139	***	***	***	***	***

*** ≤ 0.001 ** ≤ 0.01 * ≤ 0.05

The test site B1 shows that up to a penetration rate of 84%, no statistically significant impact on loss time is observed with any C-ITS service. Only at a penetration rate of 100% does a significant impact occur. As shown in Figure 2, variations in loss time compared to the baseline are observed at penetration rates up to 84%, with GLOSA demonstrating a maximum improvement of 0.8% at 50% penetration. At 100%, CACC and SC exhibit more substantial reductions in loss time, with improvements of up to 2.5% and nearly 3%, respectively. Notably, CACC and SC exhibit slight increases in loss time at 50% and 84% penetration rates, while GLOSA shows no significant change in loss time at these levels.

Tukey's HSD Post-Hoc test (Table 3) confirms that, although GLOSA leads to improvements compared to the baseline scenario (Figure 2), these are not statistically significant. The combination of CACC and GLOSA, however, results in statistically significant reductions in loss time, with the effect of CACC being the main contributor.

At test site B3, significant differences in loss time are observed except at the 2.5% penetration rate (Table 2), with the results presented in Figures 3 and 4.

At 2.5%, the changes are similar across all services. Reductions in loss time are significant for CACC and SC above 16% penetration, while GLOSA shows marginal changes. The results of Tukey's HSD Post-Hoc test are similar to the test site B1 (see Table 4). Due to the very small changes in loss times with GLOSA, the difference with the baseline scenario is

Table 3: B1 - Tukey's HSD p-Values - Loss Time.

Service 1	Service 2	100%
-	GLOSA	-
-	CACC	***
-	SC	***
GLOSA	CACC	***
GLOSA	SC	***
CACC	SC	-

*** ≤ 0.001 ** ≤ 0.01 * ≤ 0.05

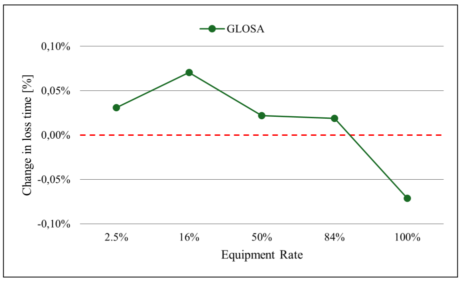

Figure 3: Results B3 - Loss Time (GLOSA).

not significant. This marginal effect of GLOSA can also be seen when looking at the differences between CACC and SC, as they show almost identical results in the reduction of lost time.

For test site B139, significant differences in loss time are observed for all penetration rates (Table 2), as illustrated in Figure 5.

Like B1 and B3, both CACC and SC exhibit a reduction in loss time as penetration rates increase, while GLOSA shows only marginal changes. Consequently, Tukey's HSD Post-Hoc test demonstrates a pattern that is mostly analogous to that observed in test locations B1 and B3. GLOSA does not result in any notable enhancement in comparison to the base scenario. With CACC, substantial differences from the baseline scenario can be identified at relatively low penetration rates, although the p-value of 2.5% or 16% is lower than at higher penetration rates. SC demonstrates a notable improvement in performance compared to GLOSA alone, but not to CACC alone.

In conclusion, while GLOSA does not show significant improvements compared to the baseline scenario at any of the test sites, CACC and SC both lead to significant reductions in loss time. The comparison between CACC and SC reveals no difference in their performance, and adding GLOSA to CACC does not result in further reductions in loss time.

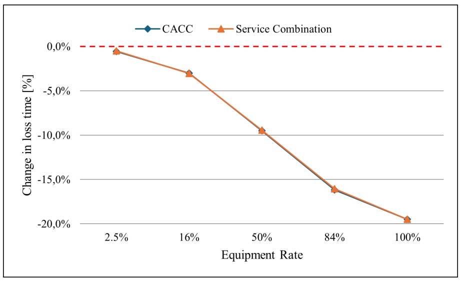

Figure 4: Results B3 - Loss Time (CACC & SC).

Table 4: B3 - Tukey's HSD p-Values - Loss Time.

Serv. 1	Serv. 2	16%	50%	84%	100%
-	GLOSA	-	-	-	-
-	CACC	***	***	***	***
-	SC	***	***	***	***
GLOSA	CACC	***	***	***	***
GLOSA	SC	***	***	***	***
CACC	SC	-	-	-	-

*** ≤ 0.001 ** ≤ 0.01 * ≤ 0.05

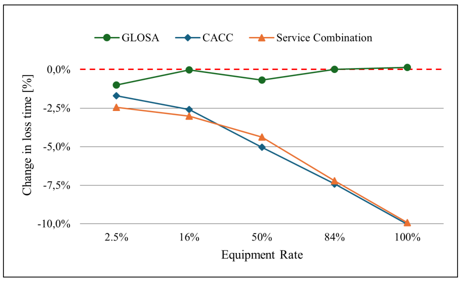

Figure 5: Results B139 - Loss Time.

4.2 Impact on Co_2

The ANOVA of CO_2 emissions across the four scenarios (i) no C-ITS services, (ii) CACC, (iii) GLOSA, and (iv) SC, reveals statistically significant differences at penetration rates of 16% and higher for all test sites, as shown in Table 6.

The detailed examination of CO_2 emissions for test site B1, depicted in Figure 6, demonstrates that at a 2.5% penetration rate, changes are minimal and not statistically significant. However, with higher penetration rates, a continuous decrease in emissions is observed. The differences in the effectiveness of services or combinations become more pronounced at higher penetration rates.

Tukey's HSD Post-Hoc test (Table 7) indicates that from a 16% penetration rate, all services except

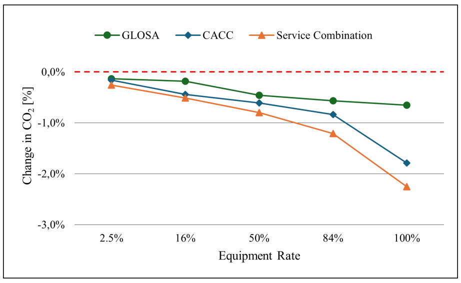

Figure 6: Results B1 - CO_2.

Table 5: B139 - Tukey's HSD p-Values - Loss Time.

Serv. 1	Serv. 2	2.5%	16%	50%	84%	100%
-	GLOSA	-	-	-	-	-
-	CACC	*	*	***	***	***
-	SC	***	**	***	***	***
GLOSA	CACC	-	*	***	***	***
GLOSA	SC	-	**	***	***	***
CACC	SC	-	-	-	-	-

*** ≤ 0.001 ** ≤ 0.01 * ≤ 0.05

Table 6: ANOVA p-Values - CO_2.

Test Site	2.5%	16%	50%	84%	100%
B1	-	***	***	***	***
B3	-	***	***	***	***
B139	**	***	***	***	***

*** ≤ 0.001 ** ≤ 0.01 * ≤ 0.05

GLOSA (at lower penetration rates) exhibit significant reductions in emissions. SC performs significantly better than GLOSA and CACC at 84% and 100% penetration rates. CACC only shows significant differences from GLOSA at 100% penetration.

Table 7: B1 - Tukey's HSD p-Values - CO_2.

Serv. 1	Serv. 2	16%	50%	84%	100%
-	GLOSA	-	**	***	***
-	CACC	**	***	***	***
-	SC	**	***	***	***
GLOSA	CACC	-	-	-	***
GLOSA	SC	-	*	***	***
CACC	SC	-	-	*	**

*** ≤ 0.001 ** ≤ 0.01 * ≤ 0.05

Similarly, for test site B3, the results show significant changes at a penetration rate of 16% and higher (Table 6), but the impact of GLOSA is minimal in comparison to CACC and SC. As demonstrated in Figures 7 and 8, the emissions from CACC and SC are almost identical, and the effect of GLOSA is negligible.

Tukey's HSD test (Table 8) confirms that GLOSA does not result in significant reductions compared to the baseline, while CACC and SC both show substantial differences from GLOSA and the baseline.

For B139, the ANOVA (Table 6) reveals that significant reductions in CO_2 emissions are observed even at 2.5% penetration rate for SC, and a continuous decrease is seen for both CACC and SC. Figure 9 illustrates these trends.

Tukey's HSD Post-Hoc test (see Table 9) again shows that there is no statistical significance in the change in CO_2 emissions between GLOSA and the baseline simulation. The difference in the similar curves between CACC and SC is also not statistically significant. Therefore, as in B3, it can be assumed that

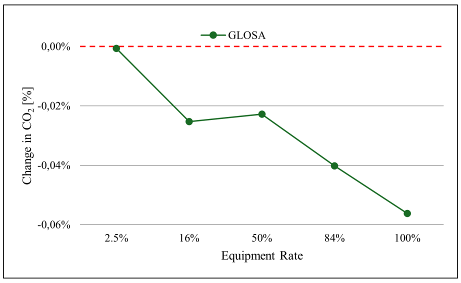

Figure 7: Results B3 - CO_2 (GLOSA).

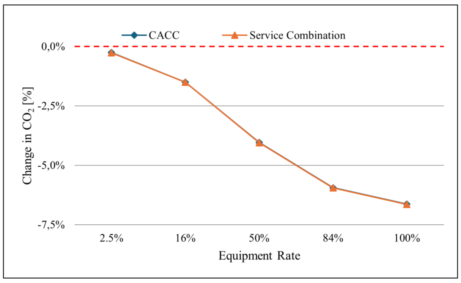

Figure 8: Results B3 - CO_2 (CACC & SC).

the simultaneous use of CACC and GLOSA does not lead to an improvement in CO_2 emissions compared to the use of CACC alone.

4.3 Discussion

A comparison of our simulation results with those in the literature reveals both similarities and key differences due to varying contexts, scales, and parameters. The simulations for CACC showed a significant reduction in loss time and CO_2 emissions at penetration rates as low as 16% for test sites B3 and B139. This is consistent with the findings of Rios-Torres and Malikopoulos (2017), who demonstrated reductions in travel times by 7-13% and CO_2 emissions by up to 53%. However, Rios Torres' study focused primarily on highway conditions, while our simulations covered a mix of urban and suburban environments. The magnitude of improvements observed in our study suggests that CACC's benefits in more complex ur-

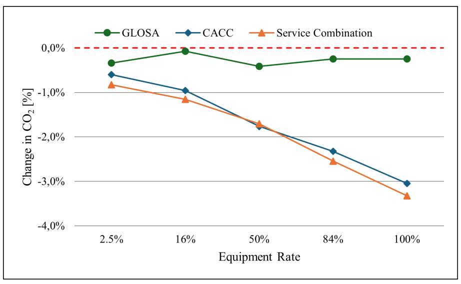

Figure 9: Results B139 - CO_2.

Table 8: B3 - Tukey's HSD p-Values - CO_2.

Serv. 1	Serv. 2	16%	50%	84%	100%
-	GLOSA	-	-	-	-
-	CACC	***	***	***	***
-	SC	***	***	***	***
GLOSA	CACC	***	***	***	***
GLOSA	SC	***	***	***	***
CACC	SC	-	-	-	-

*** ≤ 0.001 ** ≤ 0.01 * ≤ 0.05

Table 9: B139 - Tukey's HSD p-Values - CO_2.

Serv. 1	Serv. 2	2.5%	16%	50%	84%	100%
-	GLOSA	-	-	-	-	-
-	CACC	-	*	***	***	***
-	SC	**	**	***	***	***
GLOSA	CACC	-	*	***	***	***
GLOSA	SC	-	**	***	***	***
CACC	SC	-	-	-	-	-

*** ≤ 0.001 ** ≤ 0.01 * ≤ 0.05

ban settings are still present but somewhat diminished compared to controlled highway scenarios.

In contrast, the performance of GLOSA in our study did not yield significant improvements in most cases, even at higher penetration rates. This result differs from Katsaros et al. (2011), who reported up to an 80% reduction in waiting times at intersections under ideal conditions, such as single-segment optimization of traffic lights. The limited improvements in our study can likely be attributed to the use of real-world traffic data, which spanned multiple intersections with diverse traffic conditions. Moreover, Lebre et al. (2015) observed CO_2 reductions of up to 9.9% with 100% GLOSA penetration, while our results showed only modest reductions, typically below 1%. This discrepancy may be due to the fact that Lebre's study focused on intersections, whereas our test sites involved multi-kilometre roads, with traffic light-controlled intersections representing a smaller proportion of the total area. The limited impact of GLOSA, particularly at test site B3, may explain the small improvements observed. Overall, while the results of our study may not be directly comparable to previous works due to differences in experimental settings (e.g., test sites, simulation parameters, traffic volumes, C-ITS implementations), our findings align with the general trend in the literature. They suggest that C-ITS, particularly CACC, can improve traffic efficiency and sustainability, albeit with varying effectiveness depending on the conditions of the study.

5 CONCLUSION

This study provides insights into the impact of C-ITS on traffic efficiency and sustainability. By examining the performance of CACC and GLOSA, both individually and in combination, across different penetration rates, this research contributes to understanding how these systems influence loss time and CO_2 emissions.

The results demonstrate that CACC mostly yields significant improvements in both loss time and CO_2 emissions at penetration rates of 16% and above. In contrast, GLOSA shows improvements in both loss time and CO_2 emissions compared to a non-use of C-ITS, however, the effects of GLOSA mostly remain statistically insignificant. The combined use of CACC and GLOSA shows marginal improvements over CACC alone but does not produce statistically significant differences in loss time at any of the test sites. This suggests that while GLOSA may complement CACC to some extent in reducing emissions and loss time, it does not drastically enhance traffic efficiency or sustainability. The results also indicate that the effectiveness of both systems mostly increases with higher penetration rates, highlighting the importance of widespread adoption to fully leverage the benefits of these technologies.

In conclusion, this study highlights the importance of CACC as a tool for enhancing traffic flow and reducing emissions. It presents a methodological framework for evaluating individual C-ITS services as well as their combinations, and examines their varied impacts across different categories. Additionally, it proposes an approach for testing combinations of C-ITS services. Future research could further investigate the integration of additional C-ITS services to maximise the potential of cooperative driving technologies for sustainable and efficient transportation.

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