Stability Issues in Adaptive Cruise Control System and Traffic Implication

Riccardo Donà*[1], Konstantinos Mattas[1], Giovanni Albano[2], Sandor Váss[1], and Biagio Ciuffo[1]

[1]Joint Research Centre for the European Commission, Ispra (VA), 21027, Italy
[2]Piksel Italia, Milan, Italy

Short summary

Adaptive Cruise Control (ACC) systems under short headway configurations have been found to have a potentially detrimental impact on the transport network due to the string instability effect. Such phenomenon results in traffic perturbations amplification downstream causing increasing fuel consumption and posing safety threats. However, recent findings summarized in this paper show how even the simpler platoon stability might not be attained with current ACC-equipped vehicles raising additional concerns regarding their unregulated operation. In fact, as part of a recent campaign involving state-of-the-art assisted vehicles, an ACC displayed a low-frequency oscillatory behavior around the equilibrium speed. This work, by leveraging a mixed simulation/empirical approach, uncovers the harmful influences of such behavior. Ultimately, we found that despite the poor stability phenomenon might not be impactful for one vehicle, the overall repercussions on the transportation network can be dramatically detrimental raising the need for a regulatory framework for lower-level automation.
Keywords: Adaptive Cruise Control, Asymptotic Stability, Car Following, String Stability

1 Introduction

Adaptive Cruise Control (ACC) is a driving assistance feature that provides the driver with additional comfort when traveling on highways by adjusting the speed while following a leader vehicle. ACC is commonly classified as an SAE J3016 Level 1 SAE On-Road Automated Vehicle Standards Committee (2021) system (or Level 2 when coupled with lane-centering assistance) meaning that the driver will always have to be ready to take control at any time and the same will remain legally liable.

ACCs have been investigated for a long time both via theoretical simulation studies Ioannou & Chien (1993); Marsden et al. (2001) and, more recently, via real-world experiments Gunter et al. (2020); Ciuffo et al. (2021). Frequently, the two types of assessment have led to contrasting outcomes: on one side theoretical studies have envisaged a beneficial effect of ACC introduction based on the adopted assumptions, on the other side, the actual mass-market ACCs did not prove to deliver increased stability performance with respect to human driving Ciuffo et al. (2021).

Albeit higher-level automation systems, *i.e.*, systems where the feature provides proper driving automation thus transferring the legal liability to the manufacturer in contrast to driving assistance, are gradually approaching the market Donà et al. (2022), driving assistance still has the largest market penetration share. Additionally, manufacturers have a considerable interest in marketing the so-called "L2+" Brooke (2020) assistance systems where in addition to speed control and lane-change more advanced features such as system-initiated automatic lane-changes or conditional hands-off driving are present.

To the end of monitoring the evolution of driving assistance technologies, the authors have organized a testing campaign in Germany involving three vehicles featuring advanced Level 2 systems. During the testing, it became apparent to the driver sitting in one specific vehicle that the same was never able to achieve a constant speed while following a leader. That was noticeable both from the speed displayed on the speedometer and also from the GNSS speed being monitored in real-time by a supporting colleague. The original plan for the tests was thus slightly revised to have longer sections of steady car-following the vehicle demonstrating the oscillation would follow an instrumented vehicle. The leader would use cruise control (CC) to keep constant speed in such a manner that the oscillations of the follower could easily be extracted in post-processing.

The present contribution summarizes the results of such a campaign with regard to the specific instability phenomenon affecting the mentioned vehicles. The paper reports on the effect and the potential implications of a similar ACC design on the transportation network if left uncorrected by the car manufacturer. The effort leverages a mixture of experimental characterization together with a simulation-based approach to enlarge the scope of the work.

2 Methodology

Perturbations identification

The experimental campaign took place in late November 2023 and lasted four working days during which about 3000 kilometers were driven in Germany using 3 vehicles equipped with state-of-the-art SAE J3016 Level 2 SAE On-Road Automated Vehicle Standards Committee (2021) systems while trying to maximize the use of the driving assistance features. The testing campaign had the broader aim of studying the behavior of "L2+" systems that include automatic lane change and automatic speed recognition based on map and camera data. The vehicles were instrumented with external GNSS antennas to record the positions and velocities for the post-processing analysis.
To isolate the oscillation effect, once the driver became aware of the same, the testers drove for long sections of the motorway while the leader was keeping a constant speed with no disturbance upfront. The oscillating follower remained all the time in car-following ACC mode without managing to achieve a stable speed. By repeating the procedure multiple times, 40 intervals were identified covering a range of different target speeds.
The oscillations were analyzed by removing the mean component of the speed and fitting a sine wave to the residual speed profile. The sine functions calibration procedure returned the wave's frequency, amplitude, and phase. The latter signal was disregarded as it did not provide useful information for the analysis. On the contrary, two distributions could be obtained for the oscillation frequency and amplitude, respectively, by repeating the sine function fitting procedure to all the 40 intervals produced during the public road testing.

Fuel consumption study

The first research question that needs to be addressed is the fuel/energy consumption associated with the oscillation behavior with respect to a driving policy capable of achieving stable driving. To this end, a simulation approach was adopted where the trajectory profile has been forwarded to the CO_2MPAS software tool (`https://code.europa.eu/jrc-ldv/co2mpas`) developed by the Joint Research Centre for European Commission to establish the fuel consumption Fontaras et al. (2018) of passenger cars and light duty vehicles.
The CO_2MPAS' virtual driver has been tuned in a way to follow as closely as possible the speed profile recorded during the testing. Moreover, the simulation assessment was carried out assuming, in CO_2MPAS, a reference vehicle having similar physical parameters (mass, engine displacement, power, gear ratios, aerodynamic resistance) as the target vehicle.
Afterward, based on the identified frequency of the oscillation profile, the same trajectory profile was subject to a non-causal low-pass filter to remove the oscillatory component while maintaining the same average speed to match the distance traveled over the given time horizon. The fuel consumption routine was then executed once again with the newly filtered trajectory to isolate the energy expenditure associated with the ACC's reduced stability performance. The procedure was repeated for the whole set of identified perturbations to investigate if any statistical significance could be inferred.

Traffic flow implications

Following the characterization of the oscillation abnormality, a stochastic simulation study was put in place to assess the foreseen implications on longer and heterogenous platoons which was not possible to accomplish during the public road testing.
The simulation setup was derived from earlier authors' work Donà et al. (2022); Donà et al. (2023) and leveraged a simple car-following model where the car-following control law is given by the well-known linear controller model He et al. (2019):

$$u_{\text{ACC}}(t) = k_d(v_L(t-T) - v(t)) + k_p(s(t-T) - t_g v(t) - \eta). \tag{1}$$

In Eq. (1), $s(\cdot)$ represents the distance between the leader and the ego follower, $v_L(\cdot)$ the leader's speed, $v(\cdot)$ the ego's speed and $u(\cdot)$ the commanded control action. Moreover, k_d and k_p are the controller's gains, t_g the desired time-gap, T is the estimation delay which accounts for the RADAR signal gathering and processing (e.g., filtering of noisy measurements), and η is the standstill spacing. The simulated ACC platoon adopts the constant time gap policy (CTG) where the reference spacing between vehicles is proportional to the follower's speed. The target acceleration u_{ACC} is saturated in the interval $[-5.0,\, 2.0]$ m/s^2.

The ego-vehicle dynamics is given instead by a double integrator with mechanical actuation latency τ_a

$$\begin{cases} \dot{x}(t) = v(t) \\ \dot{v}(t) = a(t) \\ \dot{a}(t) = \dfrac{u_{\mathrm{ACC}}(t) - a(t)}{\tau_a}. \end{cases} \tag{2}$$

Each virtual vehicle is calibrated by randomly sampling its parameters from the intervals reported Table 1 assuming a uniform distribution assumption for each parameter. The intervals are derived from real-world characterizations of ACC behavior as of He et al. (2022); Shi & Li (2021); Gunter et al. (2020).

Table 1: Vehicle platoon simulation parameters.

$\boldsymbol{k_p}$ (s^2)	$\boldsymbol{k_d}$ (s)	$\boldsymbol{t_g}$ (s)	$\boldsymbol{\tau_a}$ (s)	$\boldsymbol{T}$ (s)	$\boldsymbol{\eta}$ (m)
$[0.03, 0.10]$	$[0.25, 0.70]$	$[1.20, 2.50]$	$[0.20, 0.50]$	$[0.75, 1.50]$	$[2.00, 3.00]$

The simulation setup is such that a platoon of ACC-equipped vehicles, starting from a steady-state condition, is subject to a perturbation induced by the leader vehicle. In particular, a set of 15 mild perturbations derived from the "highD" dataset Krajewski et al. (2018) were adopted for the purpose. To replicate the effect of the leader vehicle experiencing the oscillatory behavior observed during the testing campaign, which is not present in the highD dataset, a sinusoidal wave speed profile has been superimposed on top of the original leader's trajectory. Each simulation is repeated 20 times by randomizing over the vehicle parameters in Table 1 and over the calibrated oscillation parameters frequency and amplitude as described in Section 2.

The analysis was repeated twice for two platoon reference lengths: 5 vehicles and 20 vehicles (including the leader). Thus, the impact of the oscillation propagation can be better grasped. Eventually, a total of 1200 simulations were executed as resulting from 15 perturbations each one repeated 20 times for two 2 sets of platoon lengths and for both the nominal and oscillation-complemented behavior.

The assessment is carried out via computing the average root mean square (RMS) platoon longitudinal acceleration $a_{x,\mathrm{RMS}}$, the weak string stability Monteil et al. (2019) as defined by

$$w_{SS} = \frac{v_{leader,free-flow} - \min(v_{lastfollower})}{v_{leader,free-flow} - \min(v_{leader})}, \tag{3}$$

and the calculating the flow as of

$$q = k \cdot \bar{u}_s, \tag{4}$$

where k is the platoon's density in (vehicles/km) and $\bar{u}_s$ is the harmonic mean of the speed in (km/h). $a_{x,\mathrm{RMS}}$ can be considered a proxy for the driving policy's comfort and energy consumption; the w_{SS} and q are instead representative of traffic flow stability and efficiency. In particular, a $w_{SS} \leq 1$ suggests that the platoon exhibits a string stable behavior whereas a $w_{SS} > 1$ is indicative of string instability.

3 Results and discussion

Oscillations characterization

Fig. 1 shows an example of one recorded oscillation (blue dots) together with the calibrated sine wave (red line) and leader's speed (black dots). Albeit the leader is traveling at constant velocity

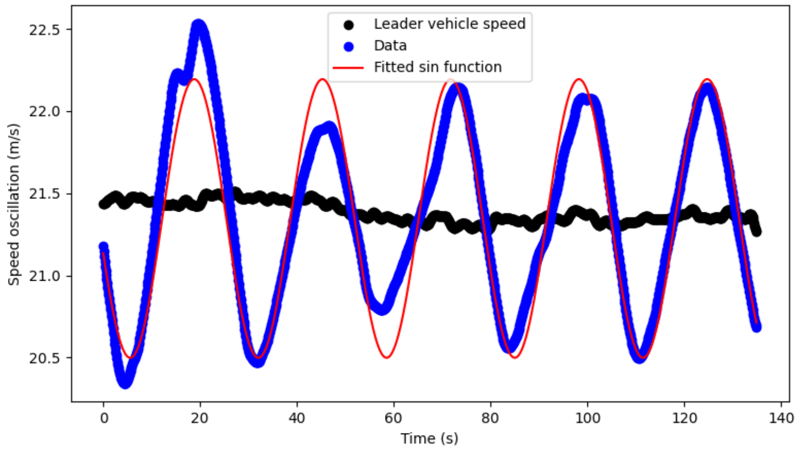

Figure 1: Example of recorded oscillation and fitted sine wave.

the follower is exhibiting a clearly undamped oscillation which can be effectively fitted with a sine function.
Fig. 2 reports the distribution of each identified oscillatory component of the speed profile versus its corresponding mean speed component for the 40 intervals identified. The chart suggests that there is no clear correlation between the two components. The computation of the Pearson correlation returns a negative statistic (-0.0108) and a p-value equal to 0.947 suggesting that the quantities are indeed uncorrelated.

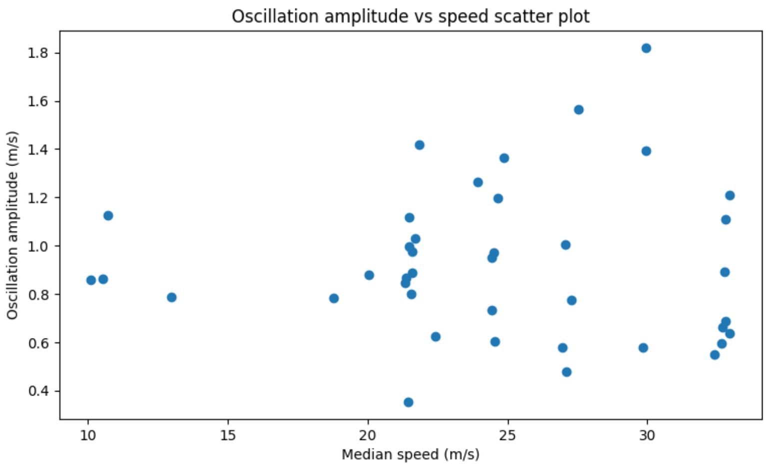

Figure 2: Oscillation amplitude vs mean speed.

Fig. 3 displays instead the calibrated distributions of the sines' frequency (left) and amplitude (right). The numerical results are given in Table 2 and include the average, standard deviation, and the p-value of the normality test. The mean oscillation corresponds to a low-frequency 0.23 rad/s (T = 27.3 s) wave having a 0.921 m/s amplitude. The statistical test assessing the normality of the distributions returns a value higher than 0.05, suggesting that the null hypothesis of the distributions being normal cannot be rejected.

Table 2: Amplitude and frequency calibration results.

	average	**std**	**p-value normal test**
Frequency	0.230 (rad/s)	0.00248 (rad/s)	0.212
Amplitude	0.921 (m/s)	0.0955 (m/s)	0.088

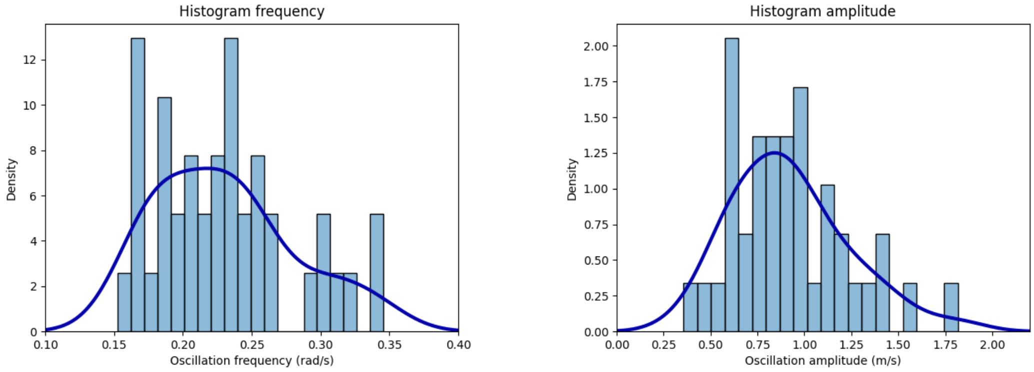

Figure 3: Histogram of oscillation frequencies (left) and amplitude (right).

Fuel consumption results

Fig. 4 summarizes the simulated median fuel consumption in g/s for each of the 40 intervals considered in this study. The light blue bars correspond to fuel consumption returned by the CO_2MPAS model for the recorded trajectory analyzed. On the contrary, the light orange ones are representative of the cases where the oscillatory component has been filtered out.

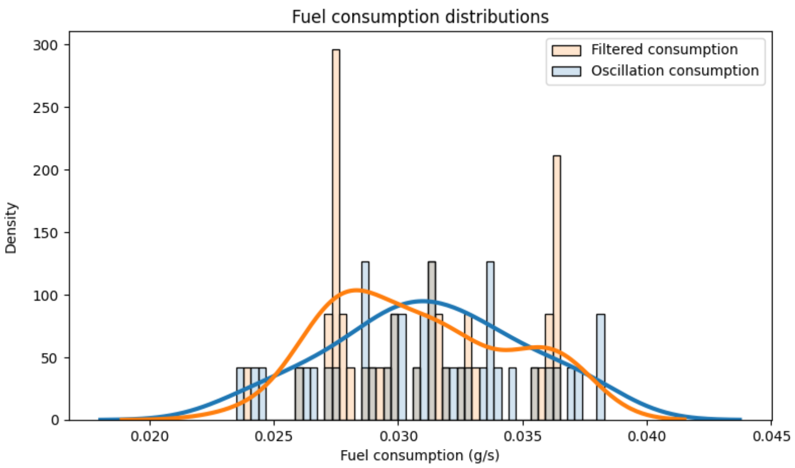

Figure 4: Oscillation filtering procedure fuel consumption reduction using CO_2MPAS.

For the particular vehicle considered in the study as representative of the tested one, an average reduction of 0.98% could be accomplished by filtering the oscillatory component of speed. Overall, the oscillation only contributes to a marginal increase in fuel consumption.

Traffic simulation results

The last part of the assessment concerns the simulation-based approach of a longer platoon of ACC vehicles following a leader exhibiting the oscillatory behavior identified up to now.
Fig. 5 displays the 5-vehicles long platoon aggregated results in terms of $a_{x,\mathrm{RMS}}$, w_{SS}, and flow. Similarly, Fig. 6 shows the outcome associated with the longer 20 vehicles platoon. Eventually, Table 3 returns the numerical assessment by means of relative changes with respect to the baseline case where no oscillation is present.
The introduction of the oscillatory components marks a clear surge in the acceleration RMS value which is increased by approximately 50% in the 5 vehicles long platoon. On the contrary, the weak string stability metrics is only marginally affected similarly to the flow metrics which is lightly reduced. The situation gets substantially worse when the longer platoon is considered. In this case, the RMS acceleration more than doubles and the platoon is hardly capable of maintaining a stable car-follow due to the added oscillations which propagate downstream and negatively affect the string stability metrics.

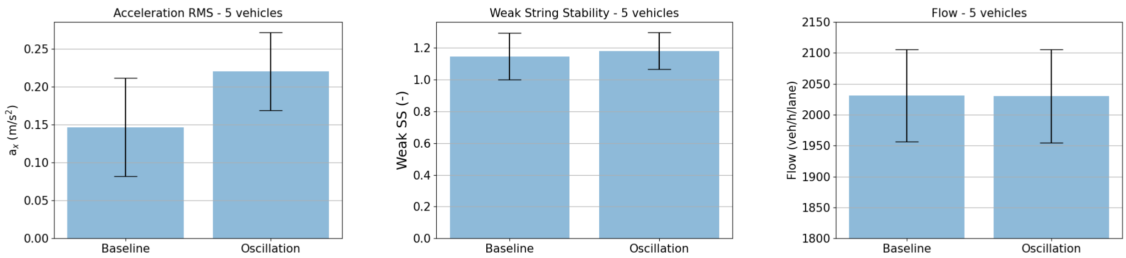

Figure 5: Bar charts: acceleration RMS (left), weak string stability (middle), and flow (right). 5 vehicles platoon.

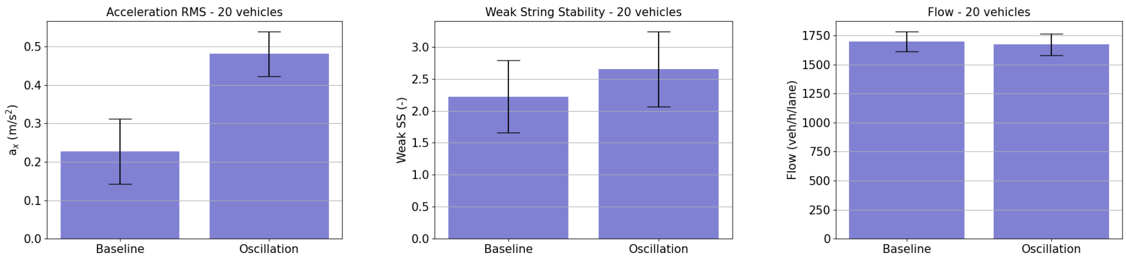

Figure 6: Bar charts: acceleration RMS (left), weak string stability (middle), and flow (right). 20 vehicles platoon.

In the real world, it is likely that manufacturers implement some sort of relaxation mechanism to avoid having a follower vehicle react to minor changes in the leader's speed and to make the tracking more robust against noisy measurements. Hence, the simulation results might overemphasize the phenomenon. Nonetheless, the empirical evidence collected during the testing campaign suggests that even an additional disturbance of ≈ 1 m/s could propagate to the follower. The concept can be better grasped from Fig. 7 which displays the recorded trajectories when the oscillating vehicle was positioned in the middle of the platoon. Indeed, its follower could not manage to dampen the oscillations thus qualitatively corroborating the simulation results discussed.

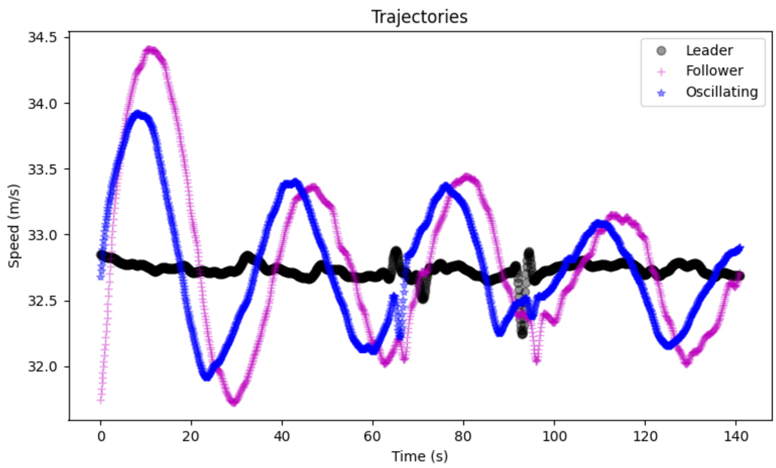

Figure 7: Follower vehicle oscillation's amplification from the public road testing campaign.

4 Conclusions

The work has summarised the results of the testing campaign including recent state-of-the-art SAE J3016 Level 2 assisted driving vehicles. The work has highlighted a list of concerns related to the poor stability performances of one of the tested vehicles in tracking the leader's speed when

Table 3: Vehicle platoon simulation results, percentage change with respect to the oscillation-free baseline.

Platoon length	$\boldsymbol{a}_{x,\mathrm{RMS}}$ (%)	$\boldsymbol{w_{SS}}$ (%)	$\boldsymbol{q}$ (%)
5	50.41	3.11	-0.03
20	111.33	19.23	-1.50

operating in ACC mode.

Firstly, the phenomenon has been characterized in terms of its frequency and amplitude showing that the oscillation has a relatively slow period of $T \approx 27$ s and a mean amplitude slightly inferior to 1 m/s. It was not possible to demonstrate the existence of a relationship between the amplitude of the oscillation and the average traveling speed. Secondly, an energy consumption analysis was presented which demonstrated how, for one vehicle only, the phenomenon yields only a slight increase in energy consumption which, in a real-world scenario, could be barely measurable. However, once we started to populate the simulation with multiple vehicles exhibiting a string unstable behavior we reported significant safety and comfort/energy worsening effects. In particular, longer platoons might be substantially negatively affected leading to a breakdown of the platoon's formation.

Overall, the results motivate the introduction of a regulation framework even for lower automation systems to reduce the chance of driving assistance systems harmfully impacting the traffic network if not properly designed. Such activity is currently taking place in the UNECE Driver Control Assistance System (DCAS) working group United Nations Economic Commission for Europe (2024).

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