Investigation of the Relationship between Traffic Hysteresis and String Stability of Vehicle Platoons

G. Albano[1], K. Mattas[2], R. Dona[3], Y. He[4], B. Ciuffo[2]

[1] Seidor Italia, Milan, Italy

[2] European Commission – Joint Research Centre Ispra, Italy

[3] Uni Systems Italy, Milan, Italy

[4] Department of Mechanical Engineering, University of Birmingham, Birmingham, UK

SHORT SUMMARY

Traffic oscillations deteriorate traffic safety and efficiency. Relevant to those oscillations, traffic hysteresis and string stability of platoons of vehicles have been extensively studied. However, the relationship between these two remains underexplored, leading to deficits in knowledge about the effect of regulating one on the other. The present paper investigates the correlation between string stability and traffic hysteresis and their possible trade-offs. The two are quantified based on trajectories that are extracted by simulation experiments and by real-world data. A strong correlation between string stability and traffic hysteresis is found. In the case of instability, hysteretic platoons are identified almost every time. It suggests that instability is one of the leading causes of hysteresis, although other factors also play a role since hysteresis loops have also been detected in string stable platoons.

Keywords: String Stability, Traffic Hysteresis, Traffic Flow, Traffic Oscillations.

1. INTRODUCTION

It has been more than 50 years since the first observation of traffic oscillations (Edie, 1961). An oscillation happens when the vehicles' speed is decreased temporarily, with adverse impacts on traffic flow, safety, and negative environmental implications (Bilbao-Ubillos, 2008). One of the reasons for the emergence and amplification of those oscillations is string instability (Wilson and Ward, 2011), with the magnitude of the perturbation increasing as it travels upstream. During those oscillations, the hysteresis phenomenon emerges, in which the traffic flow during the acceleration phase is decreased. A number of possible sources of hysteresis have been identified, such as the different behavior of a driver during the acceleration and deceleration (Yeo and Skabardonis, 2009), or the different aggressiveness of different drivers (Laval and Leclercq, 2010).

To the best of the authors' knowledge, the relationship between string stability and hysteresis has not been investigated, although the two phenomena seem to be closely related. One reason may be the difficulty in acquiring large amounts of accurate trajectory data. However, it is now becoming easier, with technological advancements to create large and accurate datasets of observed vehicle trajectories (Barmpounakis and Geroliminis, 2020). Another reason may be that human driver behavior cannot be easily influenced to be string stable or to accelerate in a non-hysteretic manner. Hence such an investigation would be without obvious practical applications. Nevertheless, the advent of Automated Driving Systems creates an opportunity to explicitly design the characteristics of future traffic flow.

In the present work, we try to investigate the relationship of string stability and traffic hysteresis using both simulation data, and vehicle trajectories from empirical observations. Several platoons are simulated using the IDM car-following model (Treiber et al., 2000), reacting to a perturbation of a leader vehicle. Moreover, platoons of vehicles undergoing a perturbation are identified in the highD dataset (Krajewski et al., 2018). String stability and hysteresis are quantified and the results show a strong correlation. The vast majority of string unstable platoons were revealed to be also hysteretic. This suggests that string instability may be one of the sources of hysteresis, bringing the platoon to a state, from which it is harder to recover without a loss in traffic flow. On the other side, some string stable hysteretic platoons have been identified, showing that hysteresis can occur even when the perturbation magnitude is dampened.

2. METHODOLOGY

Simulated Trajectories

A platoon of 20 vehicles is simulated on steady-state, with a speed of 15 m/s, and a perturbation is forced by the leading vehicle, as in the work of Sun et al. (2018). The deceleration lasts 3 s and then the leading vehicle accelerates back to steady-state with 1 m/s^2 of acceleration. The experiments have been repeated for three leader's deceleration values: 1 m/s^2, 2 m/s^2 and 3 m/s^2. The Intelligent Driver Model (IDM) is used for its capability to recreate both string instability and hysteresis (Kesting et al., 2007). The IDM parameters that have been fixed for all experiments are a desired speed of 120 km/h, $\delta = 4$, and a minimum stopping distance of 2 m. Moreover, the simulation step is 0.1 s. Regarding the acceleration, deceleration, and desired time-gap parameters of IDM, 1000 combinations are taken from a Sobol sequence (Sobol', 1967), to better examine the parameter space. The boundaries are 0.5 m/s^2 to 3 m/s^2 for the acceleration, 1 m/s^2 to 5 m/s^2 for the deceleration, and 0.5 s to 4 s for the desired time gap.

Identification of the perturbations in the real-world data

To identify platoons in the highD dataset, initially, pairs of vehicles car-following are isolated. The car-following event must last at least 5 s, and their median time-gap must be at most 3 s for low speeds and 2 s for speeds more than 60 km/h. Moreover, their speeds must have a Pearson correlation higher than 0.5, to make sure the leading vehicle's speed is affecting the follower. Secondly, where there are sequential pairs of car-following vehicles, platoons are identified. Finally, from all the platoons identified, we isolated the ones where there is an obvious perturbation, so the first vehicle initially decelerates and then accelerates to a speed more than 2 m/s faster than the lowest speed achieved. Overall, 152 events have been isolated.

Evaluating String Stability

To evaluate the string stability, the magnitude of the perturbation of the first and the last vehicle in the platoon are compared, according to the definition of weak string stability (Bouroche et al., 2018; Ploeg et al., 2014), as human-driven platoons from the highD dataset tend to be heterogeneous. For the simulation experiments, the maximum difference between the steady-state speed and the actual vehicle speeds is the perturbation magnitude for each vehicle. The magnitude of the perturbation for the last vehicle is divided by that of the first follower, and this is the stability ratio. If the platoon is string stable, the magnitude for the follower is small, hence the stability ratio is smaller than 1. On the highD, the steady-state is often unknown, so the minimum speed reached is used. The minimum speed of the leader is divided by that of the follower. Again, when this ratio is higher than 1, it shows a decrease in the speed of the platoon as the perturbation travels upstream, and so, it shows string instability.

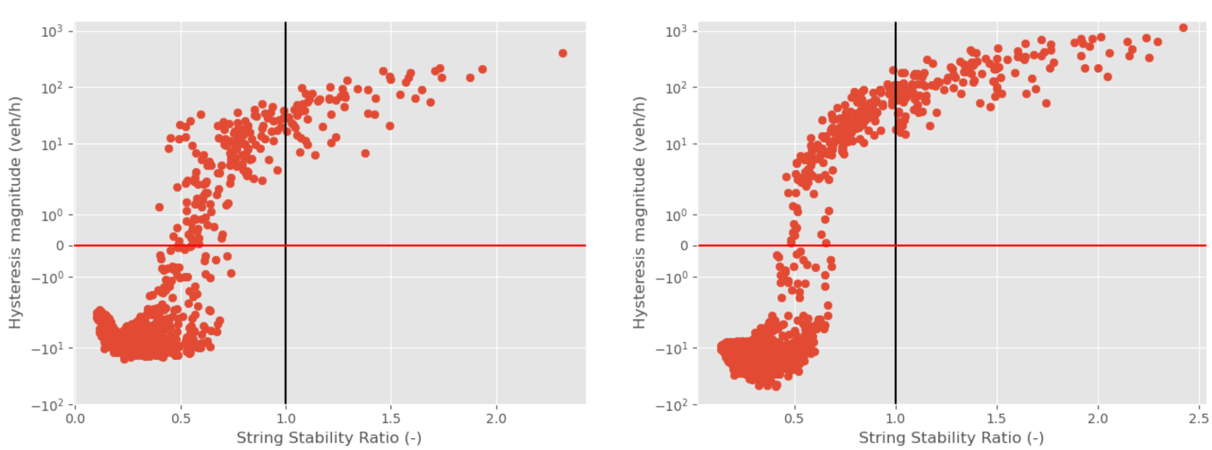
Evaluating Traffic Hysteresis

Traffic hysteresis has been evaluated using Edie's generalized formula (Edie, 1961) as in the work of Laval (2011). The acceleration and deceleration areas are identified in the speed-position plot, and the average flow is calculated for each one. The wave speed used to define the acceleration and deceleration areas is assumed to be equal to 20 km/h for the high-speed perturbations, (Cassidy and Windover, 1995; Munoz and Daganzo, 2000; Ahn et al., 2013; Zheng et al., 2011), while for cases of the speed median speed being less than 60 km/h it was visually inspected that a value of 18 km/h better suits the trajectory data used.

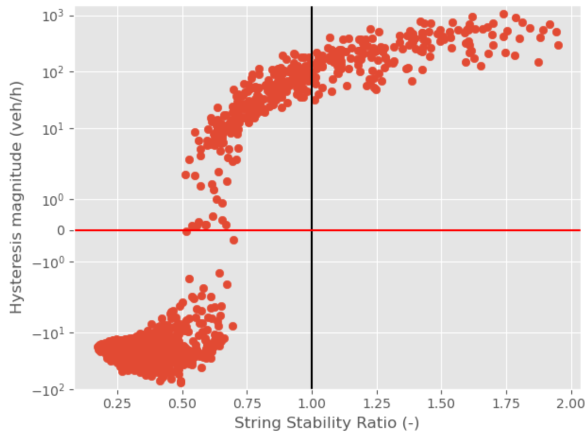
3. RESULTS

Simulations results

For each of the 1000 combinations of the IDM parameters the hysteresis magnitude on a logarithmic scale and stability ratio is evaluated and presented in Figure 1 a), b), and c) for the three different perturbations. When the stability ratio is higher than 1, the platoon was found to be string unstable. It is shown that all string unstable platoons create a positive hysteresis magnitude. On the other side, the most stable platoons, with a ratio less than 0.4 all resulted in negative hysteresis, with the flow during the acceleration being higher than the sub-optimal flow during the deceleration branch. A higher instability ratio mostly leads to higher magnitudes of hysteresis. An important finding is that for the IDM, there were a lot of string stable platoons that still resulted in hysteresis, although the drop in the flow is smaller than that of the unstable cases. These qualitative aspects of the results seem to be unaffected by initial the deceleration intensity.



(a) (b)



(c)

Figure 1. Relationship between string stability and traffic hysteresis for leader's deceleration intensity of 1 m/s^2 (a), 2 m/s^2 (b), 3 m/s^2 (c).

Describing the desired characteristics of the future traffic flow, string stability is essential. However, hysteresis can emerge even for string stable platoons. A better look into the characteristics of traffic flow for each combination is necessary. In Figure 2, the string stability ratio is presented against the average flow during the acceleration phase, for the experiments with the perturbation deceleration being equal to 3 m/s^2. The platoons that achieved the lowest values of the stability ratio are the ones for which the dampening of the perturbation magnitude was stronger. In Figure 2 it is shown that those cases provide very low values of outflow after the perturbation. In other words, "the most string stable cases" were ones in which the inter-vehicles distances are the largest. For those, even if the effect of the perturbation is small, the flow is already very small. The highest outflow seems to be for some cases of the string stability ratio being around 0.75. Those cases are string stable, and while there is hysteresis, it is mostly around the order of 10^1, which allows for high values of traffic flow even in the acceleration phase.

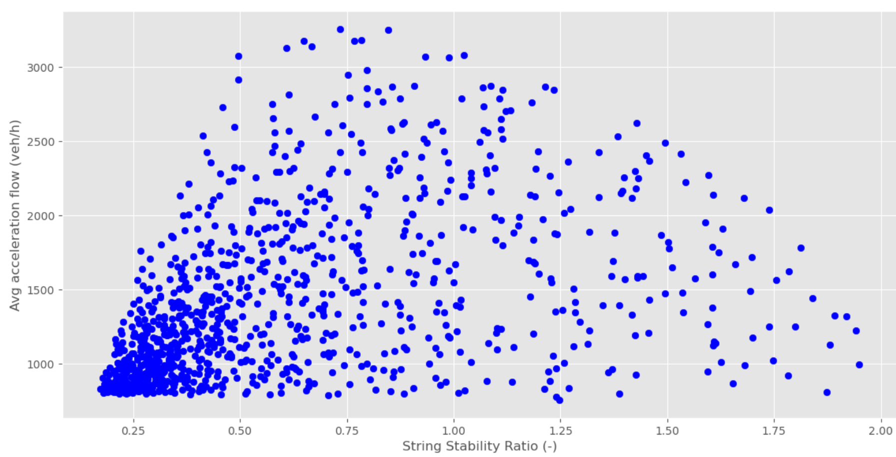


Figure 2. Average flow during the acceleration phase with respect to the stability ratio.

Looking further into the existence of hysteretic string stable platoons, the source of hysteresis seems to be the value of the acceleration parameter of the IDM model. The string stable cases are grouped according to this value and presented in Figure 3 against the hysteresis magnitude for the perturbation deceleration of 3 m/s^2. For the lowest values of the acceleration parameter, most of the cases were shown to be hysteretic, with the loss in flow being around 100 for the outliers. On the other side, for values higher than 2 m/s^2 there was no hysteretic platoon. Thus, the low values of the acceleration parameter, pose a delay in the recovery of the platoon to the steady-state flow. It should be noted that while all string stable combinations of acceleration higher than 2 m/s^2 were not hysteretic, all string unstable cases with a large value of the acceleration parameter were hysteretic. Thus, string stability is the deciding factor between positive or negative hysteresis for those combinations.

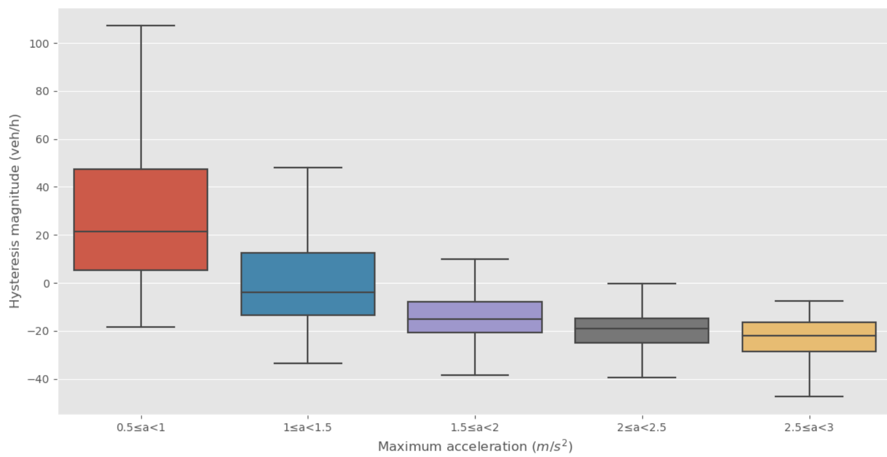
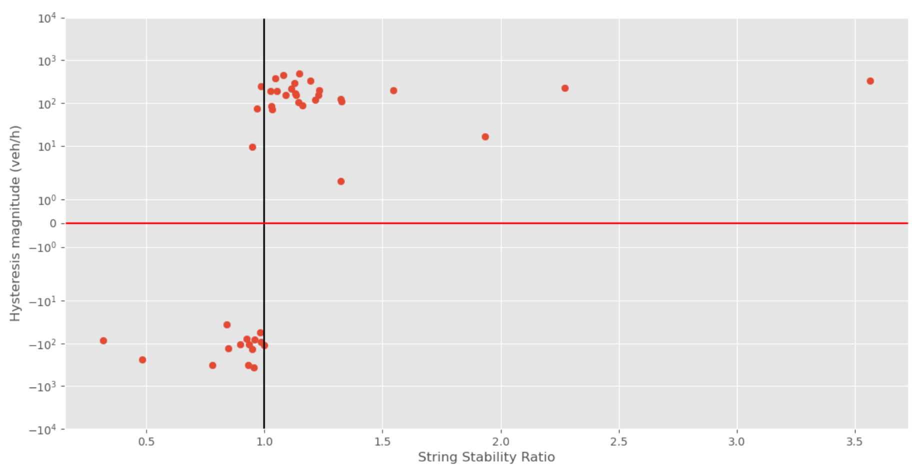


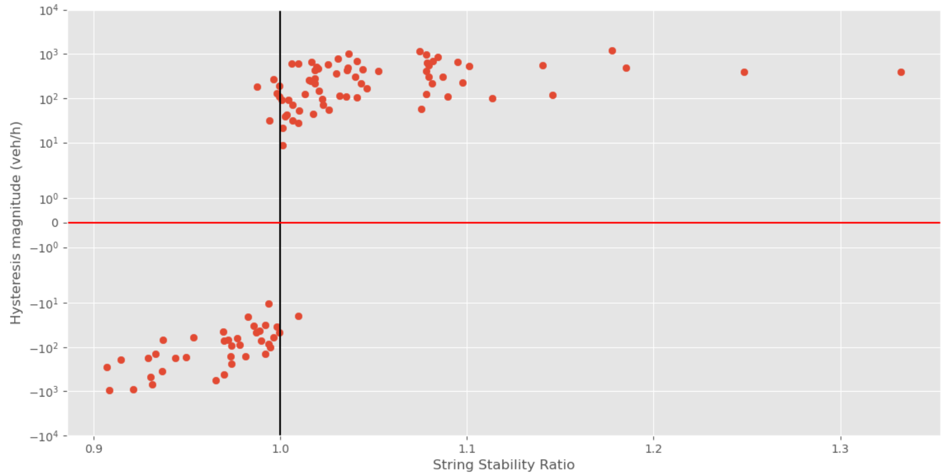
Figure 3. Hysteresis magnitude against the maximum acceleration parameter.

Real trajectories results

Regarding the data extracted from the highD dataset, the results are presented in Figure 4 a) for speeds slower than 60 km/h, and b) for speeds higher than 60 km/h. Again, the hysteresis magnitude is on a logarithmic scale for better readability. For both speed ranges there are two distinct branches, one string unstable and hysteretic, and one string stable and mostly not hysteretic. For the high speeds, there is one case of the string stability ratio being slightly larger than one, showing a small increase of the perturbation magnitude, that did not lead to hysteresis emergence. While the values of the string stability ratios have not been as wide as the ones observed in the simulation case, the relationship of string stability and hysteresis seems to be even amplified on the real data.



(a)



(b)

Figure 4. Relationship between string stability and hysteresis for the highD isolated perturbations in case of leader's median speed lower than 60 km/h (a) and higher than 60 km/h (b).

4. CONCLUSIONS

In the present work, we investigated the relationship between string stability and traffic hysteresis. Simulation experiments have been run using the IDM car-following model, and real-world trajectories have also been analyzed, extracted from the openly available highD dataset.

The first result is that hysteresis and string stability are closely correlated. From the simulation experiments, it is shown that the ability of a platoon to dampen or amplify the magnitude of a perturbation and the intensity of this effect correlates to the magnitude of the loss of flow during the acceleration phase of a perturbation. The string stable platoons with the largest dampening produce negative hysteresis, while the unstable platoons seem to be always hysteretic. The more unstable a platoon is to a given perturbation, the larger the hysteresis magnitude. The results are consistent also for the data from the highD dataset.

Furthermore, while string unstable reaction to a perturbation seems to always lead to a hysteretic recovery of the flow, the opposite does not seem to be the case in simulation. Several IDM combinations lead to string stable but hysteretic reactions. This was shown to be the effect of a low value of the acceleration parameter of the IDM car-following model. This is not as evident in the real data, with much fewer cases that are string stable and hysteretic. However, this may be a result of the specific human drivers not being restricted to use small acceleration values, which would lead to this outcome.

The IDM combinations that scored the lowest stability ratio value, were the ones for which the dampening of the perturbation was the most significant. In those cases, however, the traffic flow is already very small. The vehicles seem to need large time gaps to be able to react in a string stable way to perturbations, and those large time gaps lead to the lowest capacity and outflow values. The optimal cases were the cases with a high acceleration value, that did not amplify the perturbation but slightly dampen its magnitude.

In future work, more data from human drivers have to be used to investigate the findings of the present work. More theoretical work can also be carried out to examine the exact way that the string instability may induce hysteresis in the flow of the acceleration phase.

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