Reducing congestion at uphill freeway sections by means of a Gradient Compensation System

Bernat Goñi Ros, Victor L. Knoop, Bart van Arem, *Member, IEEE*, and Serge P. Hoogendoorn

Abstract— **Uphill sections have often been identified as capacity bottlenecks in freeway networks. One of the main reasons seems to be that drivers reduce speed when they reach the beginning of an uphill section. With high traffic demand, the deceleration of the first vehicle of a platoon can generate a flow disturbance that amplifies as it propagates upstream, triggering the formation of a traffic jam. This paper presents a proof of concept by exploring whether equipping the leader of a platoon with an in-vehicle Gradient Compensation System (GCS) can improve traffic flow efficiency on uphill sections. The GCS assists the driver in performing the longitudinal driving task at uphill sections. We present the results of a series of traffic simulation experiments in which a platoon of vehicles drive on a single-lane freeway stretch containing an uphill section. The phenomenon of speed reduction is modeled by means of a sub-microscopic traffic simulation program. The results show that if the platoon leader is not equipped with the GCS, its speed drop at the beginning of the uphill section can cause a traffic breakdown, as observed in reality. However, if the platoon leader is equipped with the GCS, the magnitude of the speed drop is reduced, preventing congestion formation.**

I. Introduction

Traffic congestion has significant negative impacts on society, including delays, travel time unreliability, air pollution and traffic accidents. For that reason, much research has been performed in the last decades in order to understand the mechanisms leading to the formation of traffic jams and to design measures aimed at reducing congestion. On freeways, traffic jams often occur at uphill sections, i.e., sections in which the gradient changes from flat or downwards to upwards. For example, in Japan's intercity expressways, 40% of traffic jams occur at uphill sections and tunnels [1]. Various measures have been proposed to improve traffic flow operations at uphill sections [1]-[4]. These measures will be discussed in Section II-B. Some of them aim to prevent vehicles from reducing speed when they reach the beginning of an uphill section [1], since that is one of the main reasons why traffic flow becomes unstable and capacity decreases [5]-[7]. A way to prevent vehicles from decelerating could be to introduce an in-vehicle system capable of detecting changes in gradient and assisting the driver in performing the longitudinal driving task on uphill sections. This paper investigates whether the use of a system based on the principle explained above —which we call Gradient Compensation System (GCS)— could improve traffic flow efficiency at uphill sections. To our knowledge, such a system has not been studied before. The methodology used is based on microscopic and sub-microscopic traffic simulation.

The paper is structured as follows. Section II describes the causes of traffic congestion at uphill sections, and provides an overview of the types of measures proposed so far to reduce congestion at that type of locations. Section III explains how the GCS concept works. Section IV describes the methodology used to evaluate the impact of the GCS on traffic flow efficiency. Section V reports the main findings. Section VI discusses the implications of the results. Finally, Section VII presents the conclusions of this study.

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B. Goñi Ros is PhD researcher at the Department of Transport & Planning, Delft University of Technology, 2628CN Delft, The Netherlands (corresponding author, phone: +31152784912; fax:+31152783179; e-mail: b.goniros@tudelft.nl).

V. L. Knoop is postdoctoral researcher at the Department of Transport & Planning, Delft University of Technology (e-mail: v.l.knoop@tudelft.nl).

B. van Arem and S. P. Hoogendoorn are full professors at the Department of Transport & Planning, Delft University of Technology (e-mail: b.vanarem@tudelft.nl, s.p.hoogendoorn@tudelft.nl).

II. Background

A. Causes of traffic congestion at uphill sections

Generally, the occurrence of traffic congestion on freeways is caused by a combination of three elements [8]: a) a high traffic volume; b) a spatial inhomogeneity on the freeway which generates a capacity bottleneck; and/or c) a temporary disturbance of the traffic flow. Changes of gradient are one of the types of spatial inhomogeneities that can generate a capacity bottleneck. For example, at some uphill sections of Japanese freeways, capacity flows have been reported to be 25-35% lower than at flat sections having the same number of lanes [5]. A complete explanation of why capacity decreases at uphill sections is not available. However, one of the most important factors seems to be that drivers unintentionally reduce speed when they reach the beginning of an uphill section driving in free-flow conditions [1], [5]-[7]. An average speed drop of around 10% is reported in [6]. This speed drop is caused by a combination of two factors: i) increase in the resistance force as a result of the increase in gradient; and ii) insufficient acceleration operation by the driver. Two main hypotheses have been formulated to explain why drivers fail to accelerate enough to counteract the increase in resistance force and keep their initial (desired) speed: a) drivers have a limited ability to perceive changes in gradient [5]; and b) drivers have a limited sensitivity to gradual speed changes [6]. With high traffic demand, long vehicle platoons are formed as a result of the presence of slow drivers. In those conditions, the speed drop of the platoon leader at the beginning of an uphill section typically generates a traffic flow disturbance. If that disturbance is of sufficient magnitude, it amplifies as it propagates backwards due to the intrinsic metastability of traffic flow at high volumes. This results in lower speeds or even complete stops upstream [1], [5]. The higher the amplitude of the initial disturbance, the greater its destabilizing effect on traffic flow tends to be [9]. In multi-lane freeways, congestion usually occurs first in the passing lane, which has higher flow rates than the other lanes. After this happens, many vehicles move from the passing lane to the cruising lanes in order to avoid stopping. As a result, those lanes become also quickly congested [1], [2], [5]. The head of the queue generally remains within a short distance from the base of the hill, usually on the first 500-1000 m of the uphill section. Further uphill the traffic situation generally recovers. Therefore, the lower part of uphill sections constitutes the capacity bottleneck [7].

B. *Measures to reduce congestion at uphill sections*

Several measures have been proposed to reduce congestion at uphill sections. In general, those measures can be sorted into four categories: 1) measures aimed at preventing speed reduction in free-flow conditions; 2) measures aimed at preventing the formation of long vehicle platoons; 3) measures aimed at correcting the imbalance in lane utilization; and 4) measures aimed at maintaining the headway between vehicles. An example of a measure in the first category is a service that uses information panels to urge drivers to accelerate at the beginning of uphill sections [1]. An example of a measure in the second category is a system that uses information panels to ask slow vehicles to keep a minimum speed and/or move to the cruising lanes [1]. The third category comprises measures such as road surface markings and variable message signs that encourage drivers to switch to cruising lanes before uphill sections, and discourage them from switching to the passing lane before and within uphill sections [1]-[4]. Finally, an example of a measure in the fourth category is an adaptive cruise control (ACC) concept that changes its target time headway when the vehicle approaches an uphill section in order to increase the bottleneck capacity [10]. The potential of measures in categories 3 and 4 to reduce or delay congestion formation has been demonstrated by [1]-[4] and [10]. However, to our knowledge, not many measures have been proposed to prevent vehicles from reducing speed (category 1). Also, the effectiveness of that type of measures has been rarely evaluated. Yet they could potentially yield significant improvements in traffic flow efficiency, since they may prevent vehicles from reducing speed at the beginning of uphill sections and generating traffic flow disturbances.

III. THE GRADIENT COMPENSATION SYSTEM (GCS)

Measures aimed at preventing speed reduction usually try to influence driving behavior by giving advice to drivers via road-side signs. We propose an alternative approach: an autonomous in-vehicle system —Gradient Compensation System (GCS)— that assists the driver in performing the longitudinal driving task when the vehicle is on an uphill section and the driver wishes to keep a constant speed.

The GCS works as follows. The system continuously monitors: i) gradient (e.g., by means of a GPS-signal receiver and a digital map containing topographic information); ii) speed; iii) gear selection; and iv) position of the throttle and brake pedals. When the vehicle reaches an uphill section, if the driver keeps a constant throttle position without braking or changing gear, the system assumes that he wishes to keep a constant speed on that section. However, the vehicle speed will start to decrease due to an increase in the grade resistance force. When the vehicle speed decreases below a certain threshold (5%), the GCS activates and assists the driver in performing the acceleration task. It does so by automatically changing the relationship between throttle position and engine power. The GCS dynamically adapts that relationship so that the vehicle accelerates, goes back to the initial speed, and then keeps that speed on the remaining of the uphill section. The driver only needs to keep a constant throttle position. A speed drop threshold of 5% guarantees that the GCS will not activate in case of slight speed oscillations or very short uphill sections. The GCS deactivates when the car leaves the uphill section and/or the driver brakes or releases the throttle pedal. The main conceptual difference between the GCS and a cruise control system is that the GCS does not take full control of the acceleration task, but only assists the driver in performing it.

The objective of the GCS is to reduce: a) the magnitude of the speed drop; and b) the time during which the vehicle is decelerating. Our hypothesis is that by equipping the leader of a platoon with the GCS, we can prevent that platoon from becoming unstable due to the speed drop of the leader. Therefore, the formation of a traffic jam would also be prevented.

IV. METHODOLOGY

A. *Assumptions about the longitudinal driving behavior of the followers*

We assumed that the acceleration behavior of all vehicles within a platoon (except the leader) can be adequately described by a microscopic model. We used an adapted version of the IDM+ model [11]. The equations of the IDM+ model are:

$$\frac{dv}{dt} = a \cdot \min\left[1 - \left(\frac{v}{v^*}\right)^4, 1 - \left(\frac{s^*(v, \Delta v)}{s}\right)^2\right] \qquad (2)$$

$$s^*(v, \Delta v) = s_s + v \cdot T + \frac{v \cdot \Delta v}{2 \cdot \sqrt{a \cdot b}} \qquad (3)$$

where: v is the current speed (m/s); t is time (s); s^* is the dynamic desired distance headway (m); Δv is the relative speed in comparison to the vehicle in front; and s is the distance headway (m).

The parameters of the IDM+ model are described in Table I. The table also provides the values used in this study, which are based on [11]. The desired speed, v^*, is the general speed limit in Japanese freeways, i.e., 100 km/h.

TABLE I
PARAMETER VALUES: IDM+ MODEL

Parameter description	Symbol	Value used
Desired speed (followers)	v^*	27.8 m/s (100 km/h)
Comfortable acceleration	a	1.0 m/s^2
Comfortable deceleration	b	2.0 m/s^2
Minimum distance headway	s_s	2 m
Desired time headway	T	1.6 s
Vehicle length	L_{veh}	4 m

Essentially, the IDM+ model works as follows. At each simulation time step, it determines whether the acceleration behavior of the driver is constrained by the vehicle in front or he is driving in free-flow regime: a) if $1-(v/v^*)^4$ is higher than $1-(s^*/s)^2$, the model assumes that the driver is in car-following regime; b) if $1-(v/v^*)^4$ is lower than $1-(s^*/s)^2$, the model assumes that the driver is in free-flow regime (2). Then, the model calculates the instantaneous vehicle acceleration based on the ratio s^*/s, in the first case, or the ratio v/v^*, in the second case (2). A time step of 0.1 s was used.

In our acceleration behavior model, we incorporated an indifference zone into the IDM+ model (Figure 1). The objective was to take into account that drivers do not perceive changes in relative speed that are lower than a certain threshold, in line with [12]. If drivers are driving in car-following regime and they are within the indifference zone, they do not accelerate according to the IDM+ model; instead, they keep a constant acceleration. If drivers are driving in car-following regime but they are outside the indifference zone, they accelerate according to the IDM+ model. We have assumed that the action points separating both zones lie on two straight lines, shown by two thick lines in Figure 1. Those lines are defined by the functions $s(\mathrm{m})=\pm 28\cdot\Delta v(\mathrm{m/s})$, based on a simplification of the empirical findings of [13]. Note that although those action point lines are symmetrical around $\Delta v=0$, according to the IDM+ model the acceleration out of the indifference zone is not symmetrical. The indifference zone does not apply if drivers are driving in free-flow regime, since then they do not base their acceleration behavior on relative speed and distance headway, but on their own vehicle speed (2). Thus, the indifference zone has an upper bound, which is shown by two dashed lines in Figure 1. The exact s-intercept and slope of the upper bound lines depend on the speed of the subject vehicle (for a fixed speed of the car in front).

The indifference zone also introduces a reaction time into our acceleration model, which is not taken into account by the IDM+ model. If drivers are in car-following regime and they are within the indifference zone, they do not change acceleration immediately. They only do so when they reach the action point line. Perception and reaction time are modeled together. However, our acceleration model does not account for reaction time if drivers are out of the indifference zone.

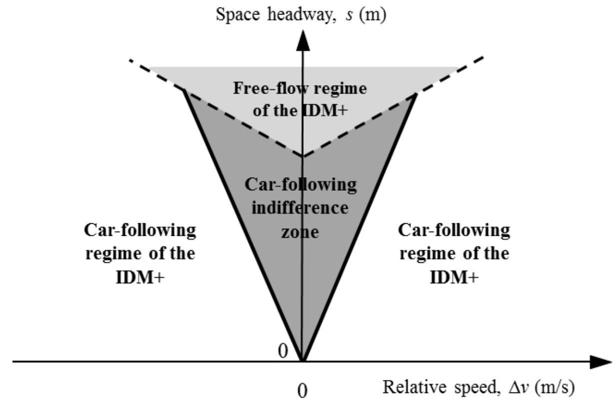

Fig. 1. Indifference zone and action point lines. The indifference zone is shown in dark grey. The thick lines are the action point lines. The dashed lines correspond to the upper bound of the indifference zone. Above that upper bound (light grey area), drivers are assumed to drive in free-flow regime.

Finally, it is important to note that we assumed that the acceleration behavior of the followers is not affected by changes in freeway gradient. This is a strong assumption that we made for the sake of simplicity. The implications of this assumption are further discussed in Section VII.

B. *Assumptions about the longitudinal driving behavior of the platoon leader*

We assumed that the acceleration behavior of the leader of a vehicle platoon approaching an uphill section can be adequately described by means of a combination of two models: a) a sub-microscopic model, describing acceleration behavior before the driver/GCS perceives the speed drop on the uphill section; and b) a microscopic model, describing acceleration behavior after the driver/GCS perceives the speed drop. The sub-microscopic approach is necessary to model the deceleration of the platoon leader at the beginning of uphill sections.

B1. Before the driver/GCS perceives the speed drop

The longitudinal driving behavior of the platoon leader is determined by the net force acting on the vehicle, which depends on both the tractive force generated by the engine and the total resistance force (4)-(7).

$$\frac{dv}{dt} = \frac{F_t + R}{m} \tag{4}$$

$$F_t = \min\left(\frac{\varphi \cdot P \cdot T_p}{v}, F_{t,max}\right) \tag{5}$$

$$R = C_a \cdot v^2 + C_r \cdot m \cdot g \cdot \cos(\gamma) + m \cdot g \cdot \sin(\gamma) \tag{6}$$

$$\gamma = \arctan\left(\frac{G}{100}\right) \tag{7}$$

In equations (4)-(7): F_t is the tractive force (N); R is the total resistance force (N); v is the vehicle speed (m/s); T_p is the throttle position (T_p=1 is full throttle and T_p=0 is throttle release); P is the power provided by the engine at full throttle in a certain gear and at a given vehicle speed (W); G is the roadway gradient (%); and γ is the roadway upgrade angle (rad).

The parameters in (4)-(7) are described in Table II, which also shows the parameter values for the reference vehicle [14] used in the experiments described in Section IV-C.

TABLE II
PARAMETER VALUES: VEHICLE DYNAMICS

Parameter description	Symbol	Value used [a]
Vehicle mass	m	1140 kg
Gravity acceleration	g	9.81 m/s^2
Maximum tractive force	$F_{t,max}$	6039 N
Transmission efficiency	φ	0.9
Max. engine power (at 6000 rpm)	P_{max}	73000 W
Air resistance factor	C_a	0.39 kg/m
Coefficient of rolling resistance	C_r	0.001

[a] Reference vehicle: Toyota Yaris [14].

The model works as follows. At each simulation time step, it computes the tractive and resistance forces based on throttle position, gear, vehicle speed and gradient (5)-(7). From F_t and R, it determines the vehicle acceleration (4). A time step of 0.1 s was used in this study.

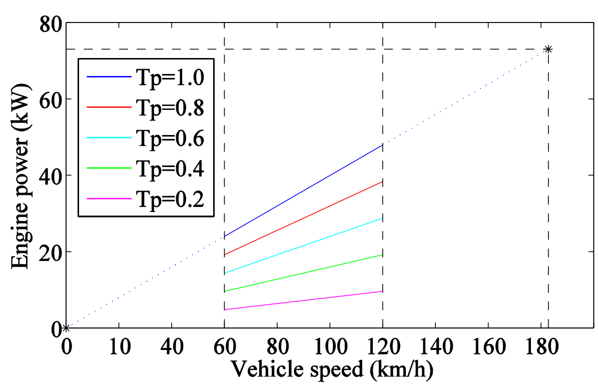

Fig. 2. Linear simplification of the relationship between engine power, vehicle speed (between 60 and 120 km/h) and throttle position for the reference vehicle (in 4th gear).

For the sake of simplicity, we linearized the relationship between power and engine speed (rpm) within the engine speed range 2000-4000 rpm. Since a constant gear fixes the relationship between engine speed and wheel speed, the relationship between power and vehicle speed also becomes linear (within a certain vehicle speed range dependent on the gear). We further assumed that a constant throttle position gives a constant fraction of the maximum available power at a given engine speed. For example, Figure 2 shows the linear relationship between engine power, vehicle speed and throttle position (in fourth gear) for the reference vehicle [14] used in the experiments described in Section IV-C. The power-speed lines in Figure 2 were constructed as follows. The engine power was assumed to be zero at a vehicle speed equal to zero. For T_p=1, the engine power equals the maximum power (73 kW) when the engine speed is 6000 rpm (which equals a vehicle speed of 183 km/h in fourth gear) [14]. The only part of the engine speed range that is relevant for this paper is 2000-4000 rpm (which equals the vehicle speed range 60-120 km/h in fourth gear). For this engine speed range, the maximum power available was assumed to be a linear interpolation of the maximum power available at 0 and 6000 rpm. This means that we assumed a constant torque for that engine speed range. For T_p<1, the power at each vehicle speed was assumed to be the power for T_p=1 multiplied by T_p (Figure 2).

The model formulated in equations (4)-(7) has two important characteristics: i) the total resistance force acting on a vehicle depends on the gradient (6)-(7); ii) the tractive force depends on the throttle position (5). To model the acceleration behavior of the platoon leader we further assumed that he has both a limited ability to perceive changes in gradient [5] and gradual changes in speed [6]. As a consequence, if a vehicle is driving on a flat section with a constant speed and then arrives to an uphill section, speed will decrease at the beginning of that section. The main reason is the following. On the flat section, the driver keeps a constant speed by applying a constant specific throttle position that results in a sufficient tractive force (5) to counteract the effect of the total resistance force when driving at that speed. However, when the vehicle reaches the base of the hill, the grade resistance force, which is zero on the flat section, becomes positive. There is also a minor decrease in the rolling resistance. As a result, the total resistance force increases (6). The driver does not push down the throttle pedal because he does not immediately perceive the changes in gradient and vehicle speed. Hence the total resistance force will be greater than the tractive force (5) and the vehicle will decelerate (4).

B2. After the driver/GCS perceives the speed drop

We assumed that the platoon leader perceives the speed drop at the beginning of an uphill section only when the speed of the vehicle has decreased by a certain percentage threshold. Then, the driver pushes down the throttle pedal in order to re-accelerate. Similarly, the GCS only reacts to the speed drop when that is greater than a certain percentage threshold. We assumed that the re-acceleration behavior can be adequately described by the IDM+ model (2)-(3), both if the vehicle is equipped with the GCS and if it is not. The parameters of the platoon leader's re-acceleration model are the same as those in Table I, except the desired speed, which in this case was assumed to be the initial speed of the platoon leader.

C. *Experimental settings*

The main objective of our simulation experiments is to analyze the impact of equipping the leader of a platoon with the GCS on traffic flow efficiency at uphill sections.

We modeled a simple network consisting of a freeway stretch, 4 km long, with a single lane and no overtaking possibilities. The freeway stretch has two different sections: a) from x<0 to x=2 km, the freeway is flat, i.e., the gradient is zero (G=0%); and b) from x=2 km to x=4 km, the freeway goes uphill with a constant positive gradient (G>0%).

We modeled a platoon of N=300 vehicles of the same characteristics driving on a freeway. The reference vehicle is a Toyota Yaris with petrol engine and 5-speed manual transmission (year 2007). The technical specifications of that vehicle can be found in [14]. The desired speed of the platoon leader, v_0, is lower than the desired speed of the followers, v^*, which is 100 km/h (Table I). The platoon leader drives in free-flow regime at his desired speed, but the remaining vehicles drive in car-following regime, so they have to drive at the same speed as the platoon leader, v_0. Initially, dv/dt is zero for all vehicles. Therefore, according to the IDM+ model (2), all vehicles (except the platoon leader) must keep an initial distance headway equal to their desired distance headway, s^*, which is dependent on v_0 (3). Before the platoon leader reaches the base of the hill, his acceleration behavior is not constrained by any vehicle in front, so it is assumed that he just tries to keep his desired speed, v_0. He does that by keeping a constant throttle position. At location x=2 km, the vehicle reaches the base of the hill and starts to decelerate. The vehicle re-accelerates only when the speed has decreased below a certain speed drop perception threshold (λ). In this study, the λ of a human driver was assumed to be 10%, in line with [6], but a value of 15% was also used in order to perform a sensitivity analysis. The GCS activates when speed drops by 5%. Also, for the sake of simplicity, we assumed that the platoon leader drives in fourth gear on the whole freeway stretch under study. This is not an unrealistic assumption, since the leader's speed stays between 85 and 95 km/h (as explained in Section V), which is within the normal vehicle speed range of that gear [14].

TABLE III
DEFINITION OF SCENARIOS: VARIABLES AND VALUES

Variable	Symbol	Values
Speed drop perception threshold	λ	15% (human) 10% (human) 5% (GCS)
Desired speed of the platoon leader	v_0	95 km/h 90 km/h
Gradient of the uphill section	G	3% 6%

We simulated traffic flow in a number of scenarios defined by all combinations of the variable values specified in Table III. The total simulation time period was 780 s (13 min). At time t=0 s, the platoon leader is located at x=0 km, and the rest of the vehicles are located upstream (x<0 km).

The impact of equipping the platoon leader with the GCS on traffic flow efficiency at the uphill section was evaluated by means of two measures:

- Capacity of the bottleneck, Q_C (veh/h): throughput downstream of the uphill bottleneck, i.e., total number of vehicles, N, divided by the time period between the first and last vehicle counts at x=3.5 km, T_C (s) (8).

$$Q_C = \frac{N}{(T_C/3600)} \tag{8}$$

- Total travel time, TT_{tot} (s): sum of the travel times of all vehicles from x=0 to x=4 km, TT_n (s) (9).

$$TT_{tot} = \sum_{n=1}^{N} TT_n \tag{9}$$

The change in throughput, ΔQ_C, and the change in total travel time, ΔTT_{tot}, were calculated by comparing the throughput and total travel time in each scenario with those in reference scenarios with no uphill section (G=0%) for v_0=95 km/h and v_0=90 km/h.

V. RESULTS

A. Scenarios without GCS

In this sub-section, we will first describe in detail the simulation results of the scenario with the platoon leader not equipped with the GCS, λ=10%, v_0=95 km/h and G=3%. Next, we will briefly describe the results of the other scenarios without GCS (Table III).

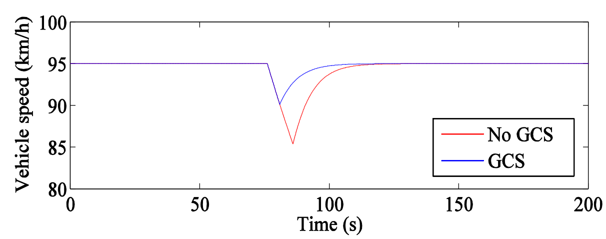

Fig. 3. Speed of the platoon leader over time in two scenarios: i) scenario without GCS, λ=10%, v_0=95km/h, G= 3%; and ii) scenario with GCS, v_0=95km/h, G= 3%.

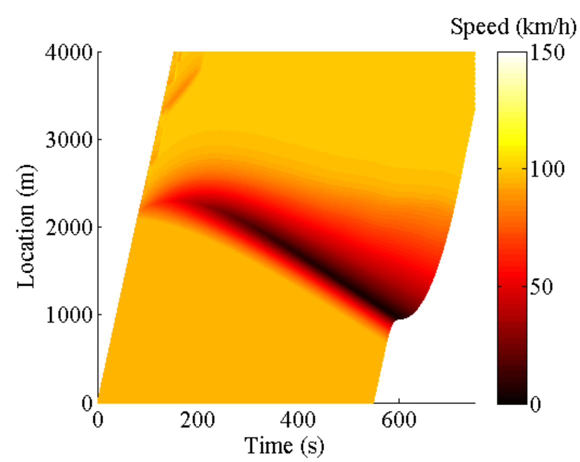

Fig. 4. Speed of the vehicles over time and space. Scenario without GCS, λ=10%, v_0=95 km/h, G= 3%. Uphill section starts at x=2 km.

In the scenario mentioned above, the speed of the platoon leader starts to gradually decrease when the vehicle reaches the beginning of the uphill section, at t=76 s (Figure 3). When the speed becomes 10% lower than the initial speed, at t=86 s, the driver perceives the speed drop and reacts to it by re-accelerating (Figure 3). The speed drop has a significant effect on the acceleration of the other vehicles within the platoon, which are driving in car-following regime. As shown in Figure 4, the followers are forced to also reduce speed, which results in smaller distance headways, higher traffic densities and lower traffic flow rates. As a consequence, a traffic jam is formed, the head of which stays close to the base of the hill. Within the jam, vehicle speeds are considerably lower than the initial speed (v_0), even reaching a value of zero. The speed of the shockwave defining the upstream front of the jam is higher than that of the shockwave defining the downstream front. As a result, the size of the traffic jam increases over time. The formation of congestion results in lower throughput and increased travel times. In comparison to the reference scenario with no uphill section, throughput decreases by 12% and total travel time increases by 26% (Table IV).

TABLE IV
CHANGES IN THROUGHPUT AND TOTAL TRAVEL TIME PER SCENARIO

Scenario	Change in throughput (%)	Change in total travel time (%)
Without GCS (λ=15%)		
v_0 =95km/h		
G=3%	-11.6	+25.9
G=6%	-11.7	+26.1
v_0 =90km/h		
G=3%	-10.8	+21.7
G=6%	-10.8	+21.9
Without GCS (λ=10%)		
v_0 =95km/h		
G=3%	-11.7	+25.7
G=6%	-11.9	+25.4
v_0 =90km/h		
G=3%	-10.9	+21.6
G=6%	-10.8	+21.2
With GCS (λ=5%)		
v_0 =95km/h		
G=3%	0.0	0.0
G=6%	0.0	0.0
v_0 =90km/h		
G=3%	+0.2	0.0
G=6%	+0.1	0.0

In the other scenarios without GCS (Table III), the pattern of vehicle speeds over time and space is similar to that shown in Figure 4. A traffic jam is also formed. The shockwaves defining the upstream and downstream fronts show similar speed patterns. As a result, changes in throughput and total travel time are also similar (Table IV). However, some differences can be identified. First, with a higher gradient (G=6%), the traffic jam originates at a closer distance to the base of the hill, but throughput and total travel time are similar. Second, if the initial speed of the platoon leader is lower (v_0=90 km/h), the traffic jam again originates at a closer distance to the base of the hill. Also, the relative decrease in throughput and the relative increase in travel time in comparison to the reference scenarios are slightly lower: -11% and +22%, respectively (Table IV). Finally, assuming a higher λ (15%) does not yield significantly different results (Table IV).

B. Scenarios with GCS

We will first analyze in detail the simulation results of the scenario with the platoon leader equipped with the GCS, v_0=95 km/h and G=3%. Next, we will briefly describe the results of the other scenarios with GCS (Table III).

In the scenario mentioned above, the speed of the platoon leader begins to gradually decrease when the vehicle reaches the uphill section, at t=76 s (Figure 3). However, when a speed drop of 5% is detected by the GCS, at t=81 s, the system activates, hence the vehicle starts to re-accelerate (Figure 3). In contrast to the scenarios without GCS, the impact of the platoon leader's speed drop on the followers' acceleration is negligible. As shown in Figure 5, traffic operations are not disturbed. The followers hardly need to reduce speed. Traffic flow does not become unstable and no traffic jam is formed. As a consequence, throughput and total travel time are equal to those in the reference scenario with no uphill section (Table IV).

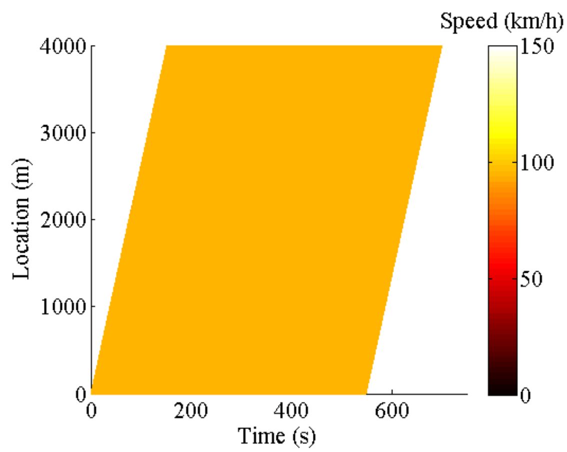

Fig. 5. Speed of the vehicles over time and space. Scenario with GCS, λ=10%, v_0=95 km/h, G= 3%. Uphill section starts at x=2 km.

In the other scenarios with GCS (Table III), the pattern of vehicle speeds over time and space is similar to that shown in Figure 5. Traffic operations are not disturbed by the speed drop of the platoon leader. No traffic jam is formed. Therefore, there are almost no changes in throughput and total travel time in comparison to the reference scenarios (Table IV).

VI. DISCUSSION

The traffic flow patterns resulting from our simulations in the scenarios without GCS are similar to those observed in real traffic [1], [5]-[7]. Capacity decreases at uphill freeway sections due to the negative effect of the vehicles' speed drop on traffic flow stability. With high traffic demand, congestion sets in, causing significant delays. Since the results of our simulations are similar to those observed in real traffic, we assume that our driving behavior models can adequately reproduce the mechanisms leading to the formation of congestion at uphill sections.

The simulation results in the scenarios with GCS show that the proposed system could be effective in increasing the stability of vehicle platoons at uphill sections. With the GCS, the amplitude of the initial traffic flow disturbance generated by the speed drop of the platoon leader can be reduced below a certain threshold so that it is damped out and does not propagate upstream. As a result, traffic flow does not become unstable and capacity increases. Similar results were obtained for different uphill gradients and platoon speeds.

VII. Conclusions and Outlook

Uphill sections can become capacity bottlenecks on freeways. The literature suggests that this is due to the fact that drivers reduce speed when they reach the beginning of an uphill section, destabilizing traffic flow. As a result of instability, traffic on uphill sections becomes congested at lower traffic volumes than on flat sections.

The main aim of this paper was to determine whether equipping the leader of a vehicle platoon with a Gradient Compensation System (GCS) could improve traffic flow efficiency at uphill sections. The GCS uses in-vehicle technology to assist the driver in performing the longitudinal driving task on uphill sections. The methodology used to evaluate the effectiveness of the GCS concept is based on a combination of microscopic and sub-microscopic traffic simulation. The sub-microscopic approach is necessary to model the speed drop of the platoon leader at the beginning of an uphill section.

The findings presented in this paper prove the concept of using the GCS to increase platoon stability at uphill freeway sections, which increases traffic flow efficiency. The main reason is that the system is more sensitive to gradual speed changes than a human driver. If the leader of a vehicle platoon is equipped with the GCS, when that vehicle reaches an uphill section the magnitude of its speed drop is lower than if the vehicle is not equipped with the GCS. The initial traffic flow disturbance is sufficiently small as to be damped out, therefore traffic flow does not become unstable. Similar results were obtained for different uphill gradients and platoon speeds.

Further research is needed to gain more insight into the effectiveness of the GCS in improving traffic flow efficiency. In particular, the driving behavior and traffic simulation models need to be developed further. Also, the GCS controller should be adjusted to ensure that it will be effective in various circumstances and drivers will actually decide to use the system.

The driving behavior and traffic simulation models used in this study need to be extended, validated and calibrated. First, several assumptions on longitudinal driving behavior need to be validated. In particular, the assumptions about the acceleration behavior of the platoon leader when he reaches the beginning of the uphill section have an important influence on the traffic simulation results. We assumed that a human driver does not perceive the change in gradient nor the related speed drop until the speed of the vehicle has decreased by a certain percentage threshold. This assumption results in stronger decelerations of the platoon leader at the beginning of the uphill section than those reported by [6]. Those authors observed average speed drops of the same magnitude as the ones assumed in this study, but over longer time periods and distances. They suggest that generally most drivers do perceive changes in gradient and react to them by pushing down the throttle pedal, but they fail to keep a constant speed anyway. No definitive explanation of why vehicles reduce speed at uphill sections is available yet. This issue needs to be addressed in further research by means of empirical data analysis. Another assumption that needs to be tested is that car-following behavior is not affected by changes in gradient. That assumption may not be valid for several reasons. For instance, drivers in car-following regime may also reduce speed at uphill sections due to the increase in resistance force and insufficient acceleration operation, like the platoon leader. In addition, drivers may keep longer headways on uphill sections than on flat sections at similar speeds, as suggested by [15]. This issue needs to be investigated further.

Second, lateral driving behavior on multi-lane freeways needs to be incorporated into the driving behavior models. In this study, we modeled a freeway stretch consisting of only one lane; therefore, the impacts of a gradient increase on lane utilization rates and lane-changing behavior were not investigated. However, lateral driving behavior seems to play an important role on the formation of congestion on uphill sections of multi-lane freeways [1], [2], [5]. Incorporation of lateral driving behavior into the driving behavior models is ongoing.

Third, the driving behavior and traffic simulation models should be extended in order to take into account traffic heterogeneity. In this study, we only took into account one type of vehicle and two types of driving behavior, i.e., that of the platoon leader and that of the followers. However, many vehicle and driver classes are usually present in real traffic. Differences in traffic composition have an influence on traffic flow efficiency; for example, the presence of heavy vehicles seems to reduce capacity on uphill sections [7]. Also, traffic heterogeneity may cause the formation of consecutive short platoons with gaps between them. This may significantly influence traffic flow stability. In general, the smaller the size of the platoons and the greater the gaps between them, the more stable traffic flow is [9].

Fourth, all the models mentioned above should be calibrated based on empirical data.

Once the models are validated and calibrated, it will be possible to adjust the GCS controller in order to ensure that the system effectively stabilizes traffic flow on uphill sections. In particular, the relationship between the amplitude of the initial disturbance (speed drop) and traffic flow stability needs to be analyzed more in depth. In this respect, a speed drop threshold for GCS activation different than 5% may be required in different circumstances, depending on freeway geometric layout, traffic conditions and vehicle/driver characteristics.

Finally, further research is needed to determine whether drivers would actually decide to use the GCS and how they would interact with it. The behavioral response of drivers to in-vehicle technology is generally related to the resulting improvements in driving performance and the effects on the drivers' total mental workload [16]. If drivers perceive that the GCS makes the driving task more uncomfortable or unsafe, they may decide to switch the system off. In that case, introducing vehicles equipped with the GCS would have no impact on traffic flow efficiency.

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