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A Study on the Safety-Capacity Tradeoff Improvement by Warning Communications

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***Abstract*— This paper studies the contribution of warning communications in a vehicles string. After having presented the capacity and safety notions, two approaches of the evaluation of the communication impact on the safety-capacity tradeoff are presented. The first approach proposes a formal expression of the number of collisions in an uniform vehicles string (unequipped or fully equipped in communication means). The second approach is complementary to the first one. It focuses on the gain in safety for a partial communication equipment of the string. Moreover this second approach includes two different safety indexes: the first one is based on the number of collisions, the second one is based on the severity of shocks. The analysis estimates the gain in respect to the penetration ratio of the new technology.**

To carry out this analysis, we focus on the safety and capacity improvement in a vehicles string. We consider a disaster scenario called *bricks wall* and alert communication systems.

I. Introduction

The traffic flow on inter-suburbs and downtown-suburbs ways is in strong expansion since twenty years. As the infrastructure was not designed for a such traffic, more and more traffic jams appear. Several types of congestions can be enumerated: recurring congestions (peak hours), exceptional congestions (accidents, bad weather) and congestions due to the heterogeneity of the performances of the various vehicles (light vehicles, trucks, motorcycles. . .). When a traffic jam is in formation some shock waves [6] are created and decreases considerably the safety (human cost). When the traffic jam is formed a lot of time is wasted, the cost is then economic.

The main problem is to deal with the safety-capacity tradeoff. How can we increase the capacity without decrease the safety without modification of the infrastructure?

In the related literature about the research on transportation, in particular about the Automated Highways System (AHS), a lot of works have been carried out. This was done especially in automatic subjects as string and platoon stability [13], [15] for instance.

Recently, more and more works focus on the vehicle-vehicle (V-V) or Infrastructure-Vehicle (I-V) communication. As guidelines papers we can quote [1], [11], [12]. These papers show the needs of communication in the road context.

More precisely, in the area of the safety and/or of the capacity, we can notice [3]–[5], [7], [14] about safety conditions and safety analysis. [10] presents a study about the capacity analysis and [2], [8] about the capacity versus safety analysis. Generally these papers approach the problem by a 'global' criteria like Average Accident Interval (AAI) or like a probabilistic number of collisions. Here, we want to compute a safety index, very relevant for the human being. We propose a microscopic simulation to manage an averaged microscopic safety index and dealing with macroscopic measurement: capacity.

In the first section, we introduce the capacity and safety concepts. The section III and IV present two different approaches. The first approach is basic and allows us to show the gain in communication. We present a comparison of two formal expressions of the number of collisions for an uniform vehicles string equipped (100%) or not (0%) in means of communication. The second approach works with partially equipped vehicles strings. A new safety index, more relevant than the previous one, is used. Moreover, to deal with the passage from the macroscopic to the microscopic aspects, considering a capacity, we generate randomly different spatial repartitions. From all these repartitions, the most unfavorable repartition will be taken into account (worst case evaluation).

II. Problem Statement

To measure the safety, let us consider the *Bricks Wall Scenario* described in the sequel. A bridge has just collapsed on the road (we call this event the *perturbation*). A string of vehicles goes on this collapsed bridge. The leader vehicle is crushed on the wall (because it does not have the time to react). Then other vehicles try to brake. A similar approach has been studied in [9].

This section presents the notations and what we denote by safety distance, capacity and safety indexes.

A. Notations

Let us consider a sub-string of two vehicles (Veh_i and Veh_{i+1}) of a main vehicle string (Fig. 1). Veh_i is the leader vehicle of this sub-string and Veh_{i+1} the follower one.

Each vehicle Veh_i is characterized by the following parameters:

- l_i, the length of the i^{th} vehicle (in m),
- m_i, the weight of the i^{th} vehicle (in kg),
- v_i, the velocity of the i^{th} vehicle (in m/s),
- γ_i, the absolute value of breaking capacity of the i^{th} vehicle (in m/s^2),
- x_i: the position of the middle of the i^{th} vehicle (in m),
- x_i^-: the position of the rear of the i^{th} vehicle (in m),
- x_i^+: the position of the front of the i^{th} vehicle (in m),
- $d_{\text{inter}_{i,i+1}} = x_i^- - x_{i+1}^+$, the interdistance between the i^{th} and the $(i+1)^{\text{th}}$ vehicle (in m),
- τ_i the reaction time of the driver (human or computer, in s),
- $d_{\tau_i} = \tau_i.v_i$, the distance covered during the reaction time τ_i (in m),
- $d_{\text{dec}_i} = \frac{v_i^2}{2\gamma_i}$, the deceleration distance of the i^{th} vehicle (in m),
- $d_{\text{stop}_i} = d_{\tau_i} + d_{\text{dec}_i}$, the stop distance of the i^{th} vehicle (in m),
- $\varepsilon_{i,i+1}$, the remaining interdistance between the i^{th} and the $(i+1)^{\text{th}}$ vehicles when they are stopped (in m). This value is also called security offset.

We denote initial conditions by a zero exponent, thus: $x_i^{-,0}$, $x_i^{+,0}$ and v_i^0 are the initial values of, respectively, the rear position, the front position and the velocity of the i^{th} vehicle. The initial moment is the moment when the perturbation occurs (the first vehicle hit the wall).

B. Safety Distance

The safety distance d_{safe} is the minimal interdistance d^0_{inter} which allows two vehicles to be in safety condition ($d_{\text{inter}}(t) > 0$) while they are not stopped when they are braking at their maximal capacities (γ).

Let us assume that Veh_i suddenly brakes (with γ_i deceleration) until it stops. In order to avoid the collision, Veh_{i+1} brakes (with γ_{i+1} deceleration) after a reaction time τ_{i+1} (see on the Fig. 1). The initial interdistance is $d^0_{\text{inter}_{i,i+1}} = x_i^{-,0} - x_{i+1}^{+,0}$ and the safety distance is defined as following:

$$\boxed{d_{\text{safe}_{i,i+1}} \triangleq \min\{d^0_{\text{inter}_{i,i+1}} / \forall t \in [0, t_{\text{stop}}], d_{\text{inter}_{i,i+1}}(t) \geq 0\}} \quad (1)$$

with t_{stop} the time until the both vehicles are stopped:

$$t_{\text{stop}} = \max\left(\frac{v_i^0}{\gamma_i}, \frac{v_{i+1}^0}{\gamma_{i+1}} + \tau_{i+1}\right) \quad (2)$$

In other words, if the initial interdistance between two vehicles is lower than the safety distance, if the first vehicle makes an emergency braking, the second vehicle will not be able to avoid the collision.

C. Capacity Index

Juste before the perturbation, the interdistance between vehicles (d^0_{inter}) implies a repartition of vehicles in the space. This repartition is expressed by the density ρ (number of vehicles / length unity):

$$\rho = \frac{1}{\bar{l} + \bar{d}^0_{\text{inter}}}, \quad (3)$$

where $\bar{l}$ is the mean length of vehicles and $\bar{d}^0_{\text{inter}}$ the averaged initial interdistance.

The only conclusion that we can reach is that if $\rho > \rho_{\text{safe}}$ the vehicles string is not in safety condition (there exists, at least, one couple of vehicles i and $i+1$ where $d^0_{\text{inter}_{i,i+1}} < d_{\text{safe}_{i,i+1}}$).

From this spacial repartition, we can express a temporal repartition of the vehicles which is the capacity c of the vehicles flow (number of vehicles / time unity):

$$\boxed{c = v\rho = \frac{v}{\bar{l} + \bar{d}^0_{\text{inter}}}} \quad (4)$$

with v the velocity of the flow [6].

D. Safety Index

There are numerous methods to create safety indexes. On one hand, different safety criteria can be chosen:

- the number of collisions,
- the collision severity of the whole vehicle string,
- the average severity…

All have advantages and disadvantages (relevancy, computation complexity…). In the related literature ([2], [3]), the approach with probabilistic number of collisions is frequently used as safety index. In this paper, two different safety indexes are being used. In a first time (section III), the safety index is function of only the number of collisions in the vehicles string. Then, in the second approach (section IV), another safety index based on the violence of a shock for a human body will be used. This index will be detailed in the subsection IV-C.

On the other hand, there are methods to estimate these criteria.

For instance, in [2] the estimation of some parameters of the driver is based on statistical data collected on highway. Then, from these data on the behavior, collision probabilities are computed. In [3], in order to compute theses collisions probabilities, a Brownian model is applied to the behaviour of the vehicle.

In this paper, we have a different approach. Considering a vehicle string with no random in the vehicle behaviors, we generate the perturbation (the brick wall, this step is described in the Section III) and then we analyse the consequences of this perturbation. The safety is a concept depending of the gravity of an event and the probability of occurrence of this event. Here, the probability of the event ”brick wall” is set to one. So, we are only computing the gravity.

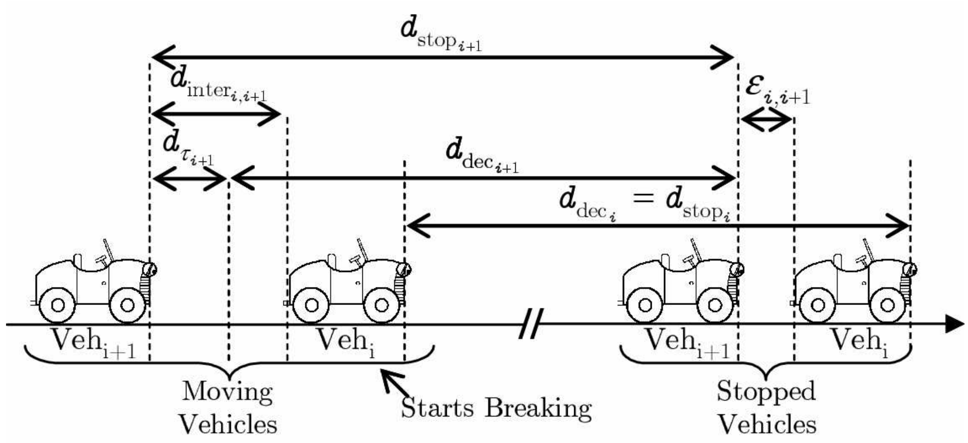

Fig. 1. Emergency Braking.

E. Conclusion

In this section, the capacity and severity measurements have been presented. These two concepts are dual (inversely related) [6]. The increase in the one implies a reduction in the other one. These notions will be used through all this paper in order to estimate the contribution of communications in a vehicles string.

III. Communications, a Basic Approach

A. Introduction

We remind that we want to evaluate the impact and the gain of communication systems in a vehicles string on the safety-capacity relation.

The aim of this section is to compare two formal expressions of the number of collisions obtained for a full or none equipped vehicles string. The considered scenario is the *brick wall* scenario (we assume a string of vehicles and a wall on the road). The leader vehicle collides the wall at full speed (it does not have the time to break) and in the case of an equipped string it emits a warning message to all other vehicles which are trying to avoid the collision. This scenario is the worst case scenario. Thus, we will be able to obtain two symbolic expressions of the number of collisions (one for 0% communications means and one for 100% communications means).

Several parameters can influence the safety and the capacity of the string. As we focus in this work only on the impact of the communication several assumptions are made (for the both approaches):

- Communications are considered ideal, *i.e.* latency time and jitter are null, no multi-path problem and signal range is infinite. Thus, when a vehicle emits a warning message, all other vehicles are informed instantaneously.
- When two vehicles collide, the length of the formed agglomerat is $2.l$ (no compression).
- The vehicles string is assumed to be homogeneous, for each vehicle i and j we have:
  - $l_i = l_j = l$
  - $m_i = m_j = m$
  - $\gamma_i = \gamma_j = \gamma$
  - $\tau_i = \tau_j = \tau$
  - $v_i^0 = v_j^0 = v^0$
  - $\Rightarrow d_{\text{dec}_i} = d_{\text{dec}_j} = d_{\text{dec}}$
  - $\Rightarrow d_{\text{stop}_i} = d_{\text{stop}_j} = d_{\text{stop}}$

  In the above assumptions, $l, v, \gamma, \tau, d_{\text{dec}}, d_{\text{stop}}$ are perfectly known.
  Moreover, $d^0_{\text{inter}_{i,i+1}} = d^0_{\text{inter}_{j,j+1}} = d^0_{\text{inter}}$ are also perfectly known (this will not be necessary for the second method).

B. All or None Communications Means

1) Presentation: We distinguish two cases.

- The first one is without communication technology. After having seen the brakes lights of the vehicle Veh_i, the driver of the vehicle Veh_{i+1} brakes after a reaction time (the first vehicle, Veh_1, starts braking when the driver (or an electronic system) sees Veh_0 collided the wall).
- The second one is with an ideal communication. When the first vehicle collides the wall, all other vehicles are informed. This scenario corresponds to a case where drivers can see the brakes lights of all the vehicles ahead them. When a driver is prevented, he brakes after his reaction time.

2) Without New Communication Technology: As the vehicles string is homogenous, when the front of the leader vehicle Veh_0 collides the wall at the time $t_{\text{collision}}$, the i^{th} vehicle is $(l + d_{\text{inter}}).i$ meters far from the wall. Let us imagine a mental representation where the i^{th} vehicle remains at the time $t_{\text{collision}}$ and the $(i-1)$ first vehicles are *virtually* going on. The braking of each vehicle is delayed of the reaction time for each vehicle. Thus, the reaction time effect is a cumulative effect. When Veh_i starts to break, $(i-1).\tau$ seconds were spent. Moreover, when the

$(i-1)$ first vehicles are *virtually* collided, the agglomerat is $i.l$ meters long. At last, the stop distance of Veh_i is $d\tau + d_{\text{dec}}$ meters. Therefore, Veh_i has to be at least at $d_\tau + d_{\text{dec}} + (i-1).d_\tau + i.l$ meters far from the wall at the time $t_{\text{collision}}$ to avoid a collision with the $(i-1)^{\text{th}}$ vehicle:

$$(l + d_{\text{inter}}).i \geq i.d_\tau + d_{\text{dec}} + i.l \tag{5}$$

As we can see on the previous inequation, without communication, reaction distances are cumulated $(i.d_\tau)$.

The minor i verifying the inequation (5) is:

$$i = \left[\frac{d_{\text{dec}}}{d_{\text{inter}} - d_\tau}\right], \tag{6}$$

with i the number of collisions (the brackets mean the integer part of the fraction) and $i+1$ the number of injured vehicles.

3) With an Ideal Communication Technology: Now, let us establish an ideal communication in the flow of vehicles. As all vehicles are equipped in communications means, when Veh_0 crashes against the wall it emits a warning message, thus all vehicles are informed.

Compared to the first case, we can notice that τ is not cumulated anymore.

Thanks to communications, reaction times appear as concurrent operation time. The effect is no cumulatif anymore. The equation (5) becomes:

$$(l + d_{\text{inter}}).i \geq d_\tau + d_{\text{dec}} + i.l. \tag{7}$$

Therefore, the number of collisions is:

$$i = \left[\frac{d_{\text{dec}} + d_\tau}{d_{\text{inter}}}\right]. \tag{8}$$

4) From the Number of Collisions to the Safety Index: From the number i we define the safety S as following:

$$\boxed{S = \frac{\text{Nb}_{\text{Veh}} - i}{\text{Nb}_{\text{Veh}}} * 100} \tag{9}$$

Since $i \in [0, \text{Nb}_{\text{Veh}}]$ (it can not happen more collisions than the number of vehicles), the safety index is normalized: $S \in [0, 100]$.

5) Application: Using the equations (6) and (8), we are able to plot the safety-capacity relation for an unequipped and a full equipped vehicles string. For this application, we consider these following parameters:

- Vehicle velocity: $v_i = 36.1$ m/s (130 km/h).
- Vehicle braking capacity: $\gamma = 0.8$ g.
- Vehicle length : $l = 5$ m.
- Reaction time: $\tau = 1$ s.
- Capacity: $c \in [1800, 3200]$ veh/h.

As we can see on Fig. 2, the safety index of an unequipped string decreases drastically when the capacity increases. At the opposite, when an ideal communication is achieved, the safety index remains very good for this capacity range. Of course, this result is obtained using

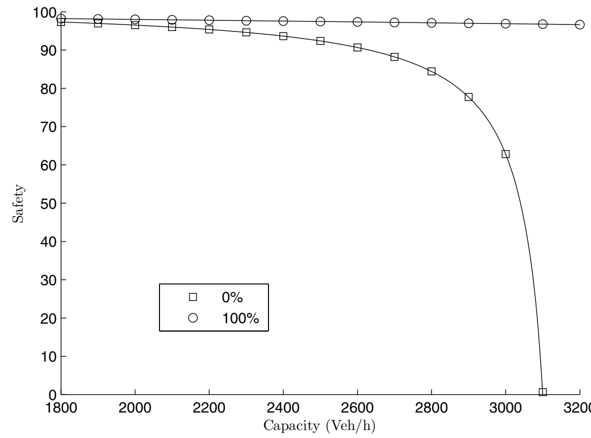

Fig. 2. Safety-Capacity relation with a full or a none equipped homogenous string of vehicles. The safety criteria is based on the number of collisions

several hypotheses but it allows to see a first contribution of warning communications in the safety-capacity relation.

C. Conclusion

This first approach shows the gain in number of collisions in an uniform vehicles string with an obstacle on the road thanks to communication contribution. But, this method can only take into account collisions which happen in the order. By this way, we can not manage partial communication equipment cases. Indeed, as the warning information is propagated faster than the braking shock wave, if a vehicle Veh_j is equipped in communications means whereas Veh_i is not (with $j > i$), Veh_j may brake before Veh_i. Thus two shock waves are generated and then collisions can potentially appear in disorder.

IV. Communications, a More Generic Framework

A. Presentation and Simulation Principle

The previous study has two main limitations. Firstly, it can only take into account collisions which happen in the order. The second limitation (in fact a consequence of the first one) is that we can not study a partial communication technology equipment and we can not study a string with a non-uniform repartition of the vehicles.

The aim of this section is to analyse the gain in safety - capacity thanks to the use of a partial communication. Car manufacturers are interested in the following question: "*Do we have to wait until 100% of vehicles are equipped to have satisfactory results ?*" or more precisely "*Which percentage of equipment do we need to obtain a significant amelioration of the safety*".

This second approach is a numerical method and allows to consider a non, partial or full equipped vehicles string.

As we have a partial communication equipment of the string, we have to elect the vehicles which are equipped in communication means. This selection is achieved through a random draw according to an uniform distribution law. Then we run the simulation. The first equipped vehicle which brakes (which is not necessarily the first vehicle of the string) emits a warning message to all other equipped vehicles instantaneously. Then these last ones brake after the reaction time τ.

The assumptions made in this second approach are very close to the first approach ones. The vehicles string is still homogenous (all vehicles have the same weight, length, reaction time…) but, the hypothesis on interdistances is disable. We set randomly several vehicles repartition from the homogenous string to the platooned string. To perform that, we assume that vehicles are located on average at least at a reaction distance. The interdistance is the reaction distance ($\tau.v$) increased of a security offset $\varepsilon \geq 0$. This interdistance between Veh_i and Veh_{i+1} ($\tau.v+\varepsilon$) is noised by a centered gaussian noise $\delta_{i,i+1}$ with a σ standard deviation:

$$\begin{aligned} d^0_{\text{inter}_{i,i+1}} &= \tau.v + \varepsilon + \delta_{i,i+1} \\ &= d_\tau + \varepsilon + \delta_{i,i+1} \end{aligned} \qquad (10)$$

with:

$$\delta_{i,i+1} \rightsquigarrow \mathcal{N}(0,\sigma)|_{[-d_\tau-\varepsilon, d_\tau+\varepsilon]}$$

As the jitter is centered, the mean density of the vehicles string is constant (it does not depend of the jitter rate). In this way, considering a density and using the equation (10), we can easily build different strings with different local configurations of vehicles repartitions. Then we will take into account only the most unfavorable jitter (*i.e.* the jitter causing the low safety index.

B. Simulation Results with a Safety Criteria Based on the Number of Collisions

The Fig. 2 shows the safety-capacity tradeoff for a full or none equipped vehicles string. Thanks to the new simulations, we are now able to plot this relation for different penetration ratio of the communication technology. The Fig. 3 shows the tradeoff for 0%, 5%, 25%, 50%, 75% and 100% of equipped vehicles considering an homogeneous string.

Now, for the same capacity, we want to plot the safety-capacity tradeoff for the most unfavorable vehicle spatial repartition. The Fig. 4 shows the safety-capacity curves for the worst case evaluation.

C. A New Safety Index

1) Introduction: As we saw in the previous Section III, under several hypotheses, the number of collisions can be easy to obtain. But this index is not a very relevant safety criteria. Indeed, this criteria does not include a severity evaluation of the shock. For instance, it is more advisable to manage a collisions mitigation *i.e.* to have several weak collisions (where no body is injured) than a huge one (where people are injured). In this case the number of collisions is increased but the safety is also.

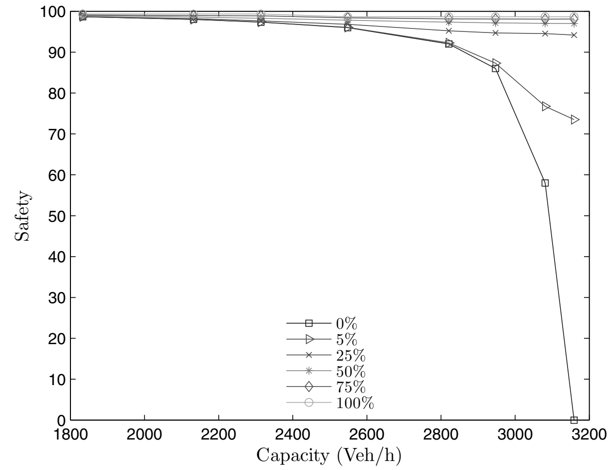

Fig. 3. Safety-Capacity relation for a homogenous string of vehicles. The relation is plotted for different ratio of penetration of the technology of warning communication. The safety criteria is based on the number of collisions

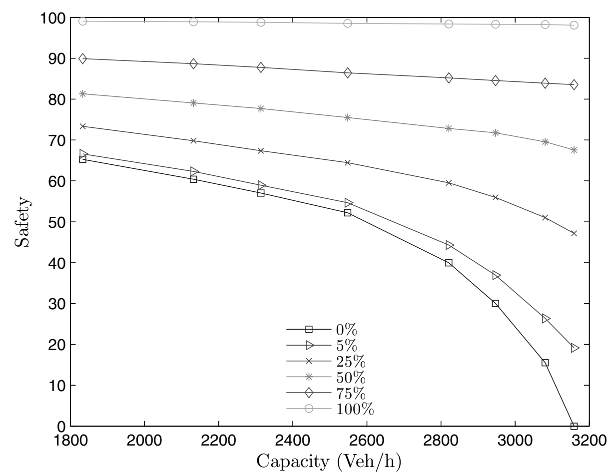

Fig. 4. Safety-Capacity relation for string of vehicles where vehicles are not regularly spaced. Only the most unfavorable repartition are taken into account. The relation is plotted for different ratio of penetration of the technology of warning communication. The safety criteria is still based on the number of collisions

Moreover, as we focus our works especially on the safety of the drivers we are using the average severity per collision as safety criteria. We want to minimize the risk for an human to be killed or severely injured. To compute a such index, we need to be able to quantify the severity of the shock for an human body. This is the purpose of the two following subsections.

2) Equivalent Energy Speed: The severity of a shock depends of the relative velocity between the two vehicles and also of their weights.

Considering the system $\{\text{Veh}_i, \text{Veh}_{i+1}\}$, if we assume that the external forces are negligible during the shock

ees ranges in km/h	<25	35	45	55	65	75	85	>85
percentage of $\sim$ persons	0	2	10	30	55	80	95	100

TABLE I
SHOCK SEVERITY WITH RESPECT TO THE *ees*

(just before and just after the collision) in respect to the internal forces, we can write the impulse conservation principle:

$$m_{i+1}.v_{i+1} + m_i.v_i = m_a.v_a \quad (11)$$

where the suffix 'a' indicates the two vehicles agglomerated after the collision. The agglomerat hypothesis is a strong assumption. This can be justified by the fact that when the collision occurs between Veh_i and Veh_{i+1}, Veh_i is breaking at this moment. So, the collision looks like a pile-up and vehicles tend to remain together.

More over, if we assume that there is no matter loss ($m_a = m_{i+1} + m_i$) during the shock, we express the velocity v_a of the agglomerated vehicles only with parameters of Veh_i and Veh_{i+1} as following:

$$v_a = \frac{m_{i+1}.v_{i+1} + m_i.v_i}{m_{i+1} + m_i}. \quad (12)$$

From this step, we can compute the variation (before and after the collision: $v_{i+1} - v_a$) of velocity for the $(i+1)^{\text{th}}$ vehicle. This value is called *equivalent energy speed* (*ees*):

$$\boxed{ees_{i+1} = (v_{i+1} - v_i)\frac{m_i}{m_i + m_{i+1}}} \quad (13)$$

Regarding the severity, this means that it is equivalent for Veh_{i+1} to collide a wall at the velocity ees_{i+1} than to collide Veh_i (with v_i and m_i parameters) at the velocity v_{i+1}. By the same way we are able to compute ees_i.

The *ees* generalizes the crash representation between two vehicles in comparison to the crash of a vehicle against a wall.

3) From the Equivalent Energy Speed to the Safety Index: The *ees* measurement is very useful to evaluate the violence of a shock, but it is not very relevant about the severity for an human body.

The Table I summarizes data provided by the LAB[1] [9]. These data express the percentage of killed and severely injured persons depending of the *ees* range.

Making a linear interpolation of the data given in the Table I, we obtain a *transfer function* f (Fig. 5). If we report the *ees* through this transfer function, we are able to quantify the severity S_e of a collision for a human being.

$$S_e = f(ees). \quad (14)$$

[1]LAB: PSA-Renault Accidentology and Biomechanic Laboratory (Laboratoire d'Accidentologie et de Biomécanique du GIE PSA-Renault)

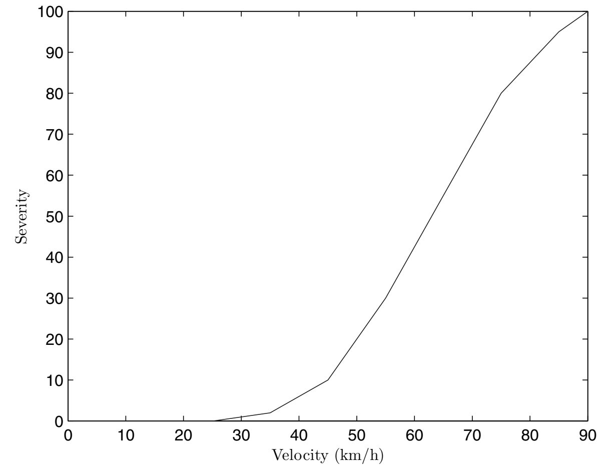

Fig. 5. Shock Severity with Respect to the *ees*

The severity index is normalized between 0 and 100. We define the safety index S as following:

$$S = 100 - S_e, \quad (15)$$

$$\boxed{S = 100 - f(ees)}. \quad (16)$$

4) Conclusion: Thanks to the computation of the equivalent energy speed and to the data provided by the LAB, we are able to compute the severity of a shock for an human body. The limit of this method is that we consider the violence only at the impact between two vehicles. After this impact we assume that vehicles are agglomerated and that no complications appear.

D. Simulation Results with the ees Based Safety Criteria

We focus on the worst case evaluation. This is meaning that, according to a given capacity, we consider the most unfavorable vehicles repartition (which is causing a maximum of gravity). To do this, we generate different strings from the homogeneous string to the string in platoon. We run several simulations with different capacities and different communications equipment rates.

For the simulations, we take the same parameters than in the previous application:

- Vehicles velocity: $v_i = 36.1$ m/s (130 km/h).
- Vehicles braking capacity: $\gamma = 0.8$ g.
- Vehicle length : $l = 5$ m.
- Reaction time: $\tau = 1$ s.
- Capacity: $c \in [1800, 3200]$ veh/h.

After each simulation we consider only the highest value of the average gravity (worst case).

The Fig. 6 has two interpretations. For a constant safety, the use of communication allows to increase the capacity, and, reciprocally, for a constant capacity, the use of communication allows to increase the safety.

For a low capacity of vehicles, communications contribution is not efficient. The higher is the capacity, the more efficient are communications, which is a good point against congestions.

Moreover, it appears that this new safety index is more relevant. Indeed, Fig. 4 and Fig. 6 represent the worst case evaluation according respectively the safety index based on the number of collisions and the safety index based on the *ees*. It appears, that the first safety index is pessimist. For instance for a capacity of 1800 Veh/h considering a 0% equipped string, the safety is estimated at 65. In fact there is some collisions but the severity of these ones are low. Thus, for the same condition, the new safety index estimates the severity at nearly 100.

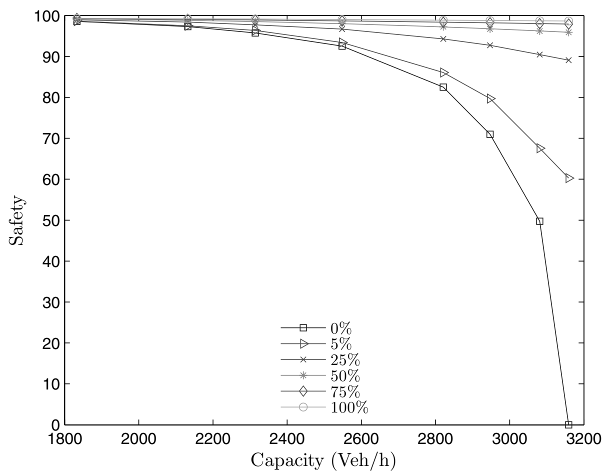

Fig. 6. Worst case evaluation of the safety-capacity relation. The safety criteria is based on the *ees* approach

V. General Conclusion

This article focuses on the impact of communication applied in a vehicle string. After having presented the safety and capacity concepts, two approaches were presented. The first one studies the number of collisions by an analytic form of an homogenous vehicles string with a none or a full communication equipments. The second approach achieves this study in a more general framework. In this approach, there are no equi-repartition of the vehicles anymore. Only the most unfavorable spatial repartition for a given capacity is taken into account. The study analyzes the impact of a partial equipment on the safety-capacity relation. This study allows to estimate which percentage of vehicles we have to equip in order to modify the safety-capacity tradeoff. As the problematic is very complex, this study has been done with strong assumptions. The further objectives are to simulate a very realistic string of vehicles (different reaction times, different lengths. . .) and to manage multi-lanes, including inter-lane movements.

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