The Traffic Management of Highways by Constant Time to Collision Cruise Control

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Abstract: The paper presents a new method of management and optimization for the highway traffic, based on the Constant Time to Collision Criterion. Each car is provided with a constant time to collision cruise controller, which is maintaining optimized distance gaps between cars, with respect to the speed and to the technical data of the cars. These cruise controllers are planned fuzzy-interpolative PD controllers designed with the help of functional computer models of the cars, following a specific scenario that is containing several complete braking actions performed for different constant times to collision. The highway administration has the possibility to control the traffic flow intensity by imposing the same TTC to all the cars: great TTCs for low traffic, small TTCs for high traffic. The CTTC controlled traffic is distributing evenly the collision risk over all the cars.

Keywords: cruise control, planned controllers, fuzzy-interpolative controller, constant time to collision.

1. Introduction

Logistics is the management of the flow of goods, information and other kind of resources, including energy and people, between the point of origin and the point of consumption, in order to meet the consumers' requirements. Logistics involves the integration of information, transportation, inventory, warehousing, material-handling and packaging. This paper is dealing with a new optimization method for the highway traffic. This method is a result of the solving of a theoretical issue: the definition of a novel optimal distance gap between cars on highways.

The Intelligent Transportation Systems enable cars to "think." Within this field there are many subdivisions like freeway management, electronic payment for tolls, and road and weather management. A set of facilities with different degrees of implication in the driving action is introduced by the Advance Driver Assistance Systems (ADAS) [1, 2], etc. ADAS are systems to help the driver in its driving process. When designed with a safe Human-Machine Interface it should increase car safety and more generally road safety. Examples of such a system are:

- The Adaptive Cruise Control (ACC), very close to the Intelligent Cruise Control (ICC) uses either radar or laser devices to allow the vehicle to slow when approaching another vehicle and accelerates again to the preset speed when traffic allows. ACC technology is widely regarded as a key component of any future generations of smart cars.

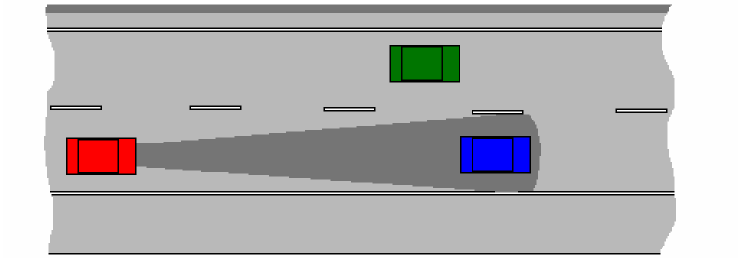

Figure 1. Following ACC cars on highway

- The Collision Warning System is a system of sensors that is placed within a car to warn its driver of any dangers that may lie ahead on the road. Some of the dangers that these sensors can reveal include how close the car is to other cars surrounding it, how much its speed needs to be reduced while going around a curve, and how close the car is to going off the road.
- The Intelligent Speed Adaptation or Intelligent Speed Advice (ISA) are systems that constantly monitor the local speed limit and the vehicle speed and implements an advice or an action when the vehicle is found to be exceeding the speed limit.
- In-vehicle navigation systems with GPS and TMC (Traffic Message Channel) for providing up-to-date traffic information.
- Lane/road departure detection/warning system
- Lane departure warning
- Lane change assistance
- Night vision
- Adaptive light control
- Pedestrian protection system
- Automatic parking
- Traffic sign recognition
- Blind spot detection
- Driver drowsiness detection

- Car to car communication
- Hill descent control, etc.

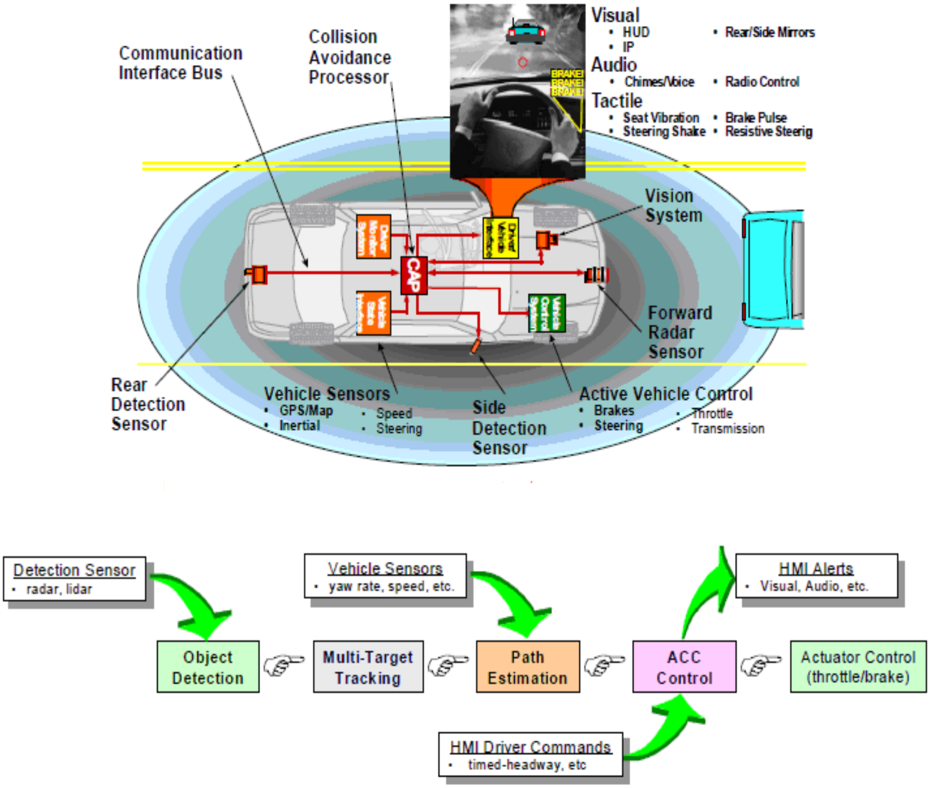

Figure 2. ACC signal processing architecture [5]

Yet, despite the safety benefits: enhanced driving performance and minimization of crash risks, reduced driver stress and fatigue, reduced conflicts and variance in behavior, etc. the effective put in practice of these developments will have to wait. The causes are economic, namely the high costs demanded by the infrastructure and the equipment installed on each car, but also technical. Automate driving is likely to produce at its turn safety risks by the driver distraction and reduced situation awareness, causing in time the reducing of the driving skill. But above all, any automate intervention into the car's operation can cause instinctive and inopportune reactions of the driver. That is why automate driving applications will probably face a transition period. A common sense approach assumes a gradual introduction of the automate features and the abortion of the automate mode at the slightest human intervention. The only ACC achievement that reached a certain popularity in the field of the automate driving, namely in the case of the following cars, is shown in Fig. 3.

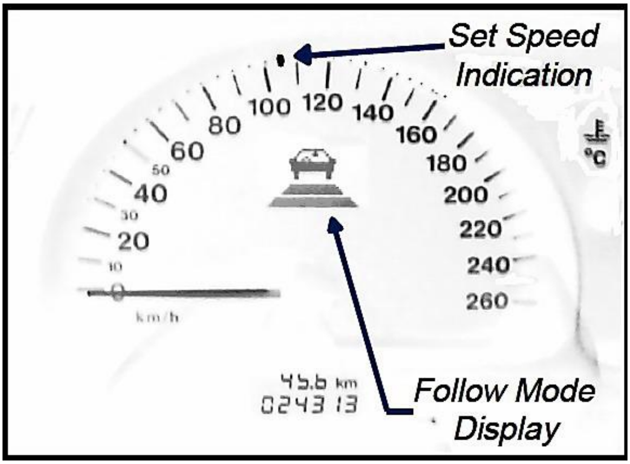

Figure 3. ACC human-machine interface

If several cars are running in the following car mode they may form platoons. Our interest is focused on the highway car platoons, whose importance is expected to grow along with the predictable constant increasing of the traffic flow. One of the essential parameters of this system is the distance gap between the following cars, which must be perfectly adapted to the speeds of the cars v1 and v2 and to the traffic conditions.

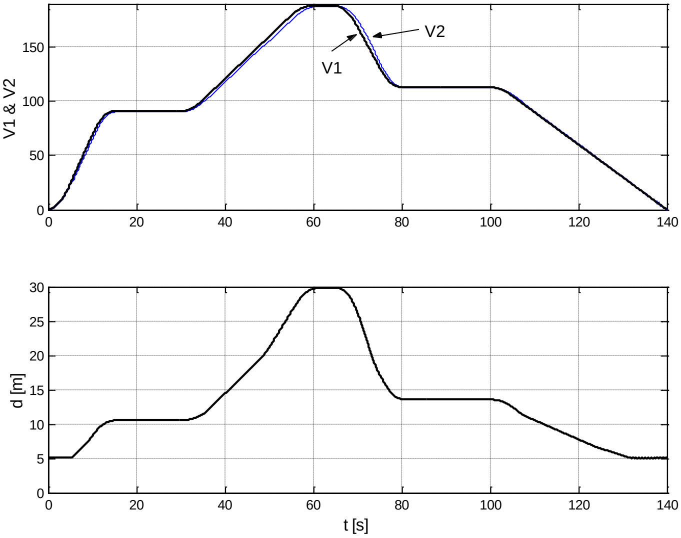

Figure 4. The car following mode

2. Measuring the Highway Traffic

Several indicators were introduced in order to measure the characteristics of the traffic flow [1, 2]:

- the time-to-collision (TTC)
- the time-to-accident (TTA)
- the post-encroachment-time (PET)
- the deceleration-to-safety-time (DTS)
- the number of shockwaves, etc.

TTC is the time before two following cars (Car2 is following Car1) are colliding, assuming unchanged speeds of both vehicles [1, 2]:

$$\mathrm{TTC} = \frac{d}{v_2 - v_1} \tag{1}$$

Negative TTCs implies that Car1 drives faster, i.e. there is no danger, while small positive TTCs are leading to unsafe situations. Fig. 5. is illustrating the evolution of the TTC during a car following regime.

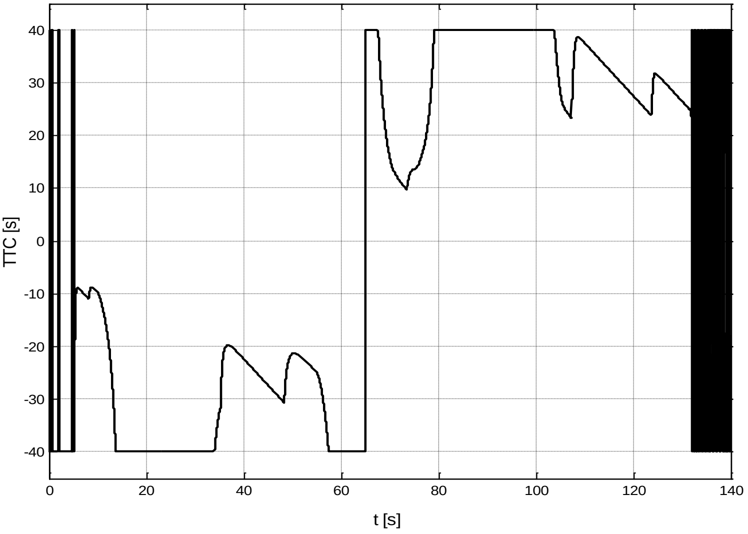

Figure 5. The TTC evolution during the following car mode

However, in Fig. 5. the TTC diagram is bounded at ±40s, because when v2 = v1 TTC becomes infinite! That is why very often another tool is preferred to TTC: the d(v2 – v1) trajectory.

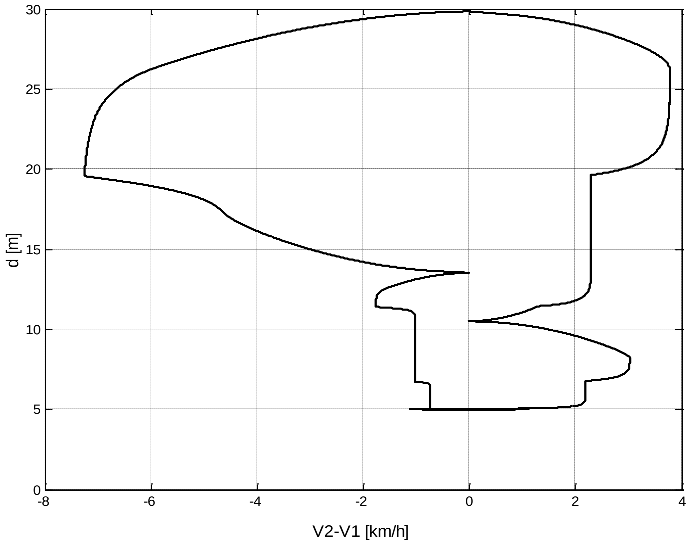

Figure 6. The d(v2 – v1) trajectory

Because d(v1 - v2) is not very suggestive when evaluating the collision risk, the Inverse Time to Collision TTC-1 was introduced [8]. TTC-1 is illustrated in Fig. 7.

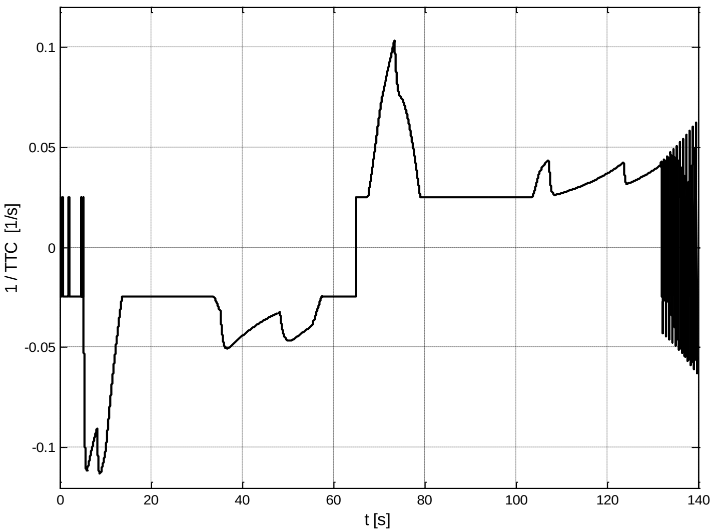

Figure 7. The time evolution of TTC-1

TTC-1 is proportional to the collision risk: the higher is TTC-1 the higher is the risk. Negative TTC-1s have the same significance as negative TTCs. A non-sensitive zone is appearing close to TTC-1 = 0s-1 corresponding to the TTC's saturation.

The TTC-1(v1 - v2) trajectory may be used as an indicator of the collision risk. The significant risk zones are pointed with fuzzy linguistic labels and with appropriate colors that are easily perceived by the driver, as shown in Fig. 8.

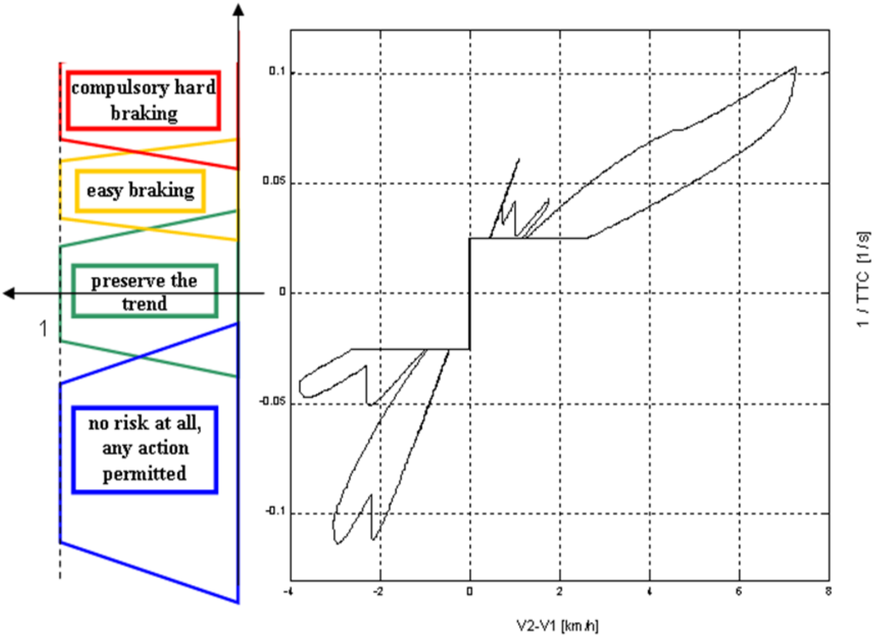

Figure 8. A TTC-1(v2 – v1) trajectory and a corresponding fuzzy partition assisting the driver

3. The Constant Time to Collision Criterion

A central issue in cars' safety is to impose an appropriate distance between cars di. ACC is imposing a particular polynomial di(v2) law [1]:

$$di(v2) = z0 + z1 \bullet v2 + z2 \bullet v22 = 3 + z1 \bullet v2 + 0.01 \bullet v22 \qquad (2)$$

Several settings are recommended, for example z1 = 0.8s or z1 = 0.6s. The parameters z1 and z2 are artificially introduced, they have no significance for humans - highway operators or drivers - and they are not linked to the physical features of the system.

The Constant Time to Collision criterion CTTC consists in imposing stabilized TTCs by means of the Car2 cruise controller. Applying CTTC brings two obvious advantages:

- an even sharing of the collision risk for each vehicle involved;
- the possibility to control the traffic flow on extended road sections, if each vehicle will apply the same TTC that is currently recommended by the Traffic Management Center [9]: a long TTC means low traffic flow and higher safety while a short TTC means high traffic flow and higher risk.

The on-line TTC control is not convenient because when the two cars have the same speed the denominator of TTC is turning null: v2-v1=0. That is why CTTC must be implemented off-line, with the help of di(v2) mappings in the sense of the planning systems [4]. The CTTC implementation by di(v2) distance-gap planners is possible because a distance gap planner using TTC will produce CTTC. We studied this method by computer simulations, using a Matlab-Simulink model of the tandem Car1-Car2, introduced in other previous papers [6], [7], [8], [9], etc. Since the design of the planners is made with the help of functional models of the cars, accurate knowledge about the behavior and parameters of each car (traction and braking forces, weight, aerodynamic coefficient, etc.) can be taken into account, which is not possible to the simplified and leveling analytic model (2). This method imposes to the car manufacturers to provide each type of automobile with a computer model.

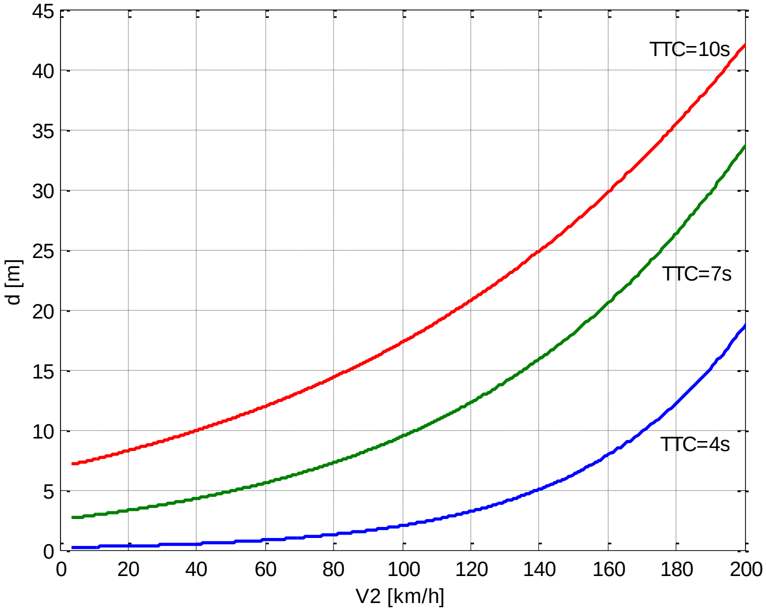

Figure 9. The di(v2) mappings for three different TTC

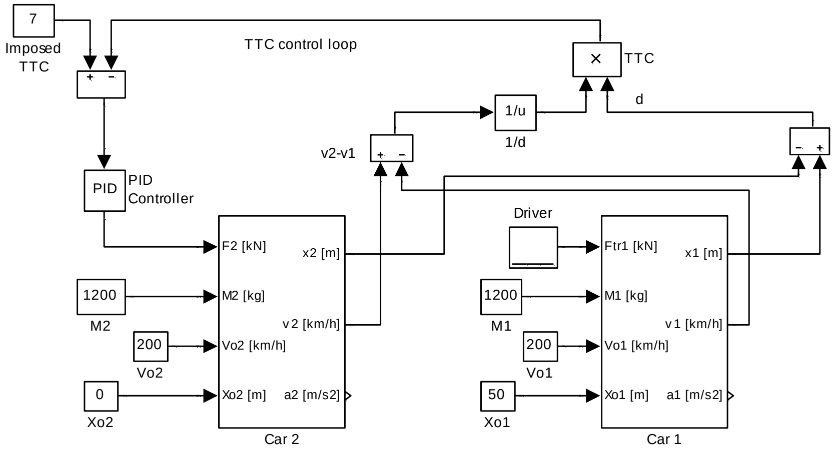

Figure 10. The SIMULINK-MATLAB model of the tandem Car1-Car2

The distance-gap planners are designed with the help of the computer model of Fig. 10. The simulation scenario consists in braking Car1 until the car is immobilized, starting from a high initial speed. A TTC controller is driving the Car2 traction/braking force such way that during the whole simulation TTC is stabilized to a desired constant value. The continuous braking allows us to avoid the v2-v1=0 case because the cars are not reaching at all the steady regime. We will use the recorded d mapping as the desired di(v2) planner for the given TTC. The Fig. 9. planners are set for three TTCs values: 4s, 7s and 10s. These planners can be easily implemented by look-up tables with linear interpolation [6].

4. The Planned Fuzzy-Interpolative Cruise Controller

For the time being we tested by simulations, with very good results, only a minimal version of the CTTC cruise controller, a PD fuzzy-interpolative one, as shown in Fig. 11.

The 2D look-up-table that is implementing the controller is the following:

Row (distance error): [-10 -5 0 5 10]
Column (error derivate): [-10 0 10] (3)

Output: [-1 -1 -1; -1 -0.3 0; -0.2 0 0.2; 0 0.3 1; 1 1 1]

This controller is extremely simple and has multiple tuning options: the look-up-table values as well as the input and output scalar factors. Any usual programmable control device used in the automotive industry can do this implementation.

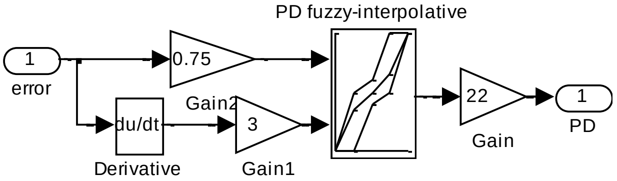

Figure 11. The PD fuzzy-interpolative cruise controller

5. The Constant Time to Collision Platoons

The current trend of the intelligent transportation developments seems to lead us towards the platoon concept. If structured into platoons the highway traffic could be optimized, the same infrastructure could be more efficiently exploited and the traffic safety could be improved. A platoon is a group of cars leaded by the first one, which is choosing the speed and the direction. We can easily imagine the advantages of a traffic structured into large platoons leaded by safety cars driven by professional drivers. Each other member of the platoon has only to follow the previous car as close as possible, with respect to all the traffic safety requirements. The essential problem of a platoon is the choice of the aggregating law that is governing its formation and evolution. The formula (2) can stand as a platoon aggregating law, if each car is respecting it. Another approach was proposed in ref. [1]: the platoon is considered as a virtual train, the connections between the participants acting like elastic springs. Different approaches are possible: non adaptive or adaptive, aiming the velocity, the distance gap and/or the acceleration. Our choice, the CTTC platoon, is an adaptive distance tracking solution.

The CTTC platoons are highway cars formations composed by automobiles provided with CCTC cruise controllers. Fig. 12. is illustrating the Matlab-Simulink model of a five car platoon that was used for the simulations. As one can remark, each car has its own specific technical parameters: weight, power, brakes, etc.

The next figures are illustrating the behavior of this platoon, for a generic simulation scenario, presented in Fig. 13. The scenario is imposing plausible variations of the speed and of the imposed TTC. It is to remark the notable TTC step that appears for t = 470…500s, that has the purpose to test the dynamics of the CTTC cruise controllers. Such fast variations of the imposed TTC are not recommendable during the usual exploitation.

Besides the demonstration of the CTTC principle, the following simulations compare two possible cruise controllers: the (3) PD fuzzy-interpolative controller and a conventional linear PID one. As expected, the nonlinear PD fuzzy-interpolative one (see Fig. 16.) is much more convenient than the PID (see Fig. 15.).

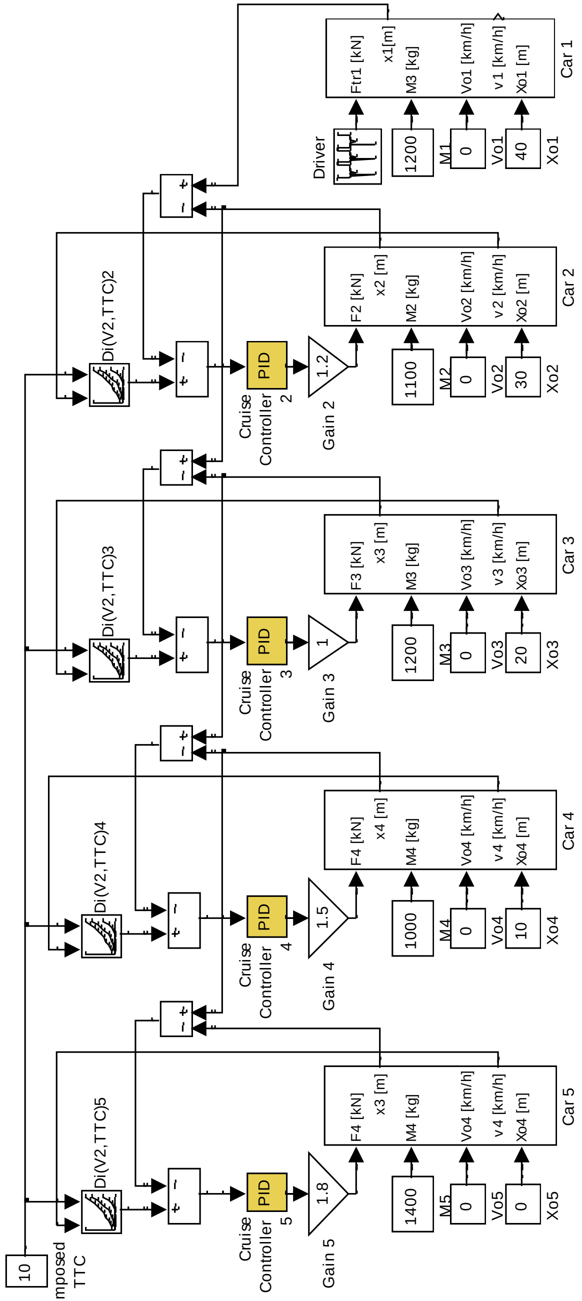

Figure 12. The SIMULINK-MATLAB model of a five car CTTC platoon

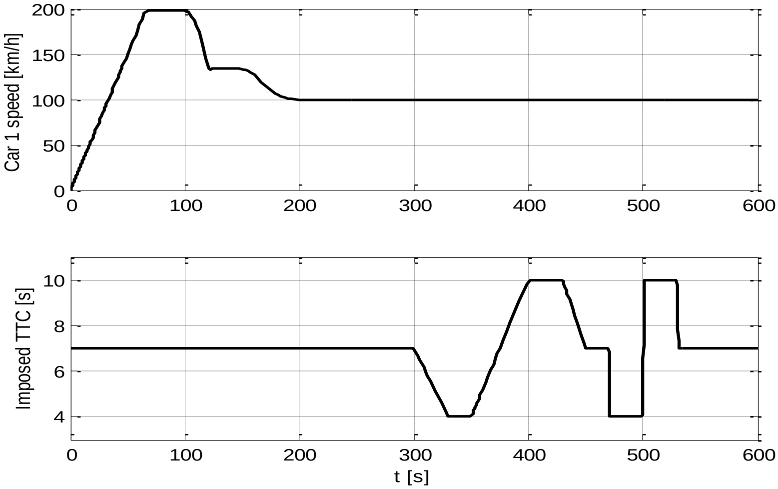

Figure 13. The simulation scenario

The two controllers are acting very similar for slow or normal changing velocities or TTCs. On the other hand the linear PID is producing higher oscillations when the parameters are changing faster (t=470s and t=500s) and especially in the transient regime of the platoon's formation (Fig. 15. and Fig. 16.).

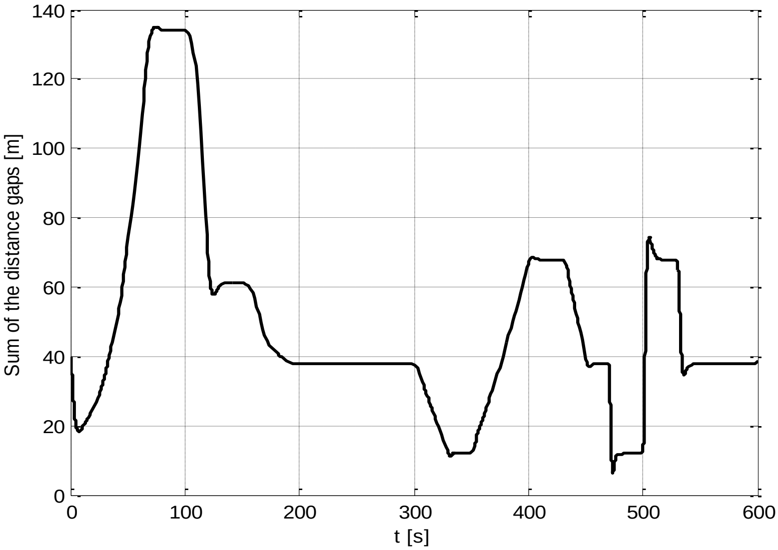

Figure 14. The sum of the distance gaps of the platoon (PD fuzzy-interpolative)

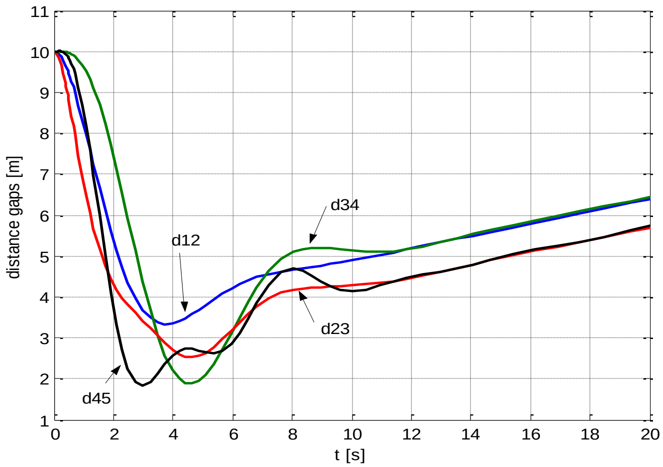

Figure 15. The formation of the platoon (linear PD, for comparison)

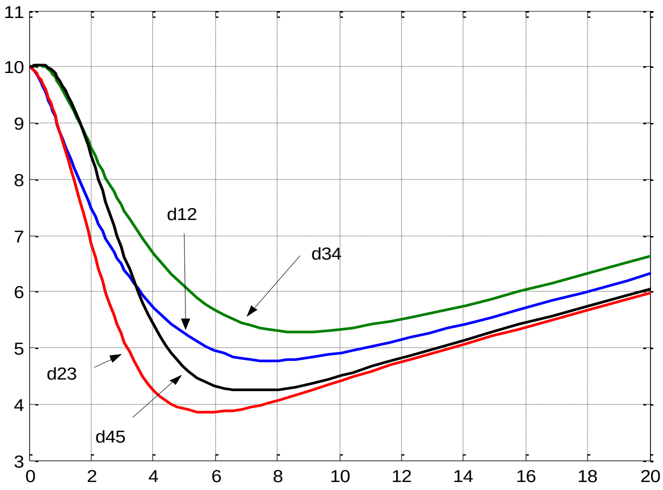

Figure 16. The formation of the platoon (using the PD fuzzy-interpolative controller)

6. Conclusions

The Constant Time to Collision Criterion CTTC is an optimization criterion that, in the case of two following cars, is imposing a particular distance gap, such way that the time to collision between cars is constant for any speed of the following car. If each car is equipped with a CTTC cruise controller and they share the same TTC then CTTC platoons are forming. The whole traffic flow can be controlled if the traffic management center of the highway can impose the same TTC to all the cars. The smaller the imposed TTC is, the smaller the distance gaps between cars will be, and the higher the traffic flow and the collision risk will be. The collision risk is evenly distributed over all the platoon's cars. The highway system becomes distributed, each car trying to reach and to maintain the position that respects the imposed time to collision to the previous car.

The CTTC cruise controllers may be conveniently implemented by PD nonlinear controllers (fuzzy-interpolative for instance). Besides the simplicity and the advantageous interpolative implementation, all the TTC based tools have a common feature: they are extremely well adapted to the changing traffic conditions because they are embedding precise knowledge about the technical data of the automobiles thanks to the functional computer model that stands behind their design.

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