Road Safety at Intersections Controlled by Traffic Lights
IVC and Risk Indexes

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Keywords: ADAS, Safety Index, Intersection Safety, Driver Reaction Time.

Abstract: The paper reports the results of safety analyses conceived to assess the effects and benefits which might be generated by the forthcoming use of the infrastructure-to-vehicle (I2V) or vehicle-to-infrastructure (V2I) communication systems at road intersections regulated by traffic lights. Road crossings are often considered as critical areas for the occurrence of accidents, because they increase the likelihood of the event given the confluence of traffic streams from and to different directions. The analyses are aimed at calculating a real-time estimate of some risk indexes of accident, which might be provided on-board when approaching road intersection regulated by traffic lights. This information can then be used by an ADAS for traffic signal approaching. Two typologies of use of the information on the risk indexes can be identified: if data can be detected in real time, the driver could be informed on-board of a potentially hazardous situation using algorithms to predict the trend of the vehicle on the basis of the data detected from the monitoring; another use would be detecting – in case the vehicle were already within the dilemma zone – the lowest risk manoeuvre and sending a message on board to inform the driver.

1 INTRODUCTION

Quantifying the road safety risk and the effects that the Advanced Driver Assistance Systems (ADAS) can generate on it – i.e. the combined value of reducing the likelihood of an accident and its severity – is a very sensitive theme, which can today resort to the infrastructure-to-vehicle and/or vehicle-to-vehicle communication systems. Together with the interest towards the quality and energy efficiency of transport, safety is contributing to the fast spreading of Intelligent Transport Systems (ITS), which include – amongst the different technologies – the ADAS. Such perspective is part of the migration – which has been in progress for years – from the mere passive safety to the study of systems, tools and applications which can ensure active, preventive and post-crash safety.

Within this context, attention is progressively concentrating on the cooperative systems, which can interact to one another, thus setting up communication between the different vehicles (Vehicle–to–Vehicle, V2V) or between the vehicles and the infrastructures (Vehicle-to-Infrastructure, V2I, or Infrastructure-to-Vehicle, I2V) to create *ad hoc* communication networks. This paper focuses on the effects of integrating such communication systems with the ADAS with the aim of improving road safety; special attention is paid to the safety of the road users, in order to reduce both the number and severity of the road accidents. The communication technologies between vehicles and between infrastructure and vehicle are suitable to intervene at the pre-crash stage, i.e. in emergency - assistance, where the action of the driver could still prevent the accident or reduce its risk.

It worth reminding a basic definition of crash, slightly reviewing the one which was proposed in Dalla Chiara, Deflorio and Diwan (2009): the crash phase of an accident occurs when the perception-reaction time of a driver plus the time necessary to actuate the procedure (e.g., braking) of the vehicle he/she is driving is greater than or equal to the time involved by the exogenous variation that occurs outside the vehicle; such a perception-reaction time of the driver plus that of the vehicle is therefore the maximum time available for the driver to respond to an emergency condition on the road and prevent an accident.

The road intersections are often considered as critical areas for the occurrence of crashes, because they increase the likelihood of the confluence of

Dalla Chiara B., Deflorio F. and Cuzzola S..
Road Safety at Intersections Controlled by Traffic Lights - IVC and Risk Indexes.
DOI: 10.5220/0004165105690577
In *Proceedings of the 9th International Conference on Informatics in Control, Automation and Robotics* (IVC&ITS-2012), pages 569-577
ISBN: 978-989-8565-22-8

traffic streams from and to different directions.

2 STATE OF THE ART

During the last years, car manufacturers and researchers experimented many ADAS (MacNeill, and Miller, 2003); (Maile and Delgrossi, 2009). These systems are in-vehicle technologies that provide support to various aspects of the driving task and they are supposed to improve traffic safety and traffic efficiency. In this field, the most famous and deployed ADAS systems are the adaptive cruise control (ACC) and the intelligent speed adaptation (ISA), collision avoidance systems, adaptive light control, lane departure warning, driver vigilance monitoring, pre-crash vehicle preparation and parking aid (Tapani, 2009); (Monteil et al., 2011).

In order to estimate the future impact of the ADAS development process from its very early stages, some studies were based on the use of microscopic traffic simulation. Torday et al. (2003) proposed to integrate the output of this tool with a safety indicator, evaluated during the micro simulation process. The microscopic level of traffic description grants the opportunity of knowing the relative position of the vehicles, their speed and deceleration. All of these parameters thus enable the computation of a safety indicator useful to compare scenarios where ADAS are activated for vehicles. Other authors (Morsink et al., 2008) provide an overview of micro-simulation modelling for road safety impact assessment of ADAS. Recent literature and expert opinions identify driver behaviour sub-models and road safety indicators as key components. In Benz et al. (2006), several existing models – on both the micro and macro scales – would be adapted and used to assess safety related effects of ITS measures. Examples of such measures include but are not limited to ADAS and IVIS. While the micro-models would determine the individual vehicles' safety related behaviour, the macro-models would investigate the network-wide aspects.

In order to enhance the performance of micro simulator for safety analysis, a Surrogate Safety Assessment Model (SSAM) has been developed (US DOT-FHWA, 2009). This technique combines micro simulation and automated conflict analysis, which analyses the frequency and type of narrowly averted vehicle-to-vehicle collisions in traffic, to assess the safety of traffic facilities, without waiting for a statistically valid number of crashes and injuries to actually occur. Applications of this method to road intersection scenarios are reported in Gettman and Pu (2006), Klunderet al. (2006) and Ki-Joon and Jaehoon (2009). An assessment of the driver behaviour at dilemma zone (Liu, Herman and Gazis, 1996) and of the effectiveness of safety indicators based on the traffic conflict technique at intersection is reported in Archer (2005) and Hurwitz (2009).

Recent international research projects have been investigating both vehicle-based and road-based monitoring. The European projects SAFESPOT, COOPERS, CVIS and COVEL aimed at improving road safety by using intelligent vehicles interconnected to each other through a vehicular ad-hoc network (VANET).

As regards the V2V and V2I communication systems and their relationships with safety and ADAS, they are a primary means for supplying information to drivers. In recent years, V2V and V2I communication systems have been submitted to intensive studies, also applied to safety at intersections (INTERSAFE-2).

In this field, FOTSIS was a large-scale field testing of the road infrastructure management systems needed for the operation of seven close-to-market cooperative I2V, V2I & I2I technologies (the FOTsis Services), which allowed assessing in detail both their effectiveness and their potential for a full-scale deployment in European roads.

We need to recall that the response time of a driver can be split into a mental processing and reaction time and a muscular time . The former includes the time from the perception of the external stimulus to the brain's message to the foot to brake. This implies the awareness of the hazard, the emotive response and the reaction itself. The muscular reaction time is needed for the right foot to move onto the brake pedal. The driver's reaction time is influenced by quick or slow reflexes, by his/her experience as well as by the complexity of the dangerous scenario that has to be faced. On the basis of tests and literature, the median perception-reaction time of a driver results to be 0.66s, measured under normal highway driving conditions, with some degree of braking expectation, since the drivers were expecting the event to happen. From the moment the driver puts his/her foot onto the pedal, almost 0.1s pass (inertia of the system) before the brake starts operating; this value may increase to 0.4s in the case of slow and older braking equipment.

The diagram reported in Johansson and Rumar (1971), as well as on ISO technical standards and in Dalla Chiara et al. (2009), in revised editions, represents the distribution of a driver's brake

perception-reaction time between 0.2 and 2.1s. The 95th percentile of perception-brake response times for these same conditions was 2.0s. The findings from this study are consistent with the relevant literature: most drivers are capable of responding to an unexpected incident in 2.0s or less. Thus, the perception-reaction time of 2.5s, adopted by the American Association of State Highway and Transportation Officials for design reasons, encompasses most of the driving population.

A driver who might need 0.3s of perception-reaction time under alerted conditions might need 1.5s under normal conditions; such response time may decrease by approximately 1s or more in an expected situation: IVC warning systems allow one to pass from an unexpected to an anticipated situation, and thus influence the perception-reaction time.

3 SAFETY ANALYSIS AT INTERSECTIONS

This article shows the results of the analyses developed on the effects and benefits which would be potentially generated by the forthcoming use of the infrastructure-vehicle (I2V) or vehicle - infrastructure (V2I) communication systems at the road intersections regulated by traffic lights (Fig. 1): a theme that – as it has been highlighted – is extensively being dealt within the literature.

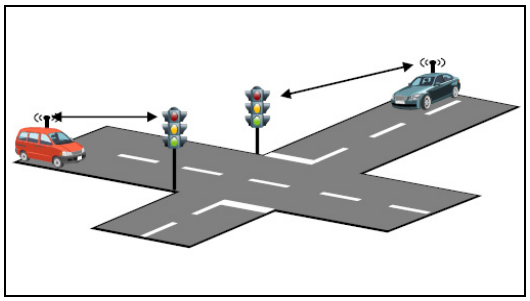

Figure 1: Evocative image of I2V and V2I at a generic intersection regulated by traffic lights (INTERSAFE-2).

The effects of the use of the I2V systems are assessed through the proposal of indicators on the likelihood and/or severity of the risk, which can timely and preventively indicate potentially critical conditions and send more or less intensive alarm messages – depending upon the criticality– on board the vehicles which are potentially involved by means of the I2V communications.

For the sake of completeness of the analysis, we also developed some proposals for the combined use of sensors to monitor the vehicles which approach the intersections (US Dept. of Transportation, 2008).

Our analyses assume that the use of I2V systems would match the increased level of attention of the driver and – consequently – the dampening of the perception-reaction-actuation time ($t_{p,r,a}$) of the driver, with the subsequent increased safety margin.

The processing concerns the study of the driver's behaviour when the yellow light is triggered. All such processes associate the use of the I2V technologies to the maximum perception-reaction - actuation time of the driver ($t_{p,r,a}$) which – in case of low levels of attention – has been estimated to 2.3 seconds (where 0.8s can be assumed for the actuation phase), on the basis of Johansson and Rumar's distribution (1971). The studies are based upon the assessment of the variation of *new road risk indexes* as a result of the reduced $t_{p,r,a}$ time; specifically, it is assumed that the I2V communications are such to send on board indications which can supply two levels of alert, namely: the former can take the attention of the driver back to normal levels ($t_{p,r,a}$ equal to 1.46s: green arrow in Fig. 3.) and the latter can generate an actual alert ($t_{p,r,a}$ equal to 1.1s: red arrow in Fig. 2).

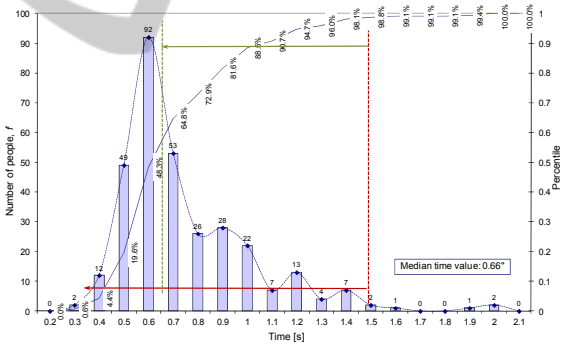

Figure 2: Johansson and Rumar's distribution of the $t_{p,r}$ highlighting the two values of $t_{p,r}$ which give $t_{p,r,a}$ =1.46s (green arrow) and 1.1s (red arrow).

4 THE DILEMMA ZONE AND ROLE OF INTEGRATED I2V-ADAS

It is worth reminding – first of all – the concept of dilemma zone, which has been most likely introduced for the first time in (Liu, Herman and Gazis, 1996). The so-called dilemma zone is the portion of approach to the intersection the driver might cover, starting from the time when the traffic

light turns into yellow, without being able to either stop in safety conditions before the stop line (or close to it) or to fully clear the intersection at the end of the yellow light or when the red one is triggered; such conditions are critical and generate an actual dilemma to the driver, who does not know what his/her behaviour should be in order to act safely, not to commit infractions or cause accidents. Such area can be eliminated with a proper yellow time calculation and if vehicle speed is lower than the established limit, but sometimes it exists and its position and length vary depending upon the cases and some parameters need to be taken into consideration.

In order to clarify the concept of dilemma zone, the behaviour of a driver is considered independently, i.e. irrespectively on the one adopted by the drivers of any vehicles which precede his/her own one. When the yellow light is triggered, the driver is faced with a choice: should he/she stop the vehicle or cross the intersection – even by accelerating – so that he/she can clear the area before the red light? We should keep in mind that – usually – the driver *does not know how long the yellow light will last or the so-called clearance time*, i.e. the *all red time*. The solution depends on factors which characterize the distance and time required to stop the vehicle and/or clear the intersection: the initial speed of the vehicle, the actual or possible deceleration, the driver's perception and reaction time, the distance between the stop line and the access, the position of the vehicle when the yellow light is triggered and the extension of the intersection. It is obvious that – as a tendency – the drivers who are far from the intersection choose to stop; those who are very close to it – instead – normally try to clear the intersection and therefore – if required – they accelerate.

In either case, the characteristics of the manoeuvres are influenced by the perception – reaction – actuation time ($t_{p,r,a}$) of the driver.

The stopping distance (Xs or d_a) is the minimum level of the distance, calculated from the stop line, a vehicle should be within in order to have a comfortable stop and in full safety conditions (beyond such position, the vehicle cannot be stopped: Cannot stop in Fig. 3). By steady deceleration, the stopping space can be calculated through a known ratio (1).

$$X_s = d_a = v \cdot t_{p,r,a} + \frac{v^2}{2 \cdot a} \quad (1)$$

where:

- Xs is the stopping distance or stopping space of the vehicle [m];
- v is the initial speed of the vehicle [m/s];
- tp,r,a is the perception – reaction – actuation time [s];
- a is the deceleration [m/s^2].

The clearance distance (Xc or d_s) is the maximum distance from the stop line below which a vehicle can clear the intersection in full safety conditions (Cannot go in Fig. 3) within a given yellow light time, which – though - he/she does not know. This was computed through ratio (2).

$$Xc=d_s=v*(Y+R)+a*(Y+R-t_{p,r,a})2/2-(W+lv) \quad (2)$$

where:

- Xc is the clearance distance in meters;
- W is the length of the intersection measured from the stop line of the access which is considered in the opposite angle, depending upon the manoeuvre to be performed; it is expressed in meters;
- lv is the length of the vehicle, in meters;
- v is the speed the vehicles approaches the intersection at, expressed in [m/s];
- Y is the duration of the yellow light phase (yellow light time) relevant to the access which is being taken into consideration, expressed in seconds;
- R is the duration of the all red stage (all red time), in seconds;
- tp,r,a is the perception – reaction – actuation time;
- a is the time of the acceleration (assumed as constant) adopted to clear the intersection. In default of more accurate data, such as the ones generated by monitoring, the value of this parameter is assumed through Gazi's equation (FHWA, 2006), i.e.:

$$a[m/s^2] = 4,9-(0,213*v[m/s])$$

Three different conditions can be generated on the basis of the relationship between the two distances which have been defined above, namely:

1. Xs>Xc
2. Xs = Xc
3. Xs<Xc

In the first case (Xs>Xc), the dilemma zone results from the overlapping of the Cannot Stop and Cannot Go portions. The position and length of such areas – when existing – vary from case to case.

The second case (Xs = Xc) represents an ideal situation: the dilemma and optional zones disappear; a driver which would find him/herself in those conditions could stop the vehicle or clear the intersection comfortably and in full safety conditions, with no doubts at all on the behaviour to

be adopted.

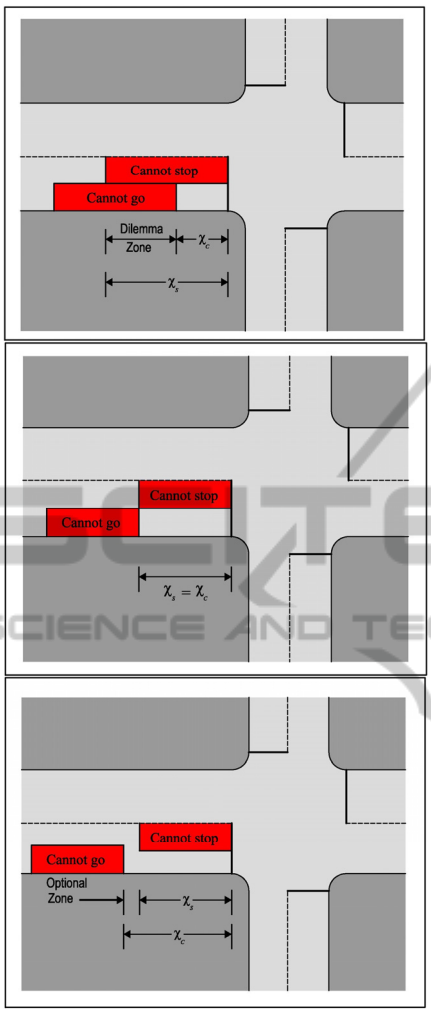

Figure 3: Graphic representation of the zone where the vehicle cannot stop in safety conditions (Cannot Stop) r cannot clear the intersection in full safety conditions (Cannot Go).

In the last case (Xs<Xc) an Optional Zone would generate, i.e. a portion of the access lane where the driver of the vehicle in it may select whether to stop comfortably and safely at the stop line or to clear the intersection in safety conditions.

It is worth mentioning that the dilemma zone depends on the kinematic parameters of the vehicle (i.e. speed, deceleration or acceleration) besides on the yellow light time, which is generally the same for all the accesses of the intersection. The most appropriate strategy to minimize the issue caused by the presence of the dilemma zone consists of determining a yellow or all red time which allows clearing the intersection from the limit position available to stop. Nevertheless, the variability in the conditions of motion, of the drivers and adherence of the carriageway might determine different circumstances than the ones which are defined *a priori.* These variations can be observed by means of position detection systems located either on-board the vehicle (GPS-with WAAS, as EGNOS) or on the infrastructure (VIP, Inductive Loops, W SN based on magnetometers, etc.).

The analyses illustrated hereinunder are aimed at providing a real time estimate of the risk of accident for an approach of road intersections regulated by traffic lights: this information can then be used by an ADAS, which *supplies the driver a risk indicator of the instrument panel*; such indicator should be able to resort to information which is usually not available to the driver or which – in any case – he/she cannot calculate in real time, namely: the road in front of him/her (navigator instrument panel) the residual time to the triggering of the red light and the clearance time (I2V), the comparison between the driving dynamics and the safe crossing or stopping conditions. This would allow assessing whether or not a situation is hazardous and – if it is – trying to avoid the potential collision by transmitting alert messages to the potentially involved vehicles.

In the analysis of the safety conditions, we have applied risk indexes formulated on the basis of the vehicle position and speed information.

5 DRIVER'S BEHAVIOUR AND RISK INDEXES

The study of the risk of the single vehicle approaching the intersection is strictly linked to the study of the dilemma zone and – subsequently – to the distances required to clear the area and stop depending upon the course state adopted by the vehicle. Two specific indicators have therefore been formulated: the former is relevant to the overall clearance of the intersection and latter refers to the complete stop of the vehicle in correspondence to the stop line. Literature proposes various approaches to risk assessment (Rausand, 2011), yet those hereafter described have been originated by our proposal, having in mind a simple approach, at least at this level of analysis.

On the grounds of the analyses described, ratios have been formulated to determine – as a result of the identification of the dilemma zone – simple *risk indexes* on the basis of specific input data.

With reference to a determined time instant (at a given spatial position D), the risk index relevant to the stop manoeuvre (IR_stop or IR1) is defined by:

$$IR1 = IR\_stop = D\_stop / D \quad (3)$$

where:

- D_stop is the distance – computed from the stop line – the vehicle needs to stop – in full safety conditions – before or in correspondence to the stop line (stop distance as previously defined);
- D is the distance – measured from the stop line – where the vehicle is at the time taken into consideration.

According to the report we have presented above, a null or almost null risk index represents the fully safe condition (D >>D_stop), since the vehicle can stop without the risk of occupying the intersection, even if partially. Values of IR_stop ≥1, on the other hand, detect potentially hazardous conditions (D <<D_stop) for safe stopping. Values of IR_stop included between 0 and 1 indicate almost totally safe or almost risky conditions, depending on whether they are closer to zero or to one.

Likewise, a risk index has been defined as related to complete intersection clearance manoeuvre (IR_clearance or IR2) :

$$IR2 = IR\_clearance = D / D\_clearance \quad (4)$$

where:

- D is the distance – measured from the stop line, where the vehicle is at the instant taken into account;
- D_clearance is the clearance distance; such distance, which is computed starting from the stop line, ensures the vehicle the complete clearance of the whole intersection, in full safety conditions, during the yellow light stage (relevant to its manoeuvre) or – in case –during the all red stage. For the sake of greater security, the all red stage has been considered as equal to zero (an all red stage is present in reality, even though it is rather limited). By this choice, we have intended to allocate the all red as safeguard fraction for those whose behaviour – perhaps because of slower reflexes – is not within the average one which was computed in these analyses; an advanced ADAS system may include the transmission on board of the all red time, consequently modifying the risk conditions; setting such value to zero would allow providing a risk indicator even to vehicles which are not equipped with ADAS-IVC.

Values of IR_clearance close to zero identify full safety conditions (D <<D_clearance) – i.e. where the vehicle can fully clear the intersection by the end of the yellow light stage relevant to its manoeuvre - also for the risk index connected to the clearance manoeuvre. On the other hand, values of risk relevant to clearance which are greater than or equal to one would identify potentially risky situations (D >>D_clearance) for the overall clearance of the area in full safety conditions. Values of IR_clearance included between 0 and 1 indicate, almost fully safe or almost risky conditions, depending upon their being closer to zero or to one.

This section of analysis focused on the behaviour – and relevant criticalities – of the different drivers who approach intersections governed by traffic lights at the moment the yellow light is triggered.

The analysis of a single vehicle is not aimed at assessing the consequences of the potential accident; it merely intends to evaluate how much a vehicle - depending upon its dynamics and on the driver's behaviour – is exposed to the risk of accidents: it is a kind of assessment of the exposure to the risk, rather than an estimate of the risk itself.

A numerical calculation tool has been created for such study so that – after the introduction of specific data into the case in exam – the presence and extensions of the dilemma zone could be assessed Fig.4, as well as the value of the risk indexes (of not completing the manoeuvres of either stop or complete clearance of the intersection by the end of the yellow light or – in case - all red stages) and if there is the actual risk of accident. The tool reproduces the motion of a single vehicle approaching a traffic signal and provides also graphic outputs for the variation of the risk indexes as a function of the initial speeds which can be assumed for the vehicle in exam.

With reference to the three t_{pra} values which have been taken into consideration in the analyses (i.e. 2.3 – 1.46 – 1.1 seconds), the presence and variation of the dilemma area have been investigated to reach the definition of risk indexes relevant to both the clearance and stop manoeuvres; such indexes highlight what the most advantageous or least disadvantageous manoeuvres would be for the drivers of the analyzed vehicle (see the analysis of a specific situation in Fig. 5).

In order to detect the risk of the vehicle when approaching the traffic signal, we can assume to update its risk level at different positions before the stop bar. Since the feasible deceleration rates for vehicles fall usually in a quite limited range (a typical range might be between 3 and 5 m/s^2), progressive sections along the approaching lanes can be defined to trace its speed and compare it with the expected value in case of stopping from that distance.

The first of these checking points (named section "A") is defined assuming a deceleration rate of 3 m/s^2 and is 64m before the stopping bar, for a

vehicle moving with a speed of 50km /h.

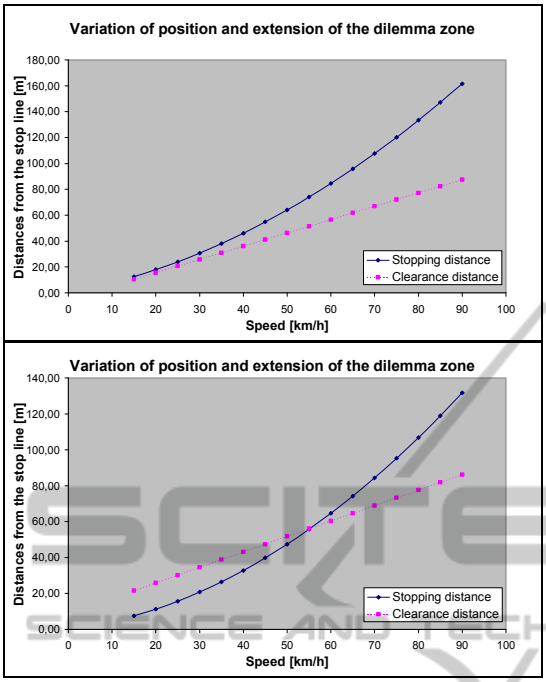

Figure 4: Numerical methodology for the analysis of the dilemma area and relevant diagrams.

Fig.5. shows – as related to this specific section (section "A") - how IR_stop (IR1) grows linearly with the increase of the speed even though the other conditions remain the same, whilst IR_clearance (IR2) decreases in an almost exponential trend.

It is worth noticing that the portions of curves above the threshold of IR = 1 (which is displayed in red in the diagrams) identify risky situations. If – at a given speed – at least one of the two IR were below such threshold, the manoeuvre to be recommended would be the one which corresponds to it (by a communication on board the vehicle).

If both the IR's were below such thresholds, then either manoeuvre would not be severely risky and - in any case – it would be appropriate to provide indications on board to apply the safest one, i.e. the one which is farther from the threshold. In those case where - at a given speed – both indexes were exceeding the IR =1 threshold, then – even though the safety conditions are lacking- it would be appropriate to provide communications on board to apply only the manoeuvre that – between the two ones – would involve lower risk (i.e. the one which is closer to the threshold) or to communicate the risk condition to the other vehicles which are approaching the intersection.

Although here only the risk indexes related to section "A" have been reported, an ADAS can easily update this simple estimation, while the vehicle is approaching the intersection and recognize critical cases by following the evolution of these risk indexes over space/time.

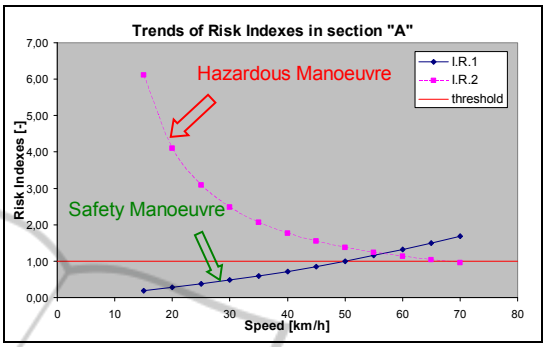

Figure 5: Trend of the risk indexes relevant to the clearance and stop manoeuvres related to a given section and to a specific $t_{p,r,a}$ as a function of the speed.

Two typologies of use of the information on the risk indexes above can then be identified. In particular, if the data can be detected in real time, the driver could be informed onboard of a potentially hazardous situation (which might occur if he/she kept such driving behaviour) using – if required – purposely-allocated algorithms to predict the trend of the vehicle on the basis of the data detected from the monitoring; another use, which is strictly linked to the utilization of the diagrams obtained, would be detecting – in case the vehicle were already within the dilemma zone – the lowest risk manoeuvre and sending a message on board to inform the driver.

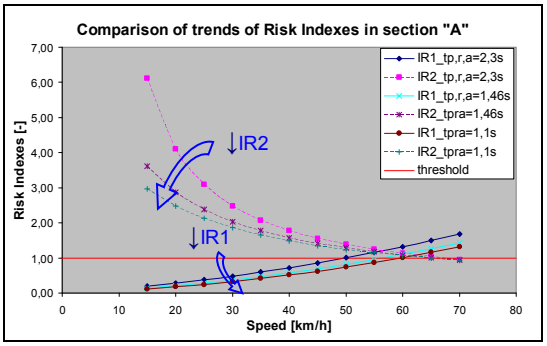

Figure 6: Comparison diagram of the risk indexes as a function of the speed, relevant to a given section, according to the three $t_{p,r,a}$ which have been taken into consideration.

Furthermore, the effects of using communication technologies between the infrastructure and the

vehicle have been assessed reducing - in the analysed situations – the driver's $t_{p,r,a}$ from 2.3 s to 1.46 s and 1.1 s, leaving the other conditions unchanged.

Fig.6 reports an example of a diagram which summarizes the curves of the risk indexes assessed for the three different $t_{p,r,a}$. It is worth noticing how – as a result of the reduced $t_{p,r,a}$ - the risk indexes relevant to both the clearance and stop manoeuvres result to be reduced as well.

Figure 7 and 8 report the trends and lengths of the dilemma zone, related to the distance needed respectively to free the crossroad area or to stop.

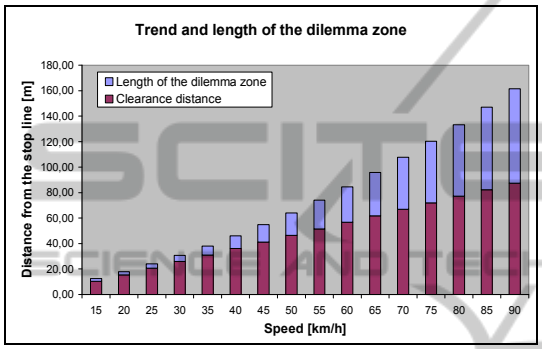

Figure 7: Trend and length of the dilemma zone, related to the distance needed to free the crossroad area.

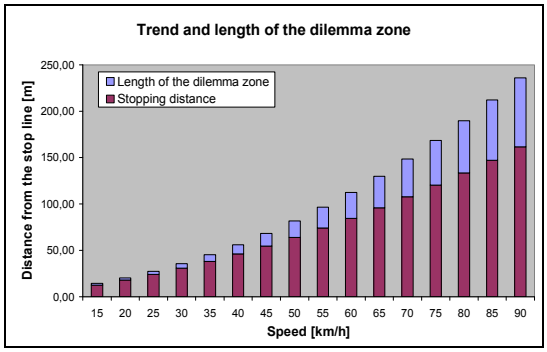

Figure 8: Trend and length of the dilemma zone, related to the distance needed to stop.

6 CONCLUSIONS

In this work an ADAS for traffic signal approaching has been analysed and two main roles have been considered:

- provide a risk estimation for alternative manoeuvres (stopping or clearance) and then communicate the driver the less hazardous manoeuvre on the basis of known, measured or estimated parameters;
- reduce the risk level, by reducing the driver perception and reaction time, since IVC increase the level of attention of the driver.

The experiments run in simulation by means of a spreadsheet have led to acknowledge – as a result of the reduction in the $t_{p,r,a}$, - a corresponding reduction in the estimated risk of accidents. The positive effects of the infrastructure–vehicle communication have been ascertained in terms of reduced exposure to the risk by a single vehicle (analyses of the trend of the single vehicle approaching the intersection regulated by traffic lights). More specifically, as related to the behaviour of a driver at the moment the yellow light is triggered for his/her traffic stream, the application of I2V systems (corresponding to a reduction in the $t_{p,r,a}$), the following has been observed:

- reduced extension of the dilemma zone;
- disappearance of the dilemma zone and growth of the zone of choice : in some cases, as a result of the increased level of attention in order to attain standard values, i.e. tp,r,a equal to 1,46 s and –in a large number of cases relevant to the forwarding of alert messages – tp,r,a equal to 1.1 s ;
- the decreasing of the risk indexes relevant to the stop (IR1 o IR_stop) and clearance (IR2 o IR_clearance) manoeuvres, mainly in correspondence to the speed values corresponding to IR values which were far greater than the safety threshold (IR=1): in correspondence to very low speeds for IR2 and high speeds for IR1;
- the advanced knowledge of IR1 and IR2, with the subsequent opportunity to warn the drivers on board (possibly before they enter the dilemma zone) about the lowest risk manoeuvre to be undertaken: such potential is useful mainly in those cases where both IR's result to be above the safety threshold IR=1;
- the opportunity to reduce instantaneously, and therefore in real time, the risk or – better – the exposure to the risk - of not completing in full safety conditions the manoeuvre which is intended to be undertaken by the end of the yellow light stage.

In short, the results of the analyses show that the use of the I2V e V2I communication systems in the intersections regulated by traffic lights – assumed in the processing as directly related to a reduction of the tp,r,a - has beneficial effects on road safety as related to the reduction of risks of accidents.

Furthermore, the analyses performed allow supporting also the combined use of sensors, to enable the most viable continuous monitoring and assess the dilemma zone and the potential risk of

accident instantaneously and in real time.

It is also worth specifying that the analyses did not consider any actual data on the use of the I2V technologies – since they are not available to date – or any active intervention on the vehicle in case of need.

The subject is in evolution and many questions remain open. For example an investigation of vehicle behaviour, when it is not isolated in approaching the traffic signal, need more tests, possibly also with a traffic micro-simulation tool. It can be assumed that the actual potential of the systems which have been taken into consideration could be assessed once said technologies are widely spread on the market.

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