Operational Conditions Effects on Safety of Urban Signalized Intersections – Main Experimental Evidences

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SYNOPSIS

The international interest for accident previsional models is always increasing at the same time preventive strategies in road management safety are developing. Because of the high concentration of accidents at urban and extra urban intersections, many studies have been developed in the last years, especially in relation to different kinds of arrangements and to road environment. The main purpose of these studies is to allow a previous evaluation of safety condition in either ordinary management of roads or in the re-qualification of their operating conditions.

Field observations carried out by the Authors on a lot of urban signalized intersections (representative of a wide range of exploitation conditions) showed the effect on safety of factors directly related to operational conditions of intersections, usually ignored in modelling safety of signalized intersections. In the considered patterns, these include both the flow distribution and the frequency of different manoeuvres and the particular signal cycle regulation carried out.

It was realized also that some drivers' behaviours - relevant for safety (i.e. the inobservance of red signal) - were in part related to the organization and to the length of the signal cycle.

Outcomes of analysis carried out on selected real cases, in addition to accounting for the influence of the above mentioned factors in producing risk conditions of signalized intersections, want to aid in the implementation of new previsional models, apt to integrate effects of operational condition realistically. Such a model could be useful both in management problems and in the choices of reorganization and / or re-qualification of intersections.

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INTRODUCTION

The difficulties about an effective approach to the theme of traffic safety are particularly evident in urban areas because of the functions and use modalities of urban roads. The latter take on a high degree of complexity due primarily to:

- the needs that the urban road has to satisfy as a public space, in which mobility functions and social and economic roles blend;
- the heterogeneity of users and the variety of use modes;
- the characteristics of the demand, particularly as regards the persistence of high volumes of traffic at most times of day and of instability phenomena that derive from it;
- the workload necessary to fulfil driving tasks (for motorized users and other traffic); user being asked to face varying and rapidly evolving situations, to handle conflicting vehicle trajectories and to integrate with other traffic components;
- the interactions between user and infrastructure which, unlike in the unbuilt area, involve not only the formal characteristics of the road (connected to its conception), but above all the functional organization of the road network and the traffic regulation systems;
- driving behaviour on the urban road which, unlike what is currently observed in the road-user interaction – where what is almost exclusively required of the user is activity for controlling the vehicle (“sensory-motorial dominant”) – is characterized by prevalently cognitive psychological activity (“cognitive dominant”).

Accident statistics in the urban area, both in Italy and in other countries, show a high concentration of accidents which is to be related to the higher exposure to risk. Despite lower crash severity – and the consequent reduction in the injury rate and even more in the death rate per accident – the seriousness of the phenomenon is worrying both in an absolute sense and in comparison to other road types.

Furthermore, accidents on urban roads have decidedly peculiar characteristics. These are:

- the high degree of dispersion along the arcs of the network;
- the high proportion of non-motorized road users involved;
- the major influence of activities at road edges.

Analogously to what happens in the non-urban area a large part of accidents on urban roads is concentrated at intersections (about 50 percent) and in particular at signalized ones. For the latter, a primary role is played for safety by violations by vehicles entering, and proceeding through, the intersection after the signal has turned red (commonly referred to as Red-Light Runners phenomena). Indeed, these behaviours are one of the main causes of accidents at signalized intersections, with a particularly high crash frequency.

Countermeasures to reduce Red-Light Running prove to be particularly problematic because of the complexity of the problem, which may be due to both infrastructural deficiencies and to psychological and sociological motivations. Hence they cannot be limited to Engineering measures, but must also include actions for Education and Enforcement (three *E*’s stakeholders).

Because of what has been said, risk management in urban areas, more than anywhere else, requires that local accident control techniques (both at intersections and along the road section) be integrated in an *approach of a preventive type*, capable of acting on accident-causing factors and in this way of increasing the effectiveness of safety measures.

In this way, the development of instruments capable of preventively evaluating the risk linked to a particular organization of signalized intersections is of fundamental importance for the design and operational conditions control of installations of this type.

This paper aims to present some exploratory results, preparatory to the implementation of a new previsional model (of a “hybrid” type) for signalized intersections, capable of realistically integrating effects of operational conditions on safety, including effects caused by irregular manoeuvres (violations). In order to model the behaviour of Red-Light Runners, in addition to what is reported in the literature, use was made of experimental field observations, derived from a sample of intersections representing significant variability in use conditions, as regards both flow intensity and frequency of different manoeuvres and the particular signalizing enacted.

INSTRUMENTS FOR EVALUATING SAFETY AT SIGNALIZED INTERSECTIONS

Risk factors at signalized intersections

The safety of signalized intersections, unlike that of other types of intersection, in addition to depending on traffic volumes and the particular geometrical layout, is influenced by regulatory control characteristics (duration of cycle, number of phases, duration of single phases, coordination and control system adopted). In some cases (e.g. very complex layouts and ones with more than four approaches, presence of phases dedicated to public transport on special lanes, etc.) the regulatory factors can take on a predominant role in accident genesis.

Numerous studies in the literature have sought to establish statistical relations between the accident phenomenon and contributing road factors (Maycock and Hall, 1984; Jones et al., 1991; Miaou et al., 1992; Kulmala, 1994).

A recent study (Chin and Quddus, 2003), carried out on a complex of 3000 accidents distributed on 52 four-arm intersections, in addition to permitting evaluation of the significance of the main explicative variables, makes it possible to identify their impact (positive or negative) on accident frequency at intersections (see Table 1).

Table 1: RENB model for total annual accident frequencies

Explicative variable	Estimated coefficient (IRR)	*t*-Statistic (*P*-value)
Total approach volume in thousand (ADT)	0.0071 (1.01)	2.712 (0.0067)
Right-turn volume in thousand (ADT)	0.0101 (1.01)	1.516 (0.1296)
Uncontrolled left-turn lane (yes 1, otherwise 0)	0.3052 (1.36)	3.520 (0.0004)
Acceleration section on left-turn lane (yes 1, otherwise 0)	0.2783 (0.76)	2.113 (0.0346)
Intersection sight distance (m)	0.0006 (1.00)	3.141 (0.0017)
Median width greater than 2m (yes 1, otherwise 0)	0.1947 (1.21)	2.462 (0.0138)
Number of bus stops	0.0556 (1.06)	1.592 (0.1114)
Number of bus bays	0.0492 (0.95)	1.738 (0.082)
Number of phases per cycle	0.1108 (1.12)	3.073 (0.0021)
Existence of surveillance camera (yes 1, otherwise 0)	0.2438 (1.28)	3.858 (0.0001)
Signal control type (adaptive 1, pre-timed 0)	0.0522 (0.95)	0.767 (0.4428)

Interpretation of the RENB model (Random Effect Negative Binomial Model) developed by Chin and Quddus is facilitated by the IRR (incidence rate ratio) values and the P-values calculated for each of the explicative variables. Specifically, examination of Table 1 shows the negative impact on safety (IRR $\geq$ 1) of variables linked to: traffic volumes; the presence of uncontrolled left turn lanes; the intersection sight distance; the median width; the presence of bus stops; the number of phases per cycle and the presence of surveillance cameras (for the latter variable, however, the result contradicts what is reported in other researches and is to be related to the specificity of the sample examined). By contrast, the presence of an acceleration section on the left-turn lane, as well as the number of bus bays and the adaptive signal control, show a positive influence on safety (IRR $\leq$ 1).

Possible instruments for safety analysis

Choices regarding the organization and regulation of signalized intersections are the product of an evaluation (implicit or explicit) of the obtainable benefits, compared to possible alternatives, in terms of the efficiency and safety of the installation. The activity of the road engineer must take into account factors and relations which are sometimes complex, often also conflicting ones, seeking the best compromise solution in the concrete case.

At present, as an alternative to judgements based on an engineering evaluation, the instruments available for assessing the safety performance of a given installation fall into two distinct families:

i. reactive safety tools, at the basis of which there is generally an accident analysis developed with in-depth study adequate to the problem to be dealt with;
ii. proactive safety tools, referring to Road Safety Audit or Road Safety Review procedures, whose degree of efficacy depends on how systematic and generalized the application is.

Between reactive safety tools, methods based on traffic conflicts (where conflicts are used as a surrogate of crashes) are surely interesting for purposes of this study; without underestimating the drawbacks due to their subjective nature, one can state that they present undoubted advantages compared to traditional accident analysis techniques (Dissanayake et al., 2003):

i. the possibility of acquiring the experimental basis in a short time;
ii. the possibility of rapidly evaluating the efficacy of the method and making any necessary corrections in a short time;
iii. the possibility of taking human factors into account through field observation of drivers' behaviours;

iv. the possibility of making safety analyses independent of the availability of accident data;
v. the possibility of including in the analysis aspects of the accident phenomenon which are generally neglected by police reports (traffic volumes, recovery manoeuvres, routine conflicts, etc.)

In the context of applications, an increasingly interesting role is being taken on by safety evaluation techniques based on potential conflict analysis, that lie astride reactive and proactive safety tools. Such techniques, though they are mainly motivated by a preventive logic, need validation through a sufficiently large observation base regarding previous accidents.

Once they are set up, potential conflict models can provide reliable predictions on expected accidents and thus permit, in the design phase too, preventive evaluation of the risk level associated with a given infrastructural installation.

Interest in these models is largely to be attributed to the possibility of overcoming some practical and conceptual difficulties involved in traditional accident models, which, as is well known, start from the supposition that previous accidents can provide useful information on future ones (i.e. that the accident phenomenon will be repeated, identical to itself, in the same place but at different times) and in any case after the implementation of corrective measures require a check on efficacy, for example through before-and-after studies possibly extended to a sufficiently big sample of similar installations.

In the case of decisions based on accident analysis, several researches have also highlighted the bias caused by the way in which exposure to accidents is measured (Council et al., 1988, Plass and Berg, 1987), as well as some problems associated with compensating for regression–to-the-mean phenomena (Hauer and Lovell, 1986). From the practical point of view, the reliability of the results of safety analyses faces further drawbacks linked to the reliability of police reported crash records, as well as to material errors in codifying and in the input of elementary archived information, and more in general to the length of time, often incompatible with management needs, required to obtain a sufficiently representative sample to submit to analysis (Katamine and Hamarneh, 1998; Salman and Al-Maita, 1995; Zegeer and Deen, 1978; Sayed and Brown, 1994).

SAFETY EVALUATION BASED ON POTENTIAL CONFLICT ANALYSIS

Modelling of the user’s behaviour in the absence of a violation

For the purposes of the present study potential conflict models, in addition to permitting integration of traffic violations, offer the irreplaceable advantage of being suited to real operational conditions, as they can include both the part referable to intersection load conditions (entering traffic, variation in demand along the day, entering flow distribution, etc.) and the part linked to the geometry and regulation of signal control type.

Among formulations present in the literature, the model proposed by Ha and Berg (1995) appears to constitute a starting point for the development of a “hybrid” model, capable of taking into account the risk linked to unencoded operations, like that of the red-light runner.

The study by Ha and Berg assumes some important conclusions provided by Council et al. (1988), in particular that the number of potential conflicts for a given type of accident represents a measure of exposure that is more reliable than the simple sum of the number of vehicles entering the intersection. The philosophy of the Council et al. model (and of the Ha and Berg one) postulates that for an accident to be able to occur it is necessary for particular prerequisite conditions to exist, correlated with the speeds of vehicles and their position in the intersection; without these conditions the accident cannot occur.

Potential conflicts for left turns (*manoeuvre*)

For potential conflicts connected to left turns (manoeuvre), the Ha and Berg model considers two possible scenarios:

i. the first is related to a left turn vehicle that does not stop, having found on arrival a sufficient gap in the opposite stream;
ii. the second is related to cases in which the gaps available for performing manoeuvres force a left turn vehicle to slow down and possibly stop before effecting the manoeuvre (the left turn vehicle performs the manoeuvre only when in the opposite current there is a larger gap than its own critical interval). In this case, for a potential conflict to arise two conditions have to occur simultaneously:
    a) the left turn vehicle must effectively be present at the intersection;
    b) the left turn vehicle must not immediately find a sufficient gap in the opposite current.

For the determination of the potential conflicts, we have to consider a gap interval within which the decision by the left turn vehicle driver can prove inadequate to the circumstances (the speed and/or the position of the vehicle coming from the opposite direction does not correspond to the evaluation by the left turn vehicle driver). This leads one to rule out both very small gaps (the left turn vehicle will not make the manoeuvre) and very large gaps, since in this case the left turn vehicle will have high safety margins for clearing the intersection safely.

In general terms, according to the behaviour model described above, to determine the likelihood of potential conflicts for the manoeuvres referred to, we need to identify the interval (t_l, t_u) within which the gap in the opposite stream can give rise to an unsafe manoeuvre. It follows that the number of potential conflicts corresponding to the behaviour described will depend on the arrival process governing the flow from the opposite direction.

The determination of the interval (t_l, t_u) and the positions to assume for the gap distribution will be discussed below. Here we will just mention the fact that Ha and Berg's model, considering an arrival process distributed according to Poisson law (and therefore a negative exponential law for gap distribution), for a generic approach *i* determines the probability of a left turn vehicle being in a situation of uncertainty (capable of giving rise to a potential conflict) through the following form:

$$P\left(t_{l_i} \le t_i \le t_{u_i}\right) = \left\{e^{-N_k \lambda t_{l_i}} - e^{-N_k \lambda t_{ui}}\right\}$$

$$\lambda = \frac{Q_k}{3600 \cdot N_k}$$

where:

t_{l_i}, t_{u_i} = lower and upper limits of the gap interval that can involve an erroneous evaluation for the vehicle coming from arm *i*

t_i = time interval required to complete the left turn

Q_K = total hourly flow on approach *k*, opposite to *i*

N_k = number of lanes in approach k, opposite to *i*

On the basis of these positions, the number of potential conflicts for left turns from approach *i* proves to be proportional to the number of left turn vehicles Q_{LT_i} and to the likelihood of conflict as determined above:

$$N_{LT_i} = Q_{LT_i} P\left(t_{l_i} \le t_i \le t_{u_i}\right) = Q_{LT_i}\left\{e^{-N_k \lambda t_{l_i}} - e^{-N_k \lambda t_{ui}}\right\}$$

Potential rear-end collision conflicts

Ha and Berg's basic model assumes the *continuum model* to describe drivers' behaviour in stopping on red lights and moving off on green lights (see *Appendix 1*). The basic hypotheses take into account the fact that vehicles arrive at the traffic lights with a uniform flow Q_i while the lights are red and the queue formed is cleared at the saturation flow rate S_i in a time interval g_{qi}, which is lower than the time in which the lights are green (g_i).

The behaviour model considered assumes that:

- during the time r_i in which the lights are red, all the vehicles reaching the stop line halt; each of them, except the first one, can collide with the vehicle in front of it during the deceleration and stopping phase. The corresponding number of potential conflicts is:

$$N_{RE,r_i} = \frac{Q_i r_i - 3600}{c}$$

with:

Q_i = flow rate at approach *i* (vph)

r_i = effective red-light time at approach *i* (s)

c = cycle time (s);

- during the green-light phase, the queue is cleared at the flow rate S_i (vph) in a time g_{qi} (s); vehicles arriving in this time interval are forced to decelerate because of the presence of a residual queue on the approach. In these conditions, each vehicle can collide with the vehicle in front of it. The number of potential conflicts is:

$$N_{RE,gq_i} = \frac{S_i g_{q_i} - Q_i r_i}{c}$$

- each vehicle arriving during the remaining green-light phase $g_{ui} = g_i - g_{qi}$ (s), i.e. after the queue has cleared, can collide with the vehicle in front of it, if the latter slows down to turn right or left. Hence the number of potential conflicts can be determined starting from knowledge of the percentage of vehicles turning right (P_{RT}) and turning left (P_{LT}):

$$N_{RE,gu_i} = Q_i \cdot g_{ui} \cdot \left(P_{LT} + P_{RT}\right)$$

THE RED-LIGHT RUNNING (RLR) PHENOMENON

Dimensions and consequences for safety

Several studies in the literature, most of them very recent, have analyzed the phenomenon of Red-Light Runners. Growing interest in this problem is to be related to the extent of the phenomenon and the seriousness of its consequences.

According to an estimate by FHWA (2001), in the USA every year there are over 200,000 accidents caused by vehicles entering intersections on red lights, almost all causing injured. According to the same Agency the social damage is equivalent to 14 billion dollars per year.

The effects of the phenomenon on road safety are amply documented by a lot of statistics (Mohamedshah et al., 2000; Milazzo et al., 2001; Thompson et al., 2001); they agree in highlighting both a very high frequency and the relative gravity of the consequences, with growing intensity in recent years.

In this connection a very extensive study was carried out by Retting et al. (1999) starting from examination of an exceptionally great database; the latter included both police reports referring to deaths due to road accidents in the USA in the period 1992-1996 and the General Estimates System (GES) database based on a sample that is highly representative of the United States situation regarding accidents with a high degree of material and/or bodily damage.

From this study, which today constitutes a reference point on the RLR phenomenon, some conclusions are more useful than others for describing the impact on safety:

- red-light running crashes, more than other accidents, potentially produce injured (in 47 percent cases as opposed to 33 percent);
- red-light running crashes with more severe consequences (fatal injured) occur more frequently on urban roads;
- red-light running crashes occur more frequently by day than by night.

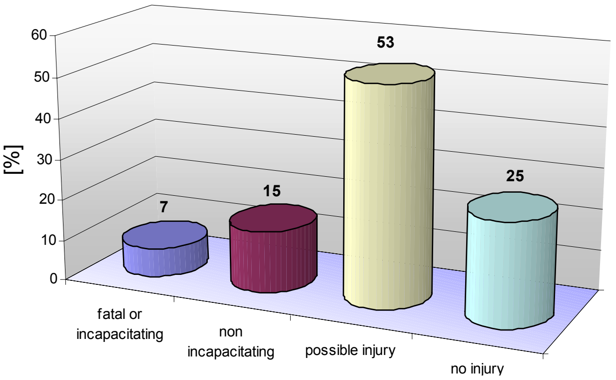


Figure 1: Distribution of RLR crashes consequences

The consequences of RLR crashes, which altogether account for about 40 percent of accidents with fatal injured at signalized intersections, can be summed up briefly through the distribution in Figure 1.

Previous researches (Retting et al., 1995) highlighted the fact that injured occur in 45 percent of accidents due to red-light running, as against 30 percent due to all other accidents. Altogether, red-light running accidents account for between 16 percent and 20 percent of all accidents at urban signalized intersections.

Table 2: Violation data for Iowa Cities

City	Intersection number (one approach per intersection)	Violations per hours	Violations per 1,000 entering vehicles
Bettendorf	Intersection 1	1.66	2.77
	Intersection 2	0.50	1.85
Davenport	Intersection 1	2.25	2.61
	Intersection 2	0.16	0.64
Dubuque	Intersection 1	9.78	38.50
	Intersection 2	0.96	3.25
	Intersection 3	0.11	0.45
Fort Dodge	Intersection 1	0.09	0.74
Iowa City	Intersection 1	3.14	6.08
Sioux City	Intersection 1	0.15	0.79
	Intersection 2	0.20	0.69
	Intersection 3	2.24	5.23
West Des Moines	Intersection 1	0.70	1.74

Frequency of violations

No less worrying is the *frequency* of red-light running violations. This is evident both from what is reported in the literature and from the direct observations reported above.

Table 2 (Kamyab et al., 2000) shows, by way of example, violations observed in some cities in Iowa.

Other field observations have highlighted violation rates as high as 18 per hour, i.e. an average of one violation every 3.5 minutes (Wissinger, 2000).

Factors influencing violations

Many studies have sought to establish the conditions that can help to give rise to the red-light running phenomenon. These include:

- grade, being responsible for the dilation times necessary for stopping the vehicle at the intersection;
- improper visibility conditions, which can jeopardize drivers' reactions at traffic signals;
- temporary roadside obstructions, which can impede visibility and generate indecision in the driver;
- line of sight, insufficiency of which can reduce the time available for reacting;
- sign reflectivity, which can influence readability and help to confuse the driver;
- distribution of signal phases, improper length of which can increase frequency of RLR manoeuvres;
- weather, which can distract drivers or increase the visibility distances for stopping.

Moreover, several regression models have been used to examine the effects of both the number of lanes on the approaches and of the traffic on RLR crashes (Mohamedshah et al., 2000; Hill and Lindly, 2004).

Mohamedshah et al., using the HSIS database, developed a model to account for the phenomenon. It was observed that the main non-driver factors are traffic volumes, intersection width and the traffic control type used. Specifically, the study by Mohamedshah et al. (2000) shows:

- an increase in the number of RLR crashes, on both the secondary and the main road, with higher flows in the stream the RLR vehicle is coming from (higher traffic volumes involve a greater likelihood of red-light violation by the vehicle approaching the intersection);
- independently of the stream of provenance, RLR crashes tend to increase at intersections with fully actuated signals, while they are more limited at semi-actuated or fixed-cycle intersections.
  This result is explained by Mohamedshah et al. by considering that fully actuated signals are prevalently used in suburban areas, where speeds are generally higher. This circumstance, together with the non-networked nature of the signals, negatively influences the RLR phenomenon due to reduction in the number of safe gaps and the fact that the appearance of the red light may be unexpected. Moreover, for this type of installation, another factor acting negatively may be greater cycle lengths, which may induce road users intentionally to violate the red light after a prolonged halt;
- the number of lanes on the secondary road does not significantly influence RLR crashes on the main road. Instead, cross-street RLR crashes increase with the number of lanes on the main road. By contrast, the volume of traffic on the secondary road significantly influences the likelihood of RLR crashes on the main road, while traffic volumes on the main road do not affect RLR crashes on the secondary road (a circumstance to be related to the shortage of safe gaps on the main road, even for relatively modest flows).

User types

As mentioned in the Introduction, the red-light running phenomenon involves multiple causal factors of different kinds (infrastructural, particularly linked to traffic control type; psychological; sociological). Some studies have been carried out in particular urban areas to identify the characteristics of RLR drivers (Fleck and Smith, 1999; Retting and Williams, 1996; Porter et al., 1999). The results of these studies provide fundamental information for orienting education and enforcement actions.

For the purpose of implementing engineering measures for counteracting the red-light running phenomenon, it must be borne in mind that red-light violations fall into two distinct categories:

- intentional behaviours, at the origin of which there may or may not be factors linked to the particular regulation of the signal cycle (e.g. duration of the cycle and the red-light phase) and to intersection and operational variables (traffic level on the main road and on the secondary one, intersection width, etc.) but which generally can be related to the state of the driver at the time and his willingness or otherwise to wait at lights;
- involuntary behaviours, like those generally observed during the change interval (also called the clearance interval of the intergreen period), where stopping at the red light is correlated with the speed of the vehicle and its distance from the traffic lights when the latter change. That is to say, there is a "dilemma zone" in which some drivers may be driving too fast both to get through the lights before they change and to stop without hard braking (Gazis, 1960; Baguley, 1988; Allos and Al-Haidithi, 1992). Other unintentional behaviours may be due to different causes (distraction, reduced time for reacting, poor signal visibility, emulation of the vehicle ahead, etc.).

More in general, the decision to stop at the intersection or keep going, when circumstances make it possible, can be linked to three main components (Bonneson et al., 2001;Van der Horst and Wilmink, 1986):

i) the driver's behaviour, and in particular his/her expectations about and knowledge of function of the intersection (especially regarding waiting at red lights);
ii) estimation of the consequences of a violation;
iii) estimation of the consequences of stopping.

Table 3 (Bonneson et al., 2001) sums up the terms of drivers' stop-go decision process.

Table 3: Factors Affecting the Stop-Go Decision

Components of the Decision Process	**Factor**		
Driver Behavior	Travel time Coordination Headway	Speed Approach grade	Actuated control Yellow interval
Estimated Consequences of Stopping	Threat of right-angle crash Threat of citation		
Estimated Consequences of Stopping	Threat of rear-end crash Expected delay		

According to this behaviour model, the intentional red-light runner, basing his judgement on the three factors mentioned, decides to violate the signal. We can imagine this type of user as being impatient about a probable wait and not very worried about the risks of a violation (citations, collision risk). Likewise, we can imagine the unintentional red-light runner as a driver that cannot stop or having approached the intersection with insufficient attention.

Milazzo et al. (2001) observe that each user can take on a different role faced with the stop-go decision, depending on a given situation, on his or her mindset and on chance. In light of this, these authors distinguish four user categories, each characterized by a different inclination to violate the red lights (see Table 4).

Table 4: Driver Population Types

Driver Type	Characteristics
Reasonable and Prudent	- Attentive and aware - Does not intentionally act in a way to endanger himself or others along the roadway
Temporarily Inattentive	- Temporarily distracted or inattentive - Under adverse circumstances, an otherwise prudent driver may act in this manner
Reckless	- Behaviour displays a wilful disregard for the safety of himself and other drivers - Aggressive driving behaviour that could result in a crash
Mistaken Driver	- Attentive driver who simply makes a mistake - Unsuccessfully attempting to drive in a reasonable and prudent manner

From studies on driver characteristics and observation of behaviours at intersections, there emerge three aspects of some practical interest that appear worth stressing:

i. it is impossible to predict by which behaviour (intentional or unintentional) the violation will be inspired, as each RLR driver can adopt a strategy faced with red lights that depends on the particular condition in which he or she reaches the intersection;
ii. in a preventive approach, it is possible to reduce the number of RLR violations (and hence the likelihood of collision associated with them), by implementing engineering measures capable of containing unintentional behaviours;
iii. enforcement alone, though enacted with remote surveillance, can reduce red-light running, acting exclusively on the percentage of intentional violations, but may have no effect (or very limited effects) if in the specific case inadequate signal regulation is the main cause of the RLR phenomenon.

These considerations highlight the inadequacy of strategies concentrating solely on enforcement, without preliminary verification of the effective operational conditions at the controlled intersection.

Crash types related to red-light running

Theoretically, red-light violation can lead to accidents involving two or more vehicles, a single vehicle or an alternative form of transport (public transport and vulnerable users).

A crash into a fixed obstacle can occur when the red light running violator or the opposing legal driver performs an action to avoid the collision and ends up against a fixed obstacle. The commonest types of accidents caused by RLR vehicles generally involve several vehicles and regarding trajectories can be angle and turning crash types.

Strictly speaking, rear-end collisions cannot be considered among the outcomes of red-light running manoeuvres, though some studies highlight an increase in this type of collision as a consequence of reinforcement of red-light running enforcement.

Hence for subsequent modelling of the consequences of red-light violations, only the following three types of accidents will be considered:

i. right-angle (side impact) crashes correlated to crossing manoeuvres;
ii. turning and merging crashes correlated to left turn manoeuvres;
iii. merging crashes correlated to right turn manoeuvres.

EXPERIMENTAL OBSERVATIONS ON THE RLR PHENOMENON

A campaign of direct observations on the RLR phenomenon was carried out on a sample of 15 urban intersections distributed in non-local streets (collector) in the Milan municipal territory.

The main geometrical and signal regulation characteristics are indicated in Table 5; where there is asymmetry regarding the number of approach lanes, these are distinctly indicated in the order north-south or centre-suburbs.

About half the sample has a tram line through it.

Regarding the control type, eight intersections in the sample have fixed-cycle regulation; the other seven, at least at night, are controlled by a semi-actuated regulation system; no intersection is regulated by a fully actuated signal.

Table 5: Main geometrical and signal regulation characteristics in the experimental sample.

	N. LANE*		**MEDIAN WIDTH**	**CONTROL TYPE**				
Site	MAIN	SECONDARY		CICLE [sec]	n. vehicle phases	P / FA / SA ***	LT **** pr/pe/pr+pe	Tram
8	4	3	5 5	90-101 61-71**	2	SA	pr	absent
12	2	1	17 -	65	2	P	pr pe	absent
2	2	2	6 -	85 - 46	2	P	pr pe	absent
18	3	2	17 -	65	3	P	pr+pe	absent
13	2	2	17 10	65	2	P	pr	absent
15	3	3	12 20	65 50*	2	P	pr	absent
11	3	2	56 -	75 50**	2	P	pr pe	absent
7	3+1s 2+1s	2	1 15	70-var 50-var**	2	SA	pe pr	present
3	4+1s 4	1 2+1s	5 -	85 55	3	P	pe pr	present
10	3 4	2 1	15 -	60-63 56-50**	3	SA	pr pe	present
1	1+1s 1	1	30 -	70 45-54**	2	P / SA	pr+pe pr	present
4	3+1p[2] 4	2	2,5 -	75-65 55**	3	P / SA	pr pe	absent
5	3	3	12 -	65 50**	2	P	pr	present
6	2 2+2s	2	15 10	65 45- var**	2	P / SA	pr	present
9	2	1	15 -	65-57 54-51**	2	SA	pr pe	present

* s=service lane; p=protected lane; ** night function; *** cicle regulation: P = fixed cycle; FA = fully actuated signal; SA = semi actuated signal; **** left turn manoeuvre: pr = protected; pe = permitted; pr+pe = protected plus permitted.

The volumes of traffic served daily and over the whole working year are shown in Table 6; they were derived from surveys carried out throughout the day in a fragmentary way both on weekdays and at weekends. For expansion of the observations for traffic modulation we assumed the distribution type indicated by regulation SN 640 005a (2001) for roads with local and commuter traffic.

Table 6 - Traffic characteristics of the experimental sample

	AADT [veh/day]				ENTERING / YEAR	
Site	MAIN Street		SECONDARY Street		MAIN Street	SECONDARY Street
	weekday	holiday	weekday	holiday		
8	21.720	18.787	9.435	8.162	**14.770.646**	**7.385.912**
	20.367	17.617	11.610	10.042		
	42.086	**36.405**	**21.045**	**18.204**		
12	21.066	18.222	10.526	9.105	**14.968.129**	**6.583.779**
	21.583	18.670	8.234	7.122		
	42.649	**36.891**	**18.759**	**16.227**		
2	16.083	13.912	6.629	5.734	**11.932.338**	**4.316.457**
	18.610	16.098	5.921	5.122		
	34.693	**30.009**	**12.550**	**10.856**		
18	21.573	18.660	14.660	12.681	**16.222.076**	**11.846.027**
	20.069	17.359	15.748	13.622		
	41.641	**36.020**	**30.408**	**26.303**		
13	30.408	26.303	21.423	18.531	**19.293.352**	**14.733.442**
	19.117	16.536	16.398	14.184		
	49.525	**42.839**	**37.820**	**32.714**		
15	18.702	16.177	14.761	12.769	**14.384.447**	**6.729.044**
	22.698	19.634	4.606	3.984		
	41.400	**35.811**	**19.367**	**16.752**		
11	14.552	12.587	7.801	6.748	**10.000.429**	**5.683.753**
	14.230	12.309	8.557	7.402		
	28.782	**24.897**	**16.358**	**14.150**		
7	34.008	29.417	26.802	23.184	**20.882.274**	**18.458.787**
	19.596	16.951	20.581	17.803		
	53.604	**46.367**	**47.383**	**40.986**		
3	30.162	26.090	4.519	3.909	**16.879.471**	**5.484.631**
	18.915	16.362	11.428	9.885		
	49.077	**42.451**	**15.946**	**13.794**		
10	23.785	20.574	22.886	19.796	**14.020.598**	**12.317.502**
	18.714	16.188	14.058	12.160		
	42.499	**36.762**	**36.944**	**31.956**		
1	15.759	13.631	9.915	8.576	**9.719.612**	**6.554.775**
	13.703	11.853	9.954	8.610		
	29.462	**25.485**	**19.869**	**17.187**		
4	20.181	17.456	12.945	11.197	**12.682.165**	**8.172.133**
	18.157	15.706	8.033	6.948		
	38.338	**33.162**	**20.978**	**18.146**		
5	57.089	49.382	24.904	21.542	**34.551.748**	**17.323.576**
	47.644	41.212	27.608	23.881		
	104.733	**90.594**	**52.511**	**45.422**		
6	54.371	47.031	14.176	12.263	**34.141.019**	**7.944.269**
	49.118	42.487	9.904	8.567		
	103.488	**89.517**	**24.081**	**20.830**		
9	28.410	24.575	15.257	13.198	**16.496.113**	**6.723.469**
	19.552	16.912	4.291	3.712		
	47.962	**41.487**	**19.548**	**16.909**		
			total entering flow		**140.257.557**	**260.944.416**

The AADT estimates were made for each approach and each direction. They are shown in Table 6 with the same convention as indicated before for the number of lanes. The overall entering volume is indicated cumulatively for the main road and secondary road directions.

On the basis of the data given, the sample includes a significant variety of traffic conditions:

- from 29,000 vpd to over 100,000 vpd, regarding vehicles entering the main road on weekdays;
- from about 12,000 vpd to over 52,000 vpd, regarding vehicles entering from the secondary road on weekdays.

The data on violations given in Table 7 were processed starting from direct observations made by the municipal police on weekdays in 2002; they concerned groups of hours (for a total of 9) distributed during the day (9:00 – 12:00 a.m.; 14:00 -17:00 p.m.) and the night (23:00 p.m. – 02:00 a.m.). The average values of the violation rates found in the sample (8.92 viol/1000 veh, for the main road during the day; 22.77 viol/veh for the secondary road during the day) show the size of the phenomenon; in agreement with the studies based on the HSIS database referred to above (Mohamedshah et al., 2000), they also confirm the higher incidence (2:1, day and night on average) of the RLR phenomenon on approaches with lower traffic volumes.

Table 7 – Summary of violation data from experimental sample

	MAIN STREET *		**SECONDARY STREET ***		**DISTRIBUTION [percent] main / secondary**		
Site	viol/h	viol/1000 veh	viol/h	viol/1000 veh	CR	LT	RT
8	16,33	6,85	7,50	6,29	36,52	56,18	7,30
	26,67	*42,24*	*10,00*	*31,68*	16,00	49,33	34,67
12	38,50	15,93	61,33	57,70	75,09	9,75	15,16
	15,33	*23,97*	*17,33*	*61,60*	79,78	37,38	10,00
2	4,67	2,37	24,67	34,68	48,48	10,61	40,91
	12,67	*24,34*	*8,00*	*42,50*	30,23	47,67	22,09
18	62,17	26,35	28,83	16,73	61,37	31,37	7,25
	45,67	*73,11*	*19,33*	*42,39*	57,58	15,15	27,27
13	34,00	12,12	155,50	72,56	67,32	8,66	24,02
	16,67	*22,44*	*55,67*	*98,13*	21,91	72,55	5,55
15	29,17	12,43	45,50	41,46	45,96	24,84	29,19
	49,00	*78,90*	*43,00*	*148,02*	33,83	29,35	36,82
11	15,33	9,40	22,83	24,63	55,64	23,31	21,05
	13,67	*31,66*	*26,33*	*107,32*	64,35	16,67	18,98
7	16,33	5,38	47,33	17,63	47,25	11,01	41,74
	30,00	*37,31*	*33,00*	*46,43*	72,06	18,02	9,92
3	22,67	8,15	7,83	8,67	26,19	29,76	44,05
	20,33	*27,62*	*9,00*	*37,63*	43,65	18,78	37,56
10	19,33	8,03	21,50	10,27	63,64	16,04	20,32
	23,67	*37,13*	*28,33*	*51,13*	73,36	4,21	22,43
1	4,17	2,50	0,83	0,74	60,47	16,28	23,26
	6,00	*13,58*	*0,67*	*2,24*	28,57	42,86	28,57
4	21,33	9,82	11,33	9,53	53,25	26,02	20,73
	6,00	*10,43*	*19,00*	*60,38*	38,40	16,80	44,80
5	27,17	4,58	40,17	13,50	51,00	4,82	44,18
	28,67	*18,25*	*15,67*	*19,89*	0,75	0,15	0,10
6	11,17	1,90	10,17	7,45	18,37	26,53	55,10
	10,33	*6,66*	*8,33*	*23,07*	29,07	51,16	19,77
9	21,67	7,97	21,83	19,71	45,96	24,84	29,19
	43,00	*59,77*	*27,67*	*94,35*	33,83	29,35	36,82
Average value	**22,93**	**8,92**	**33,81**	**22,77**	**50,43**	**21,33**	**28,23**
	23,18	***33,83***	***21,42***	***57,78***	**41,56**	**29,96**	**23,69**
			Average (main/secondary)		***56,4***	***19,7***	***23,9***
					44,6	***37,1***	***18,2***
			Average (intersection)		***50,0***	***29,2***	***20,8***

* daytime value (9:00 – 12:00 a.m.; 14:00 -17:00 p.m.); italics indicate night value (23:00 p.m. – 02:00 a.m.)

As regards distribution of violations by manoeuvre type, there is a marked prevalence of crossing of intersections (over 56 percent on the main road), while left-turn manoeuvres show a relative higher incidence on secondary roads.

The number of injury crashes per million vehicles and the distribution of crashes by type are shown in Table 8. The statistics were processed on the basis of injury and fatal accidents recorded by the municipal police in the period 2000-2003. An analysis of the accidents referable to the RLR phenomenon was also carried out starting from crash reports, through both analysis of collision and citations. The results of the analysis, also given in Table 8, show that:

- the sites present in the sample mostly have similar accident rates to one another (only in three cases the comparison with the usual control values indicate an over-representation of the accident phenomenon, while in three cases there was under-representation);
- the most frequent types of crash were the angle crash and the turning crash, accounting on average for over 50 percent of injury crashes at intersections;
- rear-end crashes and lateral ones on average do not exceed 20 percent and 15 percent, respectively; in relation to local situations (e.g. sites 8, 10 and 15) may account together for a quota close to 50 percent of total accidents;
- the incidence of the RLR phenomenon on total accidents, on average close to 50 percent, maintains slightly lower values than angle/turning crashes; in agreement with the high severity index found for RLR crashes, this suggests that the former are almost entirely due to illegal manoeuvres;
- on average, in agreement with what is reported by Retting et al. (1999), traffic situations that are less conditioned by traffic flows (as at night) do not seem to aggravate the consequences of the RLR phenomenon; in some cases, however (e.g. sites 11, 12 and 13) they can even give rise to exceptionally high risk situations, in an absolute sense and due to RLR drivers, at night, when there may be a concentration of over 70 percent of RLR-related crashes.

Table 8: Summary of crash report statistics and RLR related crashes for experimental sample

		CRASH TYPE [percent]			RLR CRASH RELATED [percent]				
Site	**I_j^***	Angle / Turning	Rear end	Lateral	crashes / total crashes	injured / total injured	injured per crash	daytime	night time
8	0,50	43,18	34,09	15,91	40,91	43,08	1,56	61,11	38,89
12	1,04	70,79	11,24	6,74	68,54	80,57	2,31	31,15	68,85
2	0,68	54,55	11,36	13,64	45,45	47,62	1,50	85,00	15,00
18	0,75	57,30	17,98	6,74	55,95	60,61	1,70	53,19	46,81
13	0,66	59,55	16,85	15,73	55,06	64,63	1,94	20,41	79,59
15	1,20	43,56	22,77	24,75	42,57	52,24	1,63	76,74	23,26
11	0,80	74,00	2,00	16,00	72,00	72,84	1,64	30,56	69,44
7	1,04	60,12	14,72	14,11	55,83	62,79	1,78	58,24	41,76
3	0,55	36,73	26,53	16,33	18,37	21,52	1,89	66,67	33,33
10	0,77	41,98	28,40	17,28	38,27	46,76	2,10	45,16	54,84
1	0,67	51,16	16,28	13,95	51,16	67,53	2,36	50,00	50,00
4	0,90	59,46	21,62	10,81	47,30	52,88	1,57	74,29	25,71
5	0,41	43,53	18,82	9,41	29,41	33,90	1,60	40,00	60,00
6	0,38	48,44	21,88	12,50	45,31	50,59	1,48	62,07	37,93
9	0,65	56,25	21,88	0,06	56,67	61,22	1,76	58,82	41,18
Average	**0,73**	**53,37**	**19,09**	**12,93**	**48,19**	**54,59**	**1,79**	**54,23**	**45,77**

* I_j = number of injury accidents x 10^6 / entering vehicles at intersection (average value in the period 2000-2003)

CONSTRUCTION OF A “HYBRID” MODEL FOR INTEGRATING VIOLATION BEHAVIOURS

As stated above, it was felt that the previously illustrated results obtained by Ha & Berg could constitute an excellent starting point for constructing a model capable of integrating the potential conflicts generated by red-light running manoeuvres.

This type of conflict, summed with those due to “legal” manoeuvres, can derive in turn from three distinct types of RLR manoeuvre, for each of which it is possible to hypothesise one or more scenarios capable of generating conflict opportunities.

For this purpose, for modelling RLR vehicle behaviour three main cases will be treated separately:
- Case **I**: red-light running through the intersection;
- Case **II**: right-turn red-light running;
- Case **III**: left-turn red-light running.

For identification of the intersection approaches and the different traffic streams, reference will be made to a four-approach scheme, for which the conventions in **Fig. 2** apply.

For the discussion below we will proceed successively to show adopted criteria for:
- evaluation of potential RLR drivers,
- evaluation of RLR potential conflicts,
- evaluation of models parameters depending from arrival process and gap distribution.

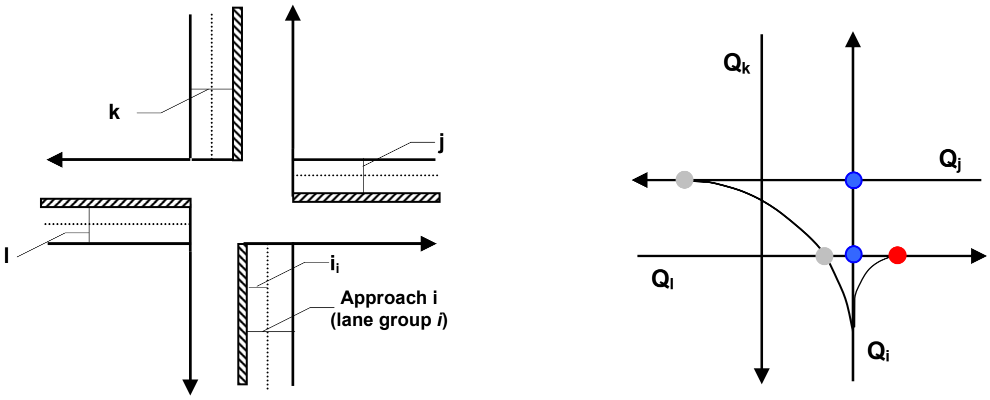


Figure 2 – Conventions used for identifying approaches and traffic streams

RLR Drivers

The number of drivers involved in red-light violation in a given time interval (e.g. an hour), as stated above, depends on multiple causal factors; they include operational conditions (traffic flows and signal regulation), geometrical characteristics of intersection (number of lanes, grade, etc.) and weather and environmental conditions, too.

Between more recent studies, the one by Hill and Lindly (2004) indicates that, according to multiple linear regression model, the following explicative variables of RLR phenomenon are the most significant:
- number of lanes on the main road (AL);
- number of lanes on the secondary road (CL);
- average daily traffic (ADT) on the main road.

The overall number of violations per hour can be evaluated with following expression:

$$Violations/h = -0.78 + 1.43AL - 0.321CL + 5.7 \cdot 10^{-5} ADT$$

Previsional model, like the one just shown, even if are suitable to value overall the dimension of RLR phenomenon, don't allow to know local values (e.g. in time interval of an hour). Unless doing gross adjustment, this is the reason why this type of previsional model are not convenient to built a model based on potential conflict generated by red-light running manoeuvres ("hybrid" model).

Hence, an alternative approach to evaluate the number of RLR drivers, can be developed considering at first the potential red-light violations (i.e. drivers for which conditions of an RLR manoeuvre exists); effective violations of red-light can be evaluated from the number of potential ones by a conversion coefficient k (related to the hour of the day). The coefficient k requires to be calibrated through field observations in the study area (for a given time period and for a given area, k expresses inclination to violate the red lights, related to the local operational conditions).

The number of potential RLR drivers can be empirically determined, considering that the following are potentially exposed to red-light running:

i. vehicles that while the lights are red are at the front of the queue;

ii. vehicles that reach the intersection while the lights are yellow, and particularly those that arrive in the interval $\Delta t = y_i - e$, where: y_i is change and clearance interval; *e* is extension of effective green time, with a duration equal to about 2 s (the time may be longer when there is traffic congestion) (HCM, 2000). This share of potential RLR drivers contains also vehicles drawn into the intersection by the leading RLR vehicle; in agreement with the ITE indications (1999) and the observations by Bonneson et al. (2001) these latter can be made to correspond to drivers that follow closely, i.e. those that in the interval $\Delta t = y_i - e$ reach the intersection with distancing of less than 2 s.

Hence altogether to calcolate the hourly number of RLR drivers we can refer to the following form:

$$Q^{e}_{RLR,i} = k \cdot Q^{p}_{RLR,i} = k\left(Q^{p}_{r_i} \cdot \delta_1 + Q^{p}_{y_i} \cdot \delta_2\right) = k\left(\frac{3600}{c} N_i \cdot \delta_1 + \cdot \frac{Q_i \cdot \Delta t}{c} \cdot \delta_2\right)$$

where

δ_1, depending on flow rate Q_i and number of lanes N_i, represents the proportion of cycles of the hour in which a sufficient probability of arriving a vehicle in the time interval r_i exists;

δ_2, depending on flow rate Q_i and number of lanes N_i, represents the proportion of cycles of the hour in which a sufficient probability of arriving a vehicle in the time interval $\Delta t = y_i - e$ exists;

N_i is the number of lanes on the i-th approach;

c is the duration of the cycle.

Evaluation of RLR Conflicts Opportunities

Case I: red-light running through the intersection

As seen in connection with the behaviour of the RLR driver, two distinct scenarios are possible.

The first corresponds to an unintentional manoeuvre (the RLR vehicle enters the intersection blindly, without stopping at the signal). In this hypothesis, the RLR vehicle coming from approach *i* subsequently comes into conflict with the two streams on the adjacent approaches Q_l and Q_j.

The conditions that may give rise to a potential conflict are:

a) an RLR vehicle reach the intersection without slowing down or halting at stop line;
b) in the time t_{clr} required for crossing the lanes on approach *i* a vehicle arrives in the stream Q_l;
c) the RLR vehicle, after crossing the stream Q_l without a collision, meeting on its trajectory a vehicle Q_j; i.e. in the time t'_{clr} required for crossing the approach j a vehicle in stream Q_j arriving.

Hence the number of potential conflicts associated with the blind crossing manoeuvre is the sum of the number of potential conflicts corresponding to events b) and c). Assuming $P(\tau_l < t_{clr})$ and $P(\tau_j < t'_{clr})$ for the probabilities of a vehicle in streams Q_l and Q_j, respectively, arriving as the RLR vehicle passes, the number of potential conflicts associated with each of the two events can be determined as follows[1]:

$$N'_{RLR,cross_i} = \alpha_1 \cdot Q^{e}_{RLR,i}\left[P\left(\tau_l \le t_{clr}\right) + P\left(\tau_j \le t'_{clr}\right)\right]$$

where τ_l e τ_j represent gaps, respectively, in streams Q_l e Q_j and the coefficient α_1 represents the share referable to unintentional behaviours of RLR vehicles.

For the determination of the intersection clearance time for non-intentional RLR crossing drivers – i.e. of the time intervals t_{clr} and t'_{clr} necessary for the RLR vehicle coming from approach i to cross the first stream (Q_l) and the second (Q_j) respectively – it can be assumed that crossing takes place at a constant speed v_i; with reference to the conventions adopted above, we have:

$$t_{clr} = \frac{N_l w_l + l_v}{v_i}; \quad t'_{clr} = \frac{N_j w_j + l_v}{v_i}$$

where: N_l, N_j = number of lane in approach *l* (*j*);
w_l,w_j = lane width in approach *l* (*j*);
l_v = vehicle length.

As regards the second scenario in the case being examined (intentional violation), it can be supposed that the RLR driver decides to violate the red lights after stopping. The conditions that may give rise to a potential conflict are analogous to those for a driver having to cross a stop-controlled intersection, after evaluating the gap required for performing his or her manoeuvre safely in relation to the positions of the vehicles in the opposite streams.

In this case too, three eventualities have to be considered:

A. an RLR vehicle reaches the intersection;
B. the RLR driver observing (and accepting) a gap in the stream Q_l in the interval $t_l < t < t_u$ which, as seen in the case of the legal left turning manoeuvre, involves a margin of error;
C. after the stream Q_l, has been crossed, a gap being available in stream Q_j, which is in the "unsafe" interval $t'_l < t' < t'_u$.

Analogously to what was seen for the scenario previously examined, the number of potential conflicts is proportional to the number of RLR vehicles fulfilling condition A) and the likelihood of events B) and C).

Hence, having set

$$P(B) = P\left(t^{cr}_{li} < t < t^{cr}_{ui}\right) \text{ e } P(C) = P\left(t'^{cr}_{li} < t' < t'^{cr}_{ui}\right),$$

relative to the scenario being examined, the number of potential conflicts associated with the RLR crossing from the generic arm *i* can be determined using the expression:

$$N''_{RLR,cross_i} = \alpha^{cr}_2 \cdot Q^{e}_{RLR,i} \cdot \left[P\left(t^{cr}_{l,i} < t^{cr}_{i} < t^{cr}_{u,i}\right) + P\left(t'^{cr}_{l,i} < t'^{cr}_{i} < t'^{cr}_{u,,i}\right)\right]$$

where α_2^{cr} represents the share of RLR vehicles, as previously defined, referable to intentional crossing of the red lights.
Altogether we have:

$$N_{RLR,cross_i} = N'_{RLR,cross_i} + N''_{RLR,cross_i} =$$
$$= Q^e_{RLR,i} \cdot \{\alpha_1 \cdot [P(\tau_l \le t_{clr}) + P(\tau_j \le t'_{clr})] + \alpha_2^{cr} \cdot [P(t^{cr}_{l,i} < t^{cr}_i < t^{cr}_{u,i}) + P(t'^{cr}_{l,i} < t'^{cr}_i < t'^{cr}_{u,i})]\}$$

Case II: right-turn red-light running
In this case, it can be supposed that the RLR driver makes the manoeuvre from a stationary position and decides to enter the stream to his right when the gap available to him is deemed sufficient for performing the manoeuvre safely.
The situations that can generate a potential conflict, as seen in the previous case, are those in which the gap for the merging manoeuvre is in the unsafe interval $t_l < t < t_u$. Alongside this eventuality, another necessary condition is that the RLR vehicle reaches the red light.
Indicating as A and B the two elementary events mentioned above, the likelihood of having a potential conflict for the case being examined proves to be equal to *P(A) · P(B) = P(A ∩ B)*; because of the positions made, the overall number of conflicts that can be evaluated is:

$$N_{RLR,rt_i} = \alpha_2^{rt} \cdot Q^e_{RLR,i} \cdot P(t^{rt}_{l,i} < t^{rt}_i < t^{rt}_{u,i})$$

where α_2^{rt} represents the share of RLR vehicles referable to intentional right-turning of the red lights from the generic arm *i.*

Case III: left turn red-light running.
As in the previous case, the RLR vehicle is likely to start its manoeuvre from a stationary position.
Depending on the median width (and hence on the recovery possibilities for the turning vehicle) the manoeuvre may be made in a single stage or in two stages.
Only the first scenario (insufficient median) will be considered: the RLR driver makes the manoeuvre after evaluating the simultaneous presence of adequate gaps both on the nearest stream to be crossed Q_l (event A), and on the final destination, i.e. the stream Q_J, he/she intends to enter (event B).
The conditions to be considered are:

A) the RLR driver is present at intersections proper;

B) the RLR driver decides to make the turn in a gap in stream Q_l in an interval $(t^{lt}_{l,i} < t^{lt}_i < t^{lt}_{u,i})$ which may be insufficient for clearing the lane (or lanes) used by Q_l; the corresponding likelihood depends on the gap distribution in stream Q_l and on the critical interval for the turn, i.e. on the time the driver deems sufficient for clearing the carriageway occupied by the Q_l vehicle:
$$P(B) = P(t^{lt}_{l,i} < t^{lt}_i < t^{lt}_{u,i}).$$

C) after crossing stream Q_l without a collision, analogously to what was seen for case I, stream Q_j is entered in an interval $(t'^{lt}_{l,i} < t'^{lt}_i < t'^{lt}_{u,i})$; the corresponding probability is:
$$P(C) = P(t'^{lt}_{l,i} < t'^{lt}_i < t'^{lt}_{u,i})$$

In the hypothesis of arrivals of streams Q_l and Q_j occurring with a law of probability of a Poisson's type, the number of potential conflicts from irregular left turns can be calculated with the expression:

$$N_{RLR,lt_i} = \alpha_2^{lt} \cdot Q^e_{RLR,i} \cdot \{(e^{-N_l \cdot \lambda_l . t^{lt}_{l,i}} - e^{-N_l \cdot \lambda_l . t^{lt}_{u,i}}) + (e^{-N_j \cdot \lambda_j . t'^{lt}_{l,i}} - e^{-N_j \cdot \lambda j \cdot t'^{lt}_{u,i}})\}$$

where α_2^{lt} represents the share of RLR vehicles referable to intentional left-turning of the red lights from the generic arm *i.*

Finally, the overall number of potential conflicts that can be evaluated of red light violation, is:

$$N_{RLR} = Q^e_{RLR,i} \cdot \{\alpha_1 \cdot [P(\tau_l \le t_{clr}) + P(\tau_j \le t'_{clr})] + \alpha_2^{cr} \cdot [P(t^{cr}_{li} < t^{cr}_i < t^{cr}_{ui}) + P(t'^{cr}_{l,i} < t'^{cr}_i < t'^{cr}_{u,i})] +$$
$$+ \alpha_2^{rt} \cdot P(t^{rt}_{l,i} < t^{rt}_i < t^{rt}_{u,i}) + \alpha_2^{lt} \cdot [P(t^{lt}_{l,i} < t^{lt}_i < t^{lt}_{u,i}) + P(t'^{lt}_{l,i} < t'^{lt}_i < t'^{lt}_{u.i})]\}$$

Evaluation of Model Parameters Depending on Arrival Process and Gap Distribution

In the modelling of users' behaviour, both legal and RLR, the arrival process and gap distribution play a primary role which is reflected through the times t_{clr} e t'_{clr}, as well as through the unsafe intervals (t_l, t_u).
As is known from the literature, the arrivals of single stream and the consequent gap distribution can be described in different ways, depending on traffic intensity and the arrival type (in platoons, random, uniform, etc.).

Generally speaking, the law of arrivals must be appropriate to the traffic condition observed in the time interval considered, and in particular to the statistical parameters (average $\bar{x}$ and variance s^2) characterizing it. Apart from the case of queue discharging after a red period, reference can be made to the following indications found in the literature.

Poisson's distribution can be retained valid for flow values not above 400 vph and flows in stationary conditions: $P(x,t) = \frac{(q \cdot t)^x}{x!} \cdot e^{-qt}$.

Outside the hypothesis above mentioned, in relation to the value of the ratio $\frac{s^2}{\bar{x}}$ we can assume:

- negative binomial distribution for $\frac{s^2}{\bar{x}} > 1$:

$$P(x,t) = \begin{pmatrix} x + k - 1 \\ k - 1 \end{pmatrix} \cdot p^k \cdot (1 - p)^x$$

where $p = \frac{\bar{x}}{s^2}$; $k = \frac{\bar{x}^2}{(s^2 - \bar{x})}$; $\bar{x} = q \cdot t$;

- binomial or generalized Poisson's distribution for $\frac{s^2}{\bar{x}} < 1$:

$$P(x,t) = \begin{pmatrix} n \\ x \end{pmatrix} \cdot p^x \cdot (1 - p)^{n-x} \text{ (binomial)}$$

where $p = \frac{(\bar{x} - s^2)}{\bar{x}}$; $n = \frac{(\bar{x}^2)}{\bar{x} - s^2}$; $\bar{x} = q \cdot t$;

$$P(x,t) = \sum_{i=1}^{k} \frac{e^{-\lambda} \cdot \lambda^{(x \cdot k + i - 1)}}{(x \cdot k + i - 1)!} \text{ (generalized Poisson's)}$$

where $\lambda = k \cdot \bar{x} + \frac{(k-1)}{2}$ $\bar{x} = q \cdot t$; ($k = 2$ for 400<Q≤1000 vph; $k = 3$ for 1000<Q≤1500 vph)

The probability of vehicular distances in a given stream being comprised between two assigned values τ_l and τ_u (which has to be determined for all manoeuvres performed by RLR drivers) can at first be calculated through the exponential negative distribution (for low traffic intensity) and for major flows and more in general through Erlang's distribution[2].

By example, for the manoeuvres performed intentionally, in agreement with consolidated assumptions by Italian researchers (Ferrari and Giannini, 1991), we can set:

- $P(t_l < t < t_u) = e^{-\lambda \cdot t_l} - e^{-\lambda \cdot t_u}$

for Q = 3600·λ < 400 vph

- $P(t_l < t < t_u) = e^{-k \cdot \lambda \cdot t_l} \sum_{n=0}^{k-1} \frac{(k \cdot \lambda \cdot t_l)^n}{n!} - e^{-k \cdot \lambda \cdot t_u} \sum_{n=0}^{k-1} \frac{(k \cdot \lambda \cdot t_u)^n}{n!}$

with K = 2 for 400 < Q < 1000 vph e k = 3 for Q > 1000 vph

At all events, whatever gap distribution is used, a univocal definition is required of the time intervals t_l and t_u to which there correspond behaviours capable of generating potential conflicts.

On the basis of what has been stated, for a conflict to arise, the amplitude (t_u - t_l) of these intervals must necessarily be a small one; it can be estimated by means of the variance of the acceptable gap (Ha & Berg, 1995). Below, as a first approximation, it will be assumed to be equal to ± 2 sec., independently of the type of manoeuvre.

In the absence of field measurement, for a given manoeuvre the central value of the interval (t_u - t_l) can be made to correspond to the critical gap, i.e. to the lower limit of its field of variability (Mauro and Cattani, 2002). Appropriate values of the critical gap, for the cases we are interested in (one-stage gap acceptance, four-leg intersection) can be calculated with the method suggested by the Highway Capacity Manual (2000), i.e. on the basis of the equation:

$$t_{c,i} = t_{c,b} + t_{c,HV} \cdot P_{HV} + t_{c,G} \times G$$

where the symbols have the same meanings as in the Manual (see table 9 for typical values of $t_{c,b}$)

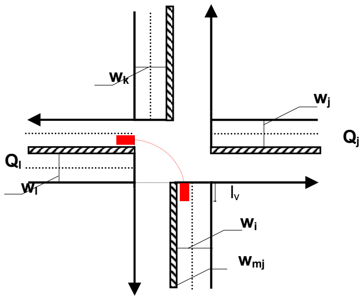
Table 9 – Typical values of the base critical gap

vehicle movement	Base critical gap, $t_{c,b}$	
	Two-lane major street	Four-lane major street
Left turn from major	4,1	4,1
Right turn from minor	6,2	6,9
Through traffic on minor	6,5	6,5
Left turn from minor	7,1	7,5

As an alternative to the use of the critical gap, the interval t_u - t_l can be centred on the intersection clearance time (Ha & Berg, 1995); in this case, there is the advantage of directly involving the geometrical characteristics of the intersection (lane width, median width) and the type of manoeuvre.

On the basis of what has been stated, for the various cases considered in the construction of the hybrid model, the parameters t_l and t_u can be assumed as specified in **Fig. 3**.

a. Left turn legal manoeuvre t express in (s)



$$t_i = \sqrt{\frac{2\cdot(d_i + l_v)}{a}}$$

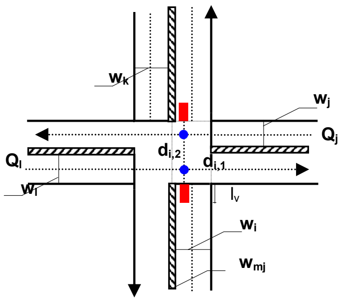
$$d_i = \frac{\pi}{2}\left(\frac{w_i}{2N_i} + w_{mi} + w_k\right)$$ with a= 1,3 m·s^{-2}

$$t_{clear} = t_i + t_{pr} = t_i + 2$$

$$t_l = t_{clear} - 2 = t_i$$

$$t_u = t_{clear} + 2 = t_i + 4$$

b. RLR crossing manoeuvre (halt manoeuvre)



a. conflicts with stream Q_l

$$d_{i,1} = w_l$$

$$t_i = \sqrt{\frac{2\cdot(w_l + l_v)}{a}}$$

$$t_{clear} = t_i + t_{pr} = t_i + 2$$

$$t^{cr}_{l,i} = t_i$$

$$t^{cr}_{u,i} = t_i + 4$$

b. conflicts with stream Q_j

$$d_{i,2} = (d_{i,1} + w_{mi} + w_j)$$

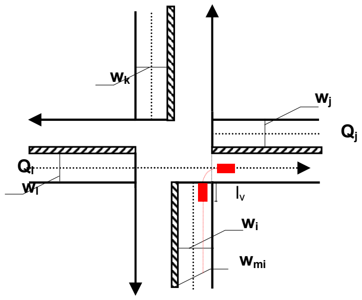
$$t'_i = \sqrt{\frac{2\cdot(d_{i,2} + l_v)}{a}}$$

$$t'_{clear} = t'_i + t_{pr} = t'_i + 2$$

$$t'^{cr}_{li} = t'_{clear} - 2 = t'_i$$

$$t'^{cr}_{ui} = t'_{clear} + 2 = t'_i + 4$$

c. RLR right – turning manoeuvre



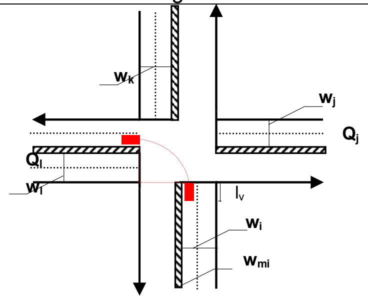
$$t_{clear} = t_{crit} + t_{pr} = t_{crit} + 2$$

$$t_{crit} = t_{CD} + t_{CHV}\cdot P_{HV} + 0{,}1\cdot G^*$$

$$t_{l,RT} = t_{crit} - 2$$

$$t_{u,RT} = t_{crit} + 2$$

d. RLR left – turning manoeuvre



a. crossing stream Q_l

$$d_{i,1} = \frac{d_i}{2}$$

$$t_{i,1} = \sqrt{\frac{(d_i + 2\cdot l_v)}{a}}$$

with a = 2 m·s^{-2}

$$t_{clear} = t_{LT} = t_{i,1} + 2$$

$$t_{l,LT} = t_{i,1}$$

$$t_{u,LT} = t_{i,1} + 4$$

b. left merging in stream Q_j

$$d_i = \frac{\pi}{2}\left(\frac{w_i}{2N_i} + w_{mi} + w_k\right)$$

$$t_{i,2} = \sqrt{\frac{2\cdot(d_i + l_v)}{a}}$$

with a = 2 m·s^{-2}

$$t_{clear} = t'_{LT} = t_{i,2} + 2$$

$$t'_{l,LT} = t'_{i,2} = t'_{LT} - 2$$

$$t'_{u,LT} = t'_{i,2} + 4$$

Figure 3 – Schemes for clearance time calculation

CONCLUSIONS AND FUTURE DEVELOPMENTS

The analysis of the RLR phenomenon, as it appears from the literature and from the field measurements carried out, has made it possible to highlight the dimension that the problem takes on in urban situations typical of the national context and to formulate a hybrid model, in which the potential conflicts depend on both legal and illegal manoeuvres. This model increases the interpretative capacities of those given in the literature for signalized intersections and makes it possible explicitly to consider the functional aspects most directly referable to working conditions typical of this kind of installation. These include:

- the main geometrical characteristics of the installation, represented at the moment by the number of lanes on the approach and the median width;
- the fundamental characteristics of signal control (cycle duration, effective green light time, yellow light time, etc.);
- the present traffic demand and its distribution in the various streams entering the intersection;
- the arrival process and gap distribution characteristics.

For the development of research in the direction of implementation of a model for predicting accidents, the analyses developed for modelling drivers' behaviour (legal and RLR) show the necessity of further widening of the research in the direction we wish to highlight here:

- enlargement of the experimental basis, through field measurements serving to specify the values of the parameters assumed for describing users' behaviour, and in particular the time intervals t_{clr}, t_l e t_u, as well as coefficients k, α_1 and α_2^{cr}, α_2^{rt}, α_2^{lt} identifying the propension to violation of the red light and the quotas of RLR drivers referable to unintentional manoeuvres and intentional ones;
- generalization of the model to any number of vehicular phases and/or to the case of manoeuvres carried out in the protected signal phases;
- consideration of conflicts affecting pedestrians present on the intersection during an RLR manoeuvre;
- clarification of the possible interactions between lateral conflicts and between the single streams on an approach and RLR vehicles, the hypothesis of uniqueness of the arrival process and gap distribution being abandoned;
- verification of the capacity of the model to identify possible conflicts for comparison with traffic conflicts observed in the field;
- calibration of the hybrid model through accident data broken down by accident type for the purpose of developing risk indicators based on potential conflicts.

ENDNOTES

[1] Bearing in mind that the collision is at all events a rare event, and in any case much less probable than the potential conflict associated with it, event C can be considered independent of the collision which does not take place as the stream Q_l is crossed.

[2] More complex gap distributions could be used, as the shifted exponential one or the bunched exponential one. The former (shifted exponential) ensures distances not inferior to a pre-established interval; the latter makes it possible to take platoon arrivals into account, separated from one another by exponential gaps.

Some researchers (e.g., Heidemann and Wegmann, 1997), have shown that in order to describe in a more general manner the arrival process of a stream one can have recourse to a "gap-block" model, using the analogy with the green and red periods typical of the signal control regulation (green-red model).

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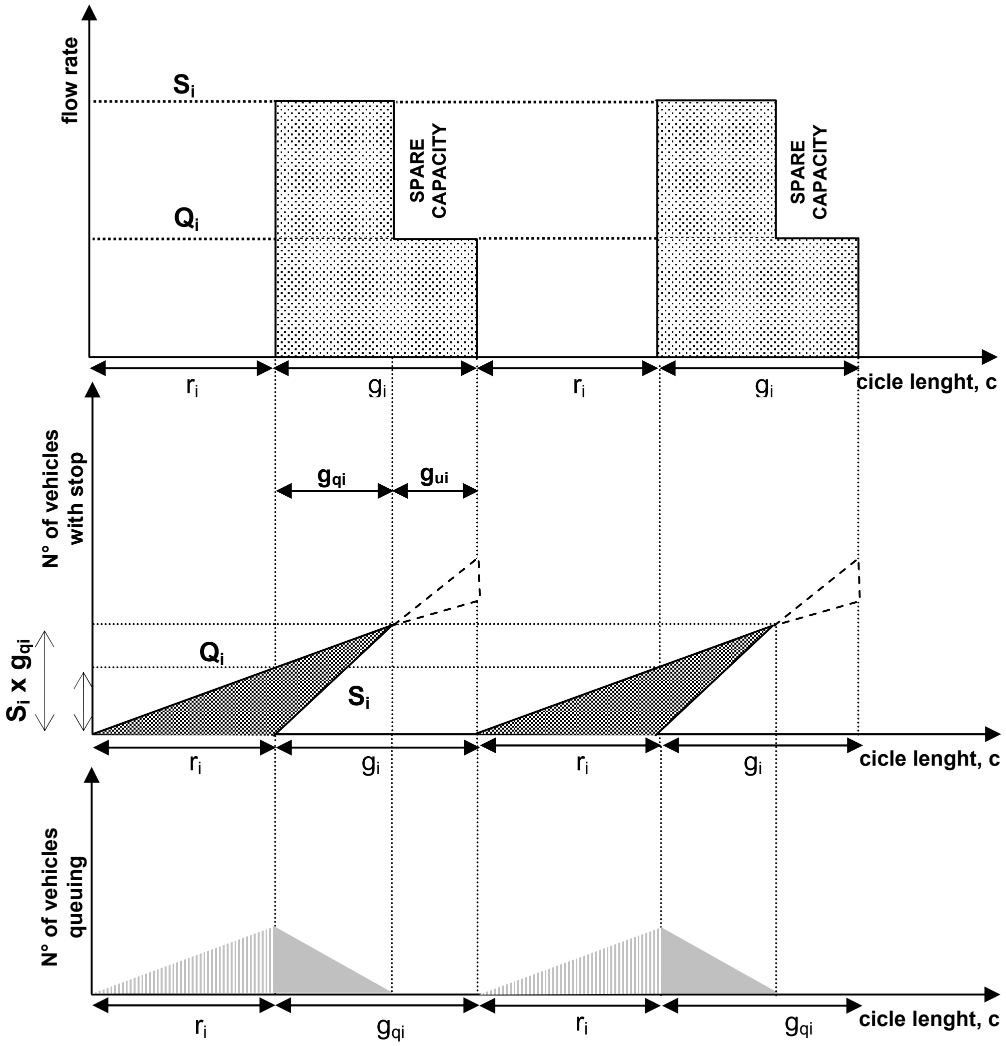
APPENDIX 1

Relevant Characteristics and Parameters for the Continuum Model Used for Evaluation of Rear–End Crash Opportunities



Saturation flow S (vph)	Time to clear queue on approach i	Effective Red time
$S_i = S_0 \cdot N \cdot f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$ where the principals adjustment factors are (otherwise, see HCM – 2000 chapter 16): $S_0 = 1{,}900$ [pc/h/ln] $f_w = 1 + \left(\frac{w - 3{,}6}{9}\right)$ $f_{HV} = \frac{100}{100 + \%HV \cdot (E_t - 1)}$ $E_t = 2.0$ pc/HV $f_{LU} = Q_g / (Q_{g1} \cdot N)$ $f_{LT} = 0.95$ if protected phasing and exclusive lane $f_{LT} = \frac{1}{1.0 + 0.05 P_{LT}}$ if protected phasing and shared lane; $f_{RT} = 0.85$ if exclusive lane $f_{RT} = 1.0 - (0.15) P_{RT}$ if shared lane $f_{RT} = 1.0 - (0.135) P_{RT}$ if single lane	$g_{q,i} = \frac{S_i \cdot r_i}{(S_i - Q_i)}$ [s] $S_i; Q_i$ [veh/h]; r_i [s]	$r_i = R_i + t_i = R_i + l_1 + l_2 = Ri + l_1 + Y_i$ - where: $l_1 = \sum_{i=1}^{N} t_i$ [s] total start-up lost time with t_i = lost time for each vehicle in queue l_2 = clearance lost time (the time between signal phases during which an intersections is not used by any traffic) e = extension of effective green time Y_i = change and clearance interval