Driver Behaviour At Urban Intersections

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Synopsis

The drivers of vehicles approaching an urban road intersection have to regulate their vehicle velocity in order to make their manoeuvre safely. This regulation depends also on the presence or not of eventual obstacles to a reciprocal and clear sighting of vehicles which belong to different streams.
In urban ambit, the presence of not eliminable obstacles to visibility causes inevitable slowing down even for the vehicles that have the right of way. Referring to an intersection whose circulating scheme is quite common in Palermo's city center (intersection of 4 branches with a one way circulation), the kinematical relations that justify the slowing down of the vehicles are recalled in the first part of this work.
Using these relations we can also demonstrates that the vehicles which go along the minor road must completely stop before being able to make their crossing manoeuvre. To verify the conclusions which derive from kinematics and only for the vehicles that have the right of way, an experimental research plan, aimed to find the characteristics of the motion of the vehicles in proximity to the studied intersections, has been prepared in advance.
After having described in brief the instruments mounted on an appropriately equipped vehicle, the processing steps necessary to reconstruct the velocity and acceleration trend are reproduced. In the end, the parameter values that have to be put in the kinematical equations and that, considering the experimental results obtained, better describe the real behaviour of the drivers close to the road intersections are proposed.

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The structure of the road network in the central areas of many cities suffers the effects of urban planning made a long time ago. Physical and environmental capacity limits of arches and road junctions are not always modifiable. They often result unacceptable with the present and elevated demand of mobility and of standing on road.
The consequent phenomenon of instability in circulation rules creates a series of negative effects that the local administrations, with appropriate measures, try to limit. Such measures have to adequately satisfy the over mentioned demand, the urgent economical needs and the needs of security, of environmental protection and of social development. In the presence of limited financial budgets, the intervention and/or alternative measure priorities must be established assigning, at first, an adequate importance to the various goals to achieve.
The correct formalization of some of these goals cannot leave out of consideration an accurate and realistic description of how the vehicular circulation proceeds in the different junctions of the road system. These are undoubtedly the most critical elements of the safety of urban road systems. Besides, they have an important role in the estimate, through appropriate simulating models, of the load on the road system, of the journey time and of the quantity of polluting emissions (acoustic and atmospheric). Therefore, it turns out useful to investigate on the behavior of a single road user in close proximity to road intersections; this should be done in order to deal, in an appropriate, coherent and faultless way, with the complex themes concerning the functionality (under many aspects) and the safety of each intersection and of the whole road network. Under this point of view, this work provides an initial contribution to the knowledge of the above mentioned behavior which is analyzed on the basis of dynamic data acquired by the sensors of the DIIV equipped vehicle.

SIGHT TRIANGLES

In order to guarantee a normal and safe vehicular traffic through road intersections it is indispensable that the drivers arriving from any road must see at least a sufficient part of every other road to avoid potential collisions. It is possible, then, to define the triangular superficies (sight triangles) in close proximity to the intersections where there aren't objects high enough to compromise a reciprocal vision of the vehicles (ESPOSITO, MAURO 2003) (FERRARI, GIANNINI 1980). The dimensions of these triangles are fixed on the basis of hypothesis on the behaviour of each road user which depends on innumerable influent factors among which the most important are:

- the psychophysical condition;
- the experience and driving skills;
- the reasons of the transfer;
- the vehicle's performances and efficiency ;
- the geometry and the regulations of the intersection;
- the distance and regulations of the previous intersection;
- the type of manoeuvre that has to be made (crossing, change of lane,…);
- the transversal dimension of the afferent stretch;
- the eventual interferences with other categories of road users on the same street space;
- the disposition of the vehicles parked (regularly or not) along the sidewalks;
- the vehicular density of the streams.

Even if the influent factors are numerous, a limited number of parameters synthesize the driver behaviour. For the yield control intersections, the technical regulations of some countries calculate the intersections sight distance (ISD) on the basis of the critical gap of the movement which is to be performed (BOLLETTINO CNR n. 90, 1983; NORME SUISSE VSS, 1998); *HIGHWAY DESIGN MANUAL*, 1998; *Traffic Flow Theory: A State Of The Art Report,* 1997; HARWOOD, D., FAMBRO, D., FISHBURN B., JOUBERT H., LAMM R., PSARIANOS, B, 1995).
The values of the gap are selected so as to reconcile requirements of safety and traffic fluidity. The definition of the gap values need accurate experimental surveys. The results of the experimental surveys, obtained in a fixed country, are not always valid in other countries. Besides we can admit that the ISD calculation, making use of the gap, certainly applies to the planning stage. For the existent intersections it have to verify that are guaranteed acceptable safety levels. This is possible making a comparison between the ISD values, really available, and the braking distance obtained from the equation of motion.

Kinematics in intersections

The geometric data we need in order to study the vehicle kinematics near to the urban intersections are shown in Fig. 1. One can suppose that:

- vehicles A and B make simple crossing movements;
- vehicle A has the right to go (major traffic flow);

- vehicle B must give the right of way (minor traffic flow);
- the drivers A and B, following the rules and in a perfectly rational and coherent way, pursue two distinct goals:
  - avoid any accident
  - minimize the time of their wait (or of their trip)

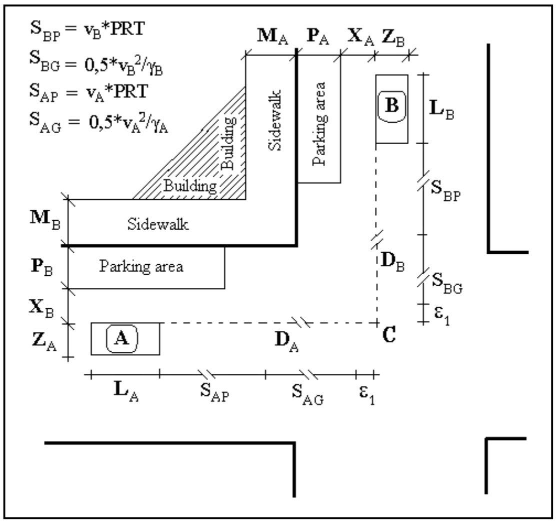

Figure 1: Intersection scheme

Besides it have to know:
- the velocities v_A and v_B in m/sec;
- the admissible accelerations a_A and a_B in m/sec^2;
- the admissible decelerations γ_A and γ_B in m/sec^2;
- the time of perception and reaction (PRT) in sec.

Apart from the approach security margin ε_1, expressed in terms of distance, one also considers the moving away security margin ε_2 not shown in Fig. 1.
We can suppose at first that the vehicle of the major traffic stream, in virtue of its right, maintains a constant velocity. The driver B who is approaching to an intersection has three options: slow down (till he/she stops), maintain his/her velocity or accelerate. The choice of one of these options happens after an elaborative process of the sensorial perceptions which, guided by past experiences, allows an evaluation of the temporal difference with which one vehicle and the other will cross the collision. The time necessary to complete such process is usually indicated with PRT (time of perception and reaction).
Considering, for both vehicles, a same PRT with Z_A=Z_A=Z e L_A=L_B=L, the stopping distances can be evaluated:

$$D_{B*} = S_{BP} + S_{BG} + \varepsilon_1 = (v_B*PRT) + 0,5*v_B^2/\gamma_B + \varepsilon_1$$
$$D_{A*} = S_{AP} + S_{AG} + \varepsilon_1 = (v_A*PRT) + 0,5*v_A^2/\gamma_A + \varepsilon_1$$

If vehicle B in the instant T=0 is at a distance $D_B=D_{B*}$, it completes the braking in the time:

$$T_{BF} = PRT + v_B/\gamma_B$$

In a T_{BF} time, vehicle A covers, with constant velocity, a distance equal to:

$$D_{AF} = v_A*T_{BF}$$

Vehicle B will be able to move again immediately (after stopping) if vehicle A, at the time T=0, is at a distance from the collision point equal to:

$$D_{AF1} = D_{AF} - Z - L - \varepsilon_2$$

If, instead, vehicle A is at a distance:

$$D_{AF2} = D_{AF} + \varepsilon_1$$

vehicle B will have to wait at least $T=(D_{AF}+Z+L+\varepsilon_1+\varepsilon_2)/v_A$. Only if vehicle A is at a distance $D_A>D_{AF2}$, the driver of vehicle B could have sufficient time to cross the intersection before the arrival of the opposing vehicle.
Vehicle B in order to complete the crossing without modifying its velocity must cover a distance equal to:

$D_{BK}= D_{B^*} +Z + L + \varepsilon_2$

The time to cover such distance will be:

$T_{BK} = D_{BK} / v_B$

The distance covered by vehicle A in a time $T=T_{BK}$ will be:

$D_{AK} = v_A*T_{BK}$

If vehicle B accelerates (uniformly accelerated motion with average acceleration α_B), the following quantities will be obtained:

$D_{BH}= D_{BK} = D_{B^*} + Z + L + \varepsilon_2$

$T_{BH} = TPR + [-v_B + (v_B^2+2* \alpha_B *(D_{BH} – v_B*PRT))^{0,5}]/ \alpha_B$

$D_{AH} = v_A*T_{BH}$

Comparing the values of D_{AF1}, D_{AF2}, D_{AK} and D_{AH} to the effective distance D_A (distance of vehicle A from the collision point), the crossing modality of the vehicle B can be deduced.

Parameter Values

The maximal decelerations and accelerations of a vehicle depend on the surface characteristics of the road, on the structural and on the efficiency of the vehicle. On a dry surface and in normal maintenance conditions, reported in literature data indicate that the maximal deceleration varies between 7,0 and 10,0 m/sec^2. The maximal decelerations obtained using the available test-vehicle did not result higher than 8,7 m/sec^2. For the design of some road elements, the AASHTOO and other regulations utilize, considering manoeuvres not in emergency, a deceleration value of 3,4 m/sec^2 (AASTHO 2001).
The maximal accelerations, in the same surface conditions, depend on the peculiarities of the vehicle and on the initial velocity. The maximal accelerations gathered with the test-vehicle did not result higher than 3,4 m/sec^2. Close to intersections, the usual accelerations, as we will say further on, vary between 1,0 and 2,0 m/sec^2.
The PRT depends on the driver psychophysical-aptitude-capabilities and varies in function both of the velocity of the vehicle and of the number of possible alternative responses to external stimulus. Some PRT experimental values are reproduced in Table 1.

Table 1: PRT Values

Motion of vehicle	Type of stimulus	Foot position	PRT
At a halt	Acustic signal	On the brake	0,24
At a halt	Acustic signal	On the accelerator	0,42
At a halt	Luminous signal	On the brake	0,26
At a halt	Luminous signal	On the accelerator	0,44
At a halt	Stop sign on a vehicle	On the brake	0,36
At a halt	Stop sign on a vehicle	On the accelerator	0,52
In normal march	Acustic signal	On the accelerator	0,46
In normal march	Stop sign on a vehicle	On the accelerator	0,83
In normal march	Hidden stop sign	On the accelerator	1,65

Report on Massachussets Highway Accident Survey, Massachussets Institute Technology and CWA-ERA Project, Cambridge.

Usually the PRT, for a dichotomous response, can be assumed equal to one second. In order to choose the geometric settling of a road intersection the ASTHOO proposes to presume a perception-reaction time variable between 1 and 2.5 sec depending on the ambit of the intersection (rural, suburban or urban).

Numerical Applications

Unless explicit instructions, the distance values have been calculated assuming:

PRT = 2,5 sec

$\gamma_A = \gamma_B = \gamma = 3,4$ m/sec^2;

$\alpha_A = \alpha_B = \alpha = 1,5$ m/sec^2;

$L_A = L_B = L = 4,0$ m (length of the vehicle variable between 2,85 and 4,90 m)

$Z_A = Z_B = Z = 1,7$ m (width of the vehicle variable between 1,66 and 1,88 m);

$\varepsilon_1 = \varepsilon_2 = 1$ m.

In order to guarantee a safe vehicular traffic at yield control intersections, the cathetus of the visibility triangles must have a length not inferior to the relative stop distances (D_{A*}, D_{B*}). In urban precincts, the buildings, the parked vehicles or other types of obstructions (hedges, aedicule, stands,…) are inflexible obstacles to the visibility. The drivers must, therefore, adjust the velocity of their vehicle to the existent state of the surroundings. Referring to Fig. 1 and not considering the direction, we can assume that:

- the parked vehicles take up the road for a P length comprised between 0 and 4 m;
- the sidewalks have an M length comprised between 2 and 5 m;
- the X distance (between a parked vehicle and one in motion) can vary between 0.5 and 1.5 m.

Supposing that the parked vehicles, in any case, do not create an obstacle for the visibility, one obtains a K distance (with K=P+M+X) comprised between 2.5 and 10,5. In order to keep adequate safety levels, a vehicle at a K distance from the collision point must travel at a velocity that would allow it to stop at a ε_1 distance from point C. Such velocities, using the data reported above and varying K, are reproduced in Tab. 2.

Table 2: Velocity versus obstacle distance (K)

K (m)	2,50	3,00	3,50	4,00	4,50	5,00	5,50	6,00	6,50	7,00	7,50	8,00	8,50	9,00	9,50	10,00	10,50
V (Km/h)	2,09	2,76	3,41	4,05	4,68	5,30	5,91	6,51	7,10	7,68	8,25	8,81	9,37	9,91	10,45	10,99	11,51

Obviously if one admits that the parked vehicles prevent a clear and reciprocal vision, one should re-calculate K and derive the corresponding approach velocity. The vehicle, aside from the stream it belongs to, must necessarily slow down if the operative velocity on the section which precedes the intersection is higher than the one derived from table GG, on the basis of the position of the obstacle (determined by the K distance).

For the vehicle on the secondary stream intervene further remarks which derive from the application of the previous kinematical expressions. If the driver of vehicle B is guaranteed with a visibility distance $DV_A = D_{A*}$, the chance that the vehicle crosses the intersection at a constant velocity or acceleration depends on the values of the ratios D_{A*}/D_{AH}, D_{A*}/D_{AK} e V_A/V_B (v_A/v_B in m/sec). Reporting these values on the graphs in Fig. 2 we deduces that only for particular combinations of the V_A e B_B velocities vehicle B could not stop. Even if $D_{A*}/D_{AH} >= 1$ and/or $D_{A*}/D_{AK} >= 1$, one easily demonstrates that vehicle B must stop if $V_A/V_B < 2$ (with $V_A/V_B < 2$, the result is $D_{AF2} > D_{A*}$). We can clearly deduce that vehicle B must necessarily stop before being able to cross if V_A=40 km/h (v_A<11,11 m/sec).

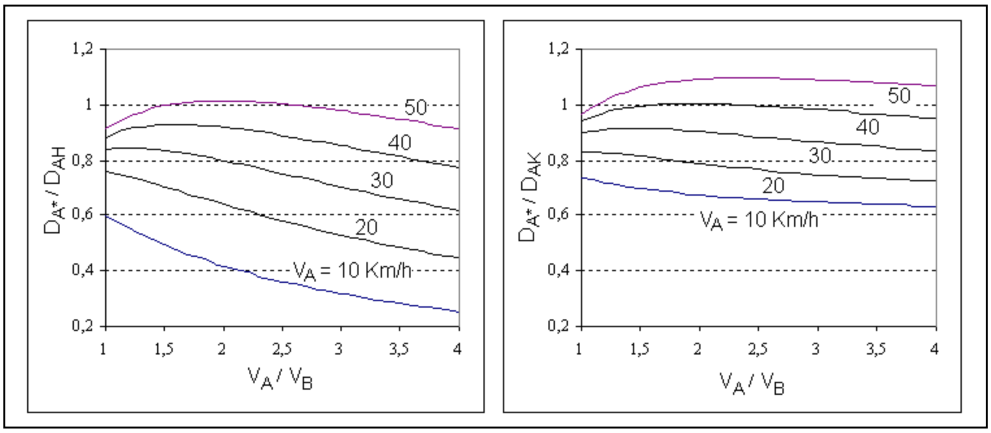

Figure 2: D_{A*}/D_{AH} and D_{A*}/D_{AK} versus V_A/V_B

Varying the γ deceleration values (3,4<γ<5 m/sec^2) and the PRT values (1<PRT<2,5 sec), one arrives at the same conclusions.

Such conclusions are also valid for lane changing manoeuvres. Data reported in literature confirm that for vehicles of the secondary stream, changing lane (access to the major stream), generally bigger lengths of time are required than those necessary for a simple crossing. The D_{AH} e D_{AK} distances raise while D_{A*} remains unchanged.

EXPERIMENTAL SURVEYS IN URBAN AMBIT

A very common opinion thinks that the behaviour of a driver is transferred in actions on the controls. Such actions lead to a variation of the dynamic parameters. The functional link between the behaviour, expressible only with the dynamic parameters, and every other influent factor (geometrical or of other type) results extremely complex. A first step towards a deeper knowledge of the behaviour of road users near intersections can be only made reducing the number of influent factors and/or neglecting some of them. Under this prospective only isolated vehicles, in the act of simple crossing manoeuvres, have been considered.

Examined intersections

The essential data for each intersection, derived on the chosen itineraries, are reported in Fig. 3. In the same figure, the parking typology along the sidewalks of the intersection branches is shown. The dimensions, instead, of the parking lines, which do not always comply with the regulations in force, are not reproduced.
However, it's correct to keep in mind that, for the vehicular fleet circulating in Italy, in average the width and length of the vehicles is respectively equal to 4 m and 1.7 m. The authentic width of the strip occupied by the parked vehicles depends on the above mentioned dimensions and is related to the organization provided for the different parking areas. The width of the road fixed to the traffic has to be cleansed by this parking strip and consequently, considering the dimensions shown in Fig. 3, all the vehicles will proceed along a single line

Survey modality

The surveys were performed during the day and during slight traffic conditions. This has made possible a reduction of the interferences and the impediments for the test vehicle produced by other vehicles which belong or not to its stream.
Some drivers have driven, with the same vehicle and many times, the three chosen urban itineraries. All the drivers knew perfectly the itineraries. It has to be said that the number of drivers, used in the test, cannot be considered a sufficiently representative sample to describe and analyze the variability of the behaviour of all the road users. In fact, it is also possible to state that this behaviour is in any case conditioned by the awareness of being drivers of a "particular" vehicle. Therefore, we wanted to make sure that the behaviours of the road users were not very different one from the other. The data obtained show, for the drivers who have participated to the test, a substantial behaviour homogeneity.

Equipment used

In order to understand the driver behaviour in proximity to urban intersections, the data acquired from proper transducers (sensors) mounted on the DIIV vehicle (see Fig. 4) have been recorded. The sensors with which the vehicle is equipped are:

1. 4 magnetic reluctance sensors (angular velocity of the four wheels of the vehicle);
2. 1 potentiometric sensor (position of the accelerator);
3. 1 potentiometric sensor (steering wheel angle);
4. 1 pressure transducer (pressure on the brake);
5. 1 inertial platform in strap down technology including:
   - 3 capacitive accelerometers (the accelerations a_x, a_y, a_z);
   - 3 Coriolis effect sensors (rotational velocity G_x, G_y, G_z);
   - 1 temperature sensor.

The platform is rigidly fixed to the vehicle with the sensible axes X, Y, Z which coincide respectively with the longitudinal axis of the vehicle (rolling axis), with the transversal axis (pitching axis) and with the vertical axis (yaw axis).
Besides, the vehicle is equipped with a video recording system (quadrivision) that, synchronized at the opportune moment with the data obtained from the sensors, provides other information useful in order to locate the test vehicle and to describe in an adequate way the road environment.
Every transducer used is "linear": this means that there is a direct proportion between the quantity to measure and the out coming electric quantity (potential difference). The variation, in time, of the physic quantity measured with such instruments is the "signal". This electric signal, given by every sensor on the DIIV vehicle, is filtered by an appropriate analogical filter. The filtered signal is sampled uniformly or

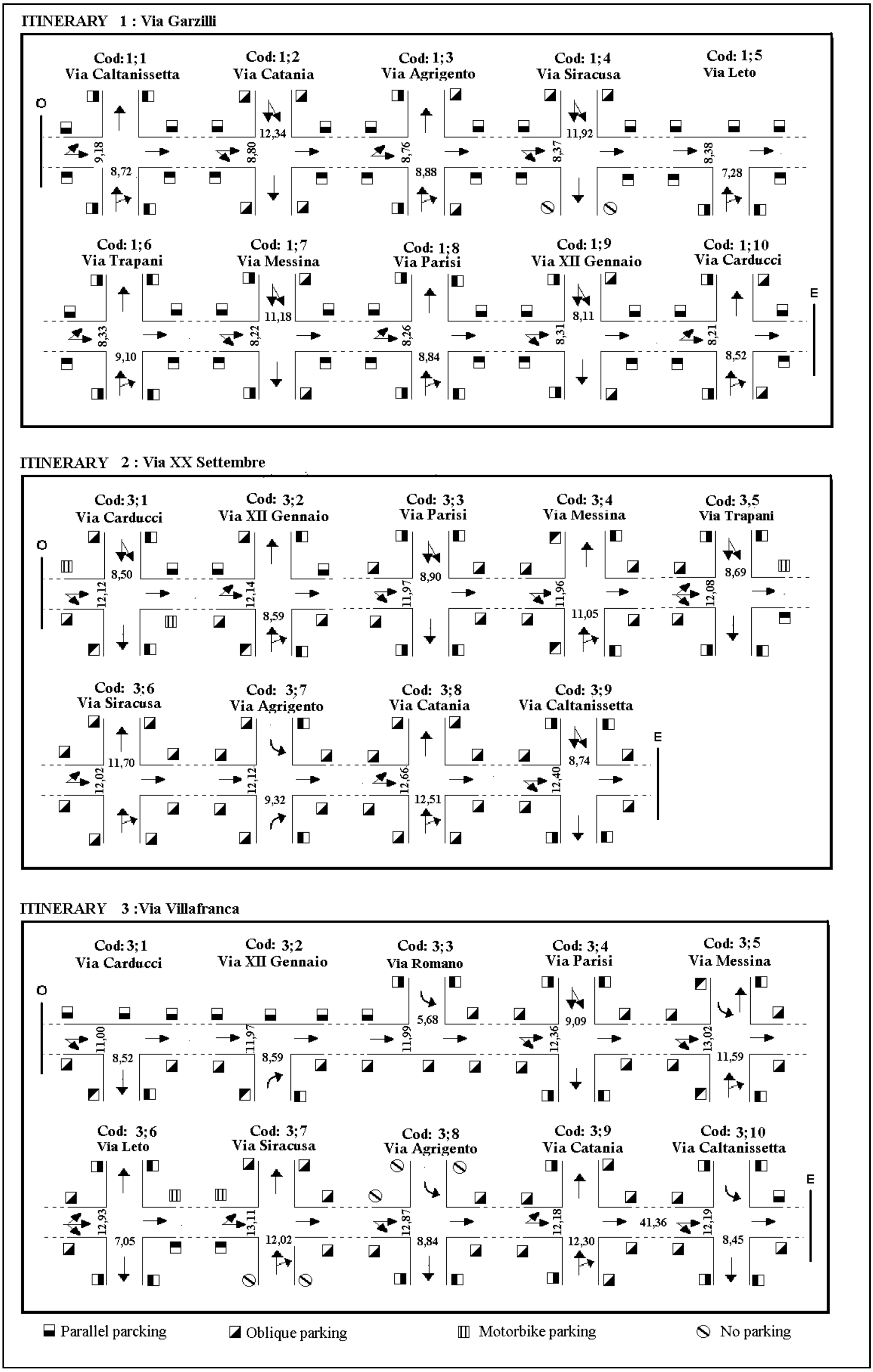

Figure 3: Intersections scheme

periodically (the signal analogical value is taken during constant temporal intervals). It has been chosen to sample all signals at 20 Hz (50m/sec). This choice derives from a compromise among various necessities: limit the amount of data to analyze; memorize data for a period compatible with the one foreseen for the experimentation; obtain, on the basis of a preliminary analysis of the signals in the frequency dominium, a sample signal which contains all the information deducible from the original signal.
Every analogical value that has been sampled is transformed into a digital one by an appropriate A/D converter (analogical/digital). The accuracy and resolution of the conversion depends on the field of in coming admissible tension values and on the number of bits of the digital output. Working on a field of tensions which have an amplitude K=5 volts, the utilized 12 bit A/D converter is characterized by a maximum value of the difference between the analogical and digital value equal to $K/2^{12} = 5/2^{12}$ volts.

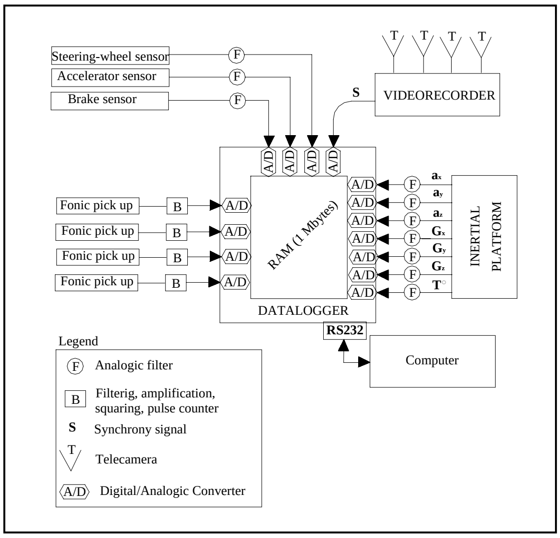

Figure 4: Equipment scheme

Signals numerical filtering

The signal given by the different sensors, treated and memorized, is taken to be elaborated in order to obtain the measure of the physic quantity associated to it. It has to be said, nevertheless, that the measures obtained with the described measure sequence are generally affected by errors (noise).
The kind and level of noise depends on the structural characteristics, on the quality and on the performances both of the employed sensors and of the other elements which constitute the measure sequence. In order to reduce the noise level a numerical filtering of the acquired signals has been utilized. It is possible to cleanse a signal from an additive noise conducting the analysis of the signal from a temporal basis to a frequency basis. For this kind of process, the use of Fourier's well known transformed (FFT) did not furnish, for the non stationariness of the signals, convincing results. Instead, the wavelet transformed has been used in the discrete form DWT (Transform Discrete Wavelet) or in the continue form CWT (Transform Continue Wavelet). In this case, one has available different transforming basis which differ one from the other for regularity and localization in the time domain. Recommending to analyze specified abstracts for a bigger investigation on the signals theory, the algorithms, that allow the wavelet decomposition (and the eventual reassembly) of the original signal, have been already included in some software on the market. Once the coefficient wavelet, that results best suited to the trend of the original data, has been individuated, the noise signal has been cleaned (de-noising). The results of the de-noising process are shown in Fig. 5 where the signal, before and after the numerical filtering, for the longitudinal acceleration a_x, is reported. However, it has to be said that the wavelet basis are different depending on the sensor from where the signal comes from (DONOHO, 1995; BOX, G., JENKINS, G. 1976; PERCIVAL, D. 1984).

Data processing

The advancing velocity v of the vehicle is obtained elaborating the data provided by the magnetic reluctance sensors located near the rear wheels. These wheels are pulled, so the slip velocity has been considered null. For the generic time interval i, $N_{rr,i}$ and $N_{rl,i}$ are the number of teeth of the phonic wheels rigidly connected to the rear right (rr) and left (rl) wheels. The covered space x_i and the velocity v_i, in the i^{th} interval, are:

$$x_i = 2\pi R(N_{rr,i}+N_{rl,i})/(2D_P)=\pi R(N_{rr,i}+N_{rl,i})/(D_P) \quad [1]$$

$v_i = x_i / \Delta T = \pi R(N_{rr,i}+N_{rl,i})/(D_P \Delta T)$ [2]

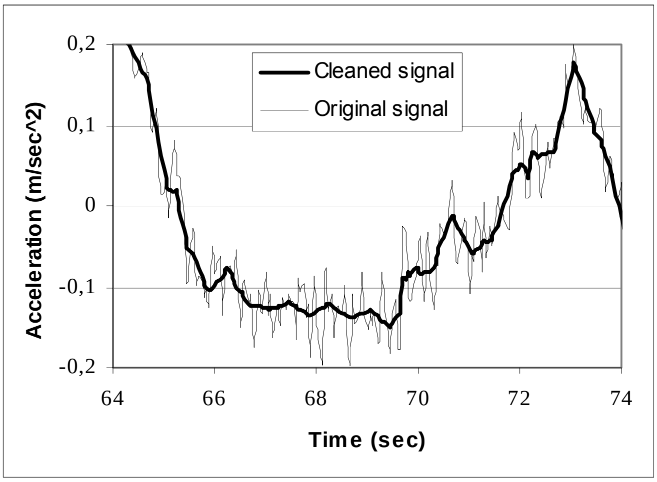

Figure 5: Acceleration original data and acceleration filtered data

where D_P=40 is the number of teeth of the rear phonic wheels; ΔT=0,05 sec is the acquisition interval and R is the dynamic rolling radius. The value of such radius R has been obtained using recorded filming. In fact, the instants, during which some steady external reference points (building corners, poles,….) were framed, have been determined. Knowing the D_k distance between the reference points and the relative crossing instants (t_1 e t_2) one sets:

$$D_k = \frac{\pi R}{D_P} \sum_{i=t1}^{t2} (N_{rr,i} + N_{rl,i}) \quad [3]$$

from which one can obtain the value of R that has to be put in relation [2] for the section length D_k. The differences among the values of R obtained are very little. Assuming a unique value for R, equal to the average of all the values gotten from relation [3], one makes an error in the estimate of v_i which is acceptable concerning the purpose of the research (BRUNO, RIZZO 2004).

The velocities of the vehicle can be calculated even starting with the data acquired from the inertial platform. Knowing the accelerations a_x, a_y, a_z on the three orthogonal axes X, Y, Z (integral tern) and the rotational velocities G_x, G_y, G_z around those axes, it is possible to calculate the components of the accelerations with reference to any other fixed tern X', Y', Z'. In order to make a reference frame change one can rely on various methods (cosine directors, Eulero axis and angle, quaternion algebra) (PIACENTINI, G. 2001).

In the case of almost rectilinear trajectories, like those covered during this experimentation, the component of the acceleration on the X' axis (assumed coincident with the axis of the chosen itinerary) results to be not distant from the value directly measured by the accelerometer located on the longitudinal axis of the same vehicle. Moreover, one can demonstrate that the values of the quantities obtained by the acceleration a_x are perfectly congruent with those calculated on the basis of the signals furnished by the magnetic reluctance sensors mounted on the vehicle.

Having available a sufficient number of values of the acceleration, the Størmer-Verlet algorithm allows to obtain iteratively the velocity and the position of the vehicle with the following expressions:

$v_i = v_{i-1} + \Delta T(a_{i-1} + a_i)/2$
[4]

$x_i = x_{i-1} + \Delta T v_{i-1} + \Delta T^2 (a_{i-1})$
[5]

where a_i are the accelerations measured on X in the generic instant T= iΔT (with ΔT = 50 m/sec). For i=0 (T=0) knowing x_0 and v_0, one can obtain the position and the velocity of the vehicle as i grows.

In Fig. 6 the values of the velocities v_i obtained with expressions [2] and [4] are reported. The trend of the two series of values are almost super imposable. The maximum differences, considering the whole itinerary, do not surmount 3,2 m/sec. If one divides the itinerary in various sections (contained between visual reference points) and assumes as initial velocity the one obtained with expression [2], the before said differences, only in few and isolated points, reach 1,2 m/sec.

Once verified the coherence but not the exact coincidence of the trend of the velocities obtained with expressions [2] and [4], the velocity data obtained starting from the phonic pick up signal are considered more trustworthy. These velocity data were verified and corrected on the basis of the knowledge of the exact distances covered and of the times employed to cover them.

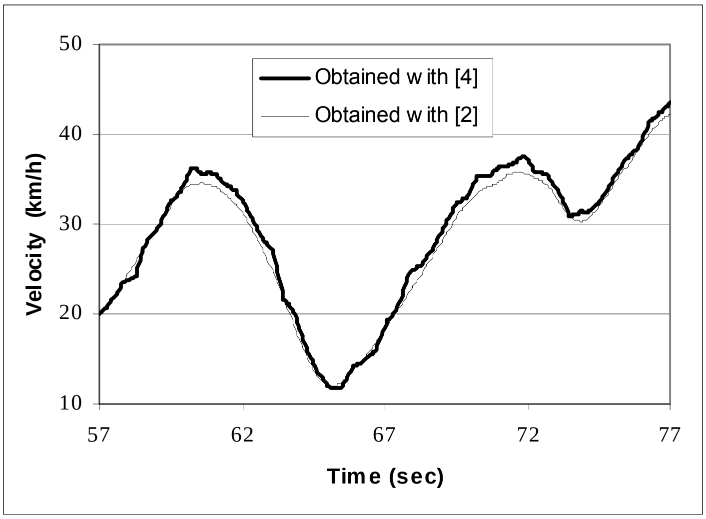

Figure 6: Velocity trend

PROCESSING RESULTS

In Fig. 7 the test vehicle velocity and acceleration along itinerary 1 are reported. It is evident that the road user, despite having the right of way, slows down significantly in close proximity to the intersections. We can notice that, at the intersection 1; 9, the road user has almost completely stopped its vehicle. Such conduct, according to the recorded footage, is justified by the interference caused by a vehicle on the opposing stream. These situations and those where evident interferences between the test vehicle and any other traffic component occur have been accurately pointed out.

The minimum velocity $V_{i;j}$ in proximity to the intersection j on the i itinerary and the maximum velocity $V_{i;j,j+1}$ reached in the section contained between two adjacent intersections (j e j+1) have been gathered, for each itinerary, in appropriate tables. In these tables (i.e. Tab. 3) the data that, for different reasons (arriving of opposing vehicles, pedestrian crossing,…), has not been considered homogeneous, have been pointed out.

For each intersection and for each itinerary, the maximum velocities $v_{i;j}$ obtained during the 30 test have been reported in Tab. 4. In the same table, the average values, obtained only considering the homogeneous data, are reported. In the last row of table 4 average velocities $V_{m,I}$, for all the intersections of the itinerary i, are reported. In table 5 maximum velocities, recorded between two contiguous intersections are reported. Besides the average of the maximum velocities $V_{M,i}$ recorded along the itinerary i is calculated.

The average values of the minimum velocities $v_{i;j}$ and the transversal dimensions of the secondary roads have been reported, the former on the abscises and the latter on the ordinates, in the graph of Fig. 7. The correlating coefficient values of some functional links among the above mentioned variables do not guarantee a sufficient reliability of these links. However, it seems to be clear, and it was also intuitive, that the approach velocity tends to decrease as the width of the secondary road grows.

Similar trends have been noticed for all the considered itineraries. The data points out that, with equal transversal dimensions of the minor road, the average approach velocities vary in function of the width of the major road. The existence of functional links between the width of the afferent roads (minor and major) and the approach velocity can be verified only enlarging the experimental basis.

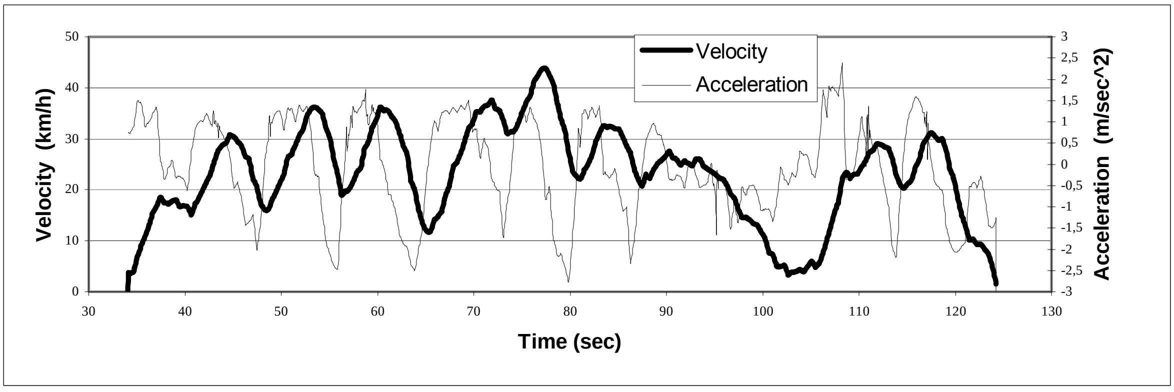

Figure 7: Velocity and acceleration measures

Table 3: Velocity along the itinerary 1

ITINERARY 1 (i=1)										
Code Inter. (j)	Survey 1		Survey 2		Survey 3		Survey N		Survey 30	
	$V_{i;j}$	$V_{i;j-1.j}$	$V_{i;j}$	$V_{i;j-1.j}$	$V_{i;j}$	$V_{i;j-1.j}$	$V_{i;j}$	$V_{i;j-1.j}$	$V_{i;j}$	$V_{i;j-1.j}$
O	0		0		0		…..	….	0	
1	13	16	14	18	16	18	…..	…..	14	18
2	18	27	10	31	16	31	…..	…..	14	31
3	23	28	17	33	19	36	…..	…..	21	40
4	16	32	24	27	12	36	…..	…..	28	34
5	32	----	29	31	36	36	…..	…..	29	31
6	21	29	29	32	31	36	…..	…..	29	----
7	8	27	24	39	21	43	…..	…..	12	34
8	22	28	21	32	21	32	…..	…..	21	32
9	24	31	14	27	3	27	…..	…..	16	27
10	19	24	21	26	20	27	…..	…..	19	24
E		28		30		31	….	….		28

Table 4: Velocity close to the intersections

ITINERARY 1			ITINERARY 2			ITINERARY 3		
Code Inters.	Max ($V_{i;j}$)	Mean ($V_{i;j}$)	Code Inters.	Max ($V_{i;j}$)	Mean ($V_{i;j}$)	Code Inters.	Max ($V_{i;j}$)	Mean ($V_{i;j}$)
1;1	20	16	2;1	22	19	3;1	28	24
1;2	20	19	2;2	28	22	3;2	33	26
1;3	23	20	2;3	25	21	3;3	38	26
1;4	28	20	2;4	29	22	3;4	31	24
1;5	37	28	2;5	33	25	3;5	26	23
1;6	38	23	2;6	30	21	3;6	33	28
1;7	24	20	2;7	27	21	3;7	30	23
1;8	29	21	2;8	24	20	3;8	31	24
1;9	27	22	2;9	25	18	3;9	27	22
1;10	27	23				3;10	23	19
$V_{m,1}$		21,20	$V_{m,2}$		20,00	$V_{m,3}$		23,90

Table 5: Velocity in intermediate sections

ITINERARY 1			ITINERARY 2			ITINERARY 3		
Code. Strecth.	Max ($V_{i;j,j+1}$)	Mean ($V_{i;j,j+1}$)	Code Strecth	Max ($V_{i;j,j+1}$)	Mean ($V_{i;j,j+1}$)	Code Strecth	Max ($V_{i;j,j+1}$)	Mean ($V_{i;j,j+1}$)
1;O,1	28	26	2;O,1	28	25	3;O,1	28	26
1;1,2	39	33	2;1,2	40	32	3;1,2	40	36
1;2,3	38	31	2;2,3	40	34	3;2,3	44	32
1;3,4	42	33	2;3,4	42	34	3;3,4	42	36
1;4,5	45	37	2;4,5	39	35	3;4,5	42	38
1;5,6	41	35	2;5,6	42	33	3;5,6	49	34
1;6,7	45	34	2;6,7	42	31	3;6,7	42	33
1;7,8	40	34	2;7,8	41	33	3;7,8	40	31
1;8,9	43	32	2;8,9	39	23	3;8,9	41	33
1;9,10	33	30	2;9,E	32	26	3;9,10	33	29
1;10,E	45	28				3;10,E	33	26
$V_{M,1}$		32,09	$V_{M,2}$		30,60	$V_{M,3}$		32,18

Accelerations and decelerations

Data acquired from accelerometers indicate that approaching the potential collision point, the deceleration of the vehicle increases gradually. If there are not interferences with opposing vehicles, the maximum deceleration reaches values between 2 – 3,7 m/sec^2. Only in a few cases the deceleration reaches the value of 3,7 m/sec^2; usually it is equal to 2 - 2,7 m/sec^2.

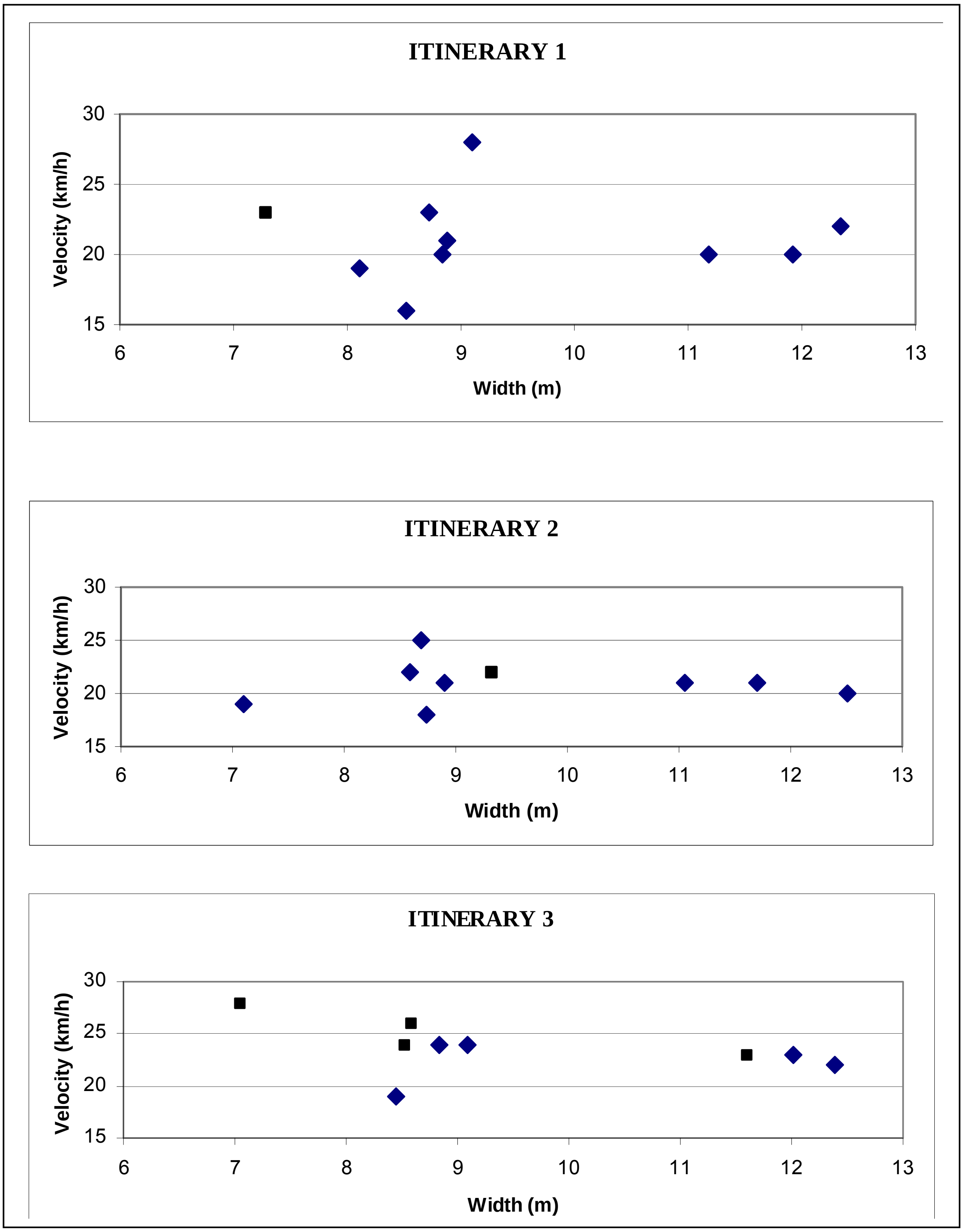

Figure 8: Velocity versus width of the secondary road

Even if from Fig. 7 it appears clear that the effective deceleration is surely not constant, it has been noticed that the measured vehicle velocities can be interpolated quite well utilizing the known relations of an uniformly decelerated motion (see Fig. 9). For every itinerary, the deceleration value, supposed constant, that allows the best adaptation is comprised between 0,8 e 2,1 m/sec^2.
The maximum acceleration instead is comprised between 0,6 and 2,3 m/sec^2. Repeating the previous considerations, we can assume that a constant acceleration is equal to 1,1 and 2,1 m/sec^2.

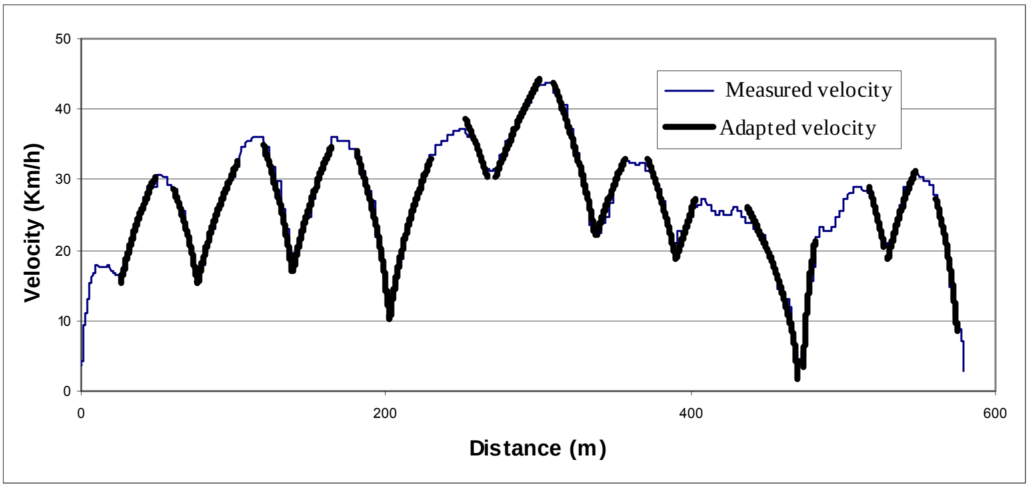

Figure 9: Adaptation of the laws of the uniformly accelerated motion

Delay at the intersections

In order to evaluate empirically the test vehicle delay, considered isolated, in the presence of only one intersection along its itinerary, the following procedures are suggested.

An initial procedure starts from the analysis of the velocity trends in proximity to each crossing. Referring to Fig. 10, which schematizes the velocity trend in proximity to an intersection, sections X and Y are determined, in the high and low part of the generic intersection, where the maximum velocity is registered (V_X V_Y). Therefore, the distance D_{XY} and the instants t_X and t_Y, where the vehicle passes through the X and Y sections, are known. Assuming that the vehicle covers the above mentioned distance D_{XY} at an average velocity equal to $v_M = (v_X + v_Y) / 2$, the time theoretically employed equals to $T_T=D_{XY}/v_M$. The time really employed equals $T_R= t_Y-t_X$ and the delay is $R_{XY}= T_T-T_R$. In absence of interferences, the type of intersections described in Fig. 1 generally cause a delay which oscillates between 1,5 e 3,7 sec. With circulation schemes different from the one in observation (see intersection 3;6 – 3;8) and with T intersections (see intersection 1;5 – 3;1), one obtains an almost null delay.

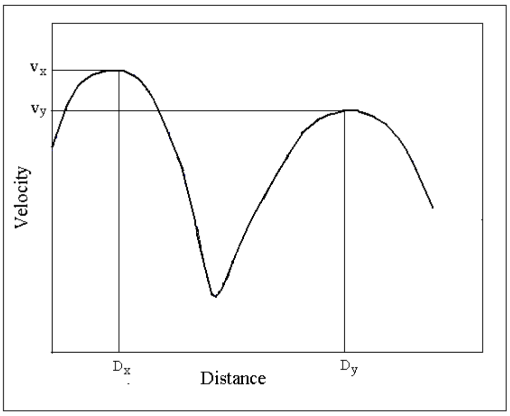

Figure 10: Delay calculation scheme

The delay of the vehicle of the main stream is surely superior to the previous one, in case of an almost simultaneous arrival of a vehicle of the secondary stream is registered. But the data available are very few to allow the evaluation of the delay at the intersection in that situation.

An estimation of the delay at the intersection can be obtained considering all the time employed to cover the considered itinerary. The commercial average velocities $V_{C,i}$ are obtained in relation with the examined itinerary i. The so determined values implicitly consider both the presence of intersections and the interferences with other traffic components.

We also want to remind that the maximum average velocity in each stretch of road, excluding the initial and final sections, differ of only a few Km/h (see Tab. 5). We could, therefore, assume that the isolated vehicles, without intersections, would have covered the entire central stretch of the itinerary at a velocity similar to the average (not excluding the initial and final sections) of the velocity $V_{M,i}$ (See Tab. 5, last row). The total delay for the entire itinerary is $R_i=D_i*(1/V_{C,i}–1/V_{M,i})$. Dividing this delay by the number of intersections present in each itinerary one obtains the values reproduced in the last column of Tab. 6.

The experimentation, in any case, does not provides any information on the entity of the delay when the vehicular density of the main traffic stream increases.

Table 6: Commercial velocity $V_{C,i}$ and delays

ITINERARY (j)	$V_{C,j}$ (km/h)	$V_{M,i}$ (km/h)	Total delay R_j (sec)	Average delay at intersections (sec)
1	23,14	32,09	25,12	2,51
2	21,18	30,60	30,40	3,38
3	26,12	32,18	15,39	1,54

CONSIDERATIONS ON THE REAL BEHAVIOUR

Analyzing the velocity (and/or acceleration) trend in time (or space) one is able to formulate an hypothesis, more or less suitable, on the driver behaviour. One can suppose, at first, that the road user can estimate, on the basis of its past experience and whatever the velocity of the vehicle is, the minimum distance which is necessary to stop. Being able to estimate this distance doesn't necessarily imply that the road user has knowledge of the maximum deceleration γ_{max} he can attain with his vehicle. It is known, however, that, on a dry road in normal conditions, γ_{max} results comprised between 7 and 10 m/sec^2. Some breaking experimental tests, carried out on a test vehicle, have confirmed these values. Besides, one must admit that the driver attention is essentially focused on the evaluation of the possibility to make or not his/her crossing manoeuvre in compliance with the above mentioned goals. The answer to stimulus, despite what has already been said, can be considered dichotomist. In fact, the driver, as soon as he/she sees an adequate section of the opposing stream lane, has only two alternatives: brake or not with the maximum deceleration possible. If the driver is not forced to brake he/she can decide how to proceed (at a constant velocity or accelerating) in order to complete the manoeuvre. On the basis of the acquired data, one must emphasize that usually the road user, at a certain distance from the secondary road, puts its foot on the brake pedal exercising a pressure that doesn't always determine an effective braking action. Using the formulas of classical kinematics, the braking distances, with γ_{max}=8,0 m/sec^2 and PRT comprised between 0.4 e 1 sec, have been calculated.

V (km/h)	PRT (sec)			
	0,40	0,60	0,80	1,00
5	0,68	0,95	1,23	1,51
10	1,59	2,15	2,70	3,26
15	2,75	3,59	4,42	5,25
20	4,15	5,26	6,37	7,48
25	5,79	7,18	8,57	9,96
30	7,67	9,34	11,01	12,67

Table 7: Emergency stopping distance

At an approach velocity of about 20 Km/h (deriving from experimentation, see Tab.4, the stopping distance strictly necessary is comprised between 4,10 and 7.5 m. In order to avoid an accident, a vehicle on the main road, at a distance of at least 8 m (considering a minimum security margin ε_1 = 0.5 m) from the conflict point shown in Fig. 1, should necessarily be able to see a sufficient section of the secondary one. This last condition is valid considering the geometry of the intersections analyzed. The data deduced have pointed out that the minimum velocity of the test vehicle is registered at a distance comprised between 4 - 10 m.
One can remark that, if the distances K (see Tab. 2) are less than 10 m, the velocities, assuring a safe approach, are not higher than 10 km/h. This clash with the experimental results.

CONCLUSION

The results of the experimental test indicate that drivers, even if having the right of way, divide their crossing manoeuvre of an urban intersection in different phases. In a first phase the driver slows down with a deceleration that, as we said in the previous paragraphs, can be considered uniform and comprised between 0.8 – 2.1 m/sec^2.

The deceleration starts at a distance from the conflict point that, at the end of this phase, brings the vehicle to proceed at a velocity of 20 Km/h in a section which is distant 4 - 10 m from the margin of the secondary road. The variability range of this distance should depend on the positioning and on the type of vehicles parked in proximity to the intersection.
During the elaboration of the data and of recorded images, the influence of the positioning of parked vehicles on the approach velocity has not been analyzed. But it is believed that a road user perceives in a certain advance the rate of hindrance caused by parked vehicles and decides the velocity that he should have in the point where he thinks he'll be able to see a sufficient section of the secondary road.
If, at the end of the decelerating phase, there aren't vehicles arriving from the secondary road, the driver accelerates with an uniform acceleration comprised between 0.9 e 2.1 m/sec^2. If, instead, there is a vehicle approaching from the secondary road, the driver, with his/her foot already placed on the brake pedal, exercises a bigger pressure.
Theoretically, in the above mentioned conditions, the road user has at his/her disposal, employing the maximum breaking stress, a sufficient security margin to stop the vehicle before the potential conflict point. Using, instead, the usual parameter values that must be put in the kinematical relations, the above mentioned velocities and distances do not result sufficient to carry out the crossing manoeuvre safely. During the surveys, the test vehicle had to carry out this emergency manoeuvre only in a few cases. The maximum deceleration value has never exceeded 3.7 m/sec^2.
Theoretic considerations and the data obtained demonstrate that the drivers, behaving in the way described above, adapt the priority necessity of a safe running and the need to limit the time of their journey. But a significant discordance between the driver effective behaviour and the behaviour "prescribed", which makes us plan the intersection and/or evaluate its safety, has been registered.
Considering the obtained results, it would be useful to impose, even for vehicles that have the right of way, a speed limit of about 20 km/h in close proximity to urban intersections analogous to the one observed. Imposing these limits and/or adopting adequate measures to make one respect them does not imply an increase of the journey time compared to the actual one. The delay caused by the "presence" of intersections along any itinerary would have the same order of magnitude of the one calculated following the two proposed forms. Despite the conceptual difference between the two forms, the above mentioned delay for an almost isolated vehicle results just about identical and comprised between 1 and 4 sec.

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