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## SURVEY AND ANALYSIS OF VEHICULAR TRAJECTORIES AT ROUNDABOUTS

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# SURVEY AND ANALYSIS OF VEHICULAR TRAJECTORIES AT ROUNDABOUTS

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## ABSTRACT

The paper presents the results of a video survey of vehicular movements at roundabouts which aimed at deriving the Entry-Exit matrix, compiling a vehicle classification, and tracking individual trajectories together with corresponding speeds along paths. To this end the authors utilised a proprietary software called VeTRA (Vehicle Tracking for Roundabout Analysis) which is based on a technique of image analysis. The paper represents part of an extensive research targeted at the validation of operational models for roundabouts.
In order to collect video images and minimize the problems related to wind, cloud cover, shadows, and obstructions, several camera configurations were adopted. In fact, five different video camera set-up configurations were considered with equipment being placed on central or external poles, and on fixed locations such as buildings or a raised working platform outside the confines of the intersection area.
The five resulting case studies, each with a different video camera set-up, are presented and analysed in the paper. The results obtained suggest that each configuration presents critical aspects that should be addressed separately using appropriate techniques to obtain usable images. On examination of the various options, the best compromise in terms of video quality and elaboration costs would appear to be the one using an external pole.
Furthermore, from an analysis of video records the authors derived a relationship between operating speed and trajectory that demonstrates the benefits resulting from the imposition of deflected trajectories on drivers by geometrical elements designed to curb driver speed in the circulatory roadway, and approaching and departing arms.

*Keywords: roundabout, operating speed, video image analysis, vehicle tracking, entry-exit matrix.*

## INTRODUCTION

In many countries roundabouts have increasingly become the intersection of choice due to the positive and acknowledged operational benefits deriving from their geometrics (Rodegerdts et al., 2010, Curti et al. 2008). Nevertheless, capacity and safety (Sacchi et al. 2010) remain a focus of investigation due to the number of variables, in addition to geometrics, affecting trajectories and speeds of crossing vehicles (Chen et al. 2012). With the objective of developing more reliable models, investigations should be conducted using robust tools and with attention being paid contextually to all the arms and the circulating roadway.

The use of video recording surveys and related image processing techniques can contribute to this aim (Masselodi et al. 2005, Bonarini et al. 2006, Mussone et al. 2011a). This work presents the activities undertaken by the authors in the development and use of a video recording system in conjunction with the proprietary software VeTRA for the derivation of the Entry-Exit (E-E) flow matrix, and vehicle classification, trajectories, and speeds along the paths traversing a roundabout.

Five separate cases studies in Northern Italy were considered. In each case, up to three video cameras were used in several set-ups. In the case of the Poncarale 4-arm rural roundabout, three video cameras were installed at a height of approximately 32 m on two lighting poles located on the split islands. In the Ghisalba 4-arm rural roundabout, three video cameras were installed on the central lighting pole. In the Biella 4-arm suburban roundabout only one video camera was used, while in the Sarnico and Chiari urban roundabouts, characterized by three and five arms respectively, three cameras were used.

The authors first focused their attention on three case studies the results of which allowed a comprehensive pre-processing and data analysis. In the remaining two cases, some difficulties arose during the image processing phase due to the swaying motion of the video cameras and to the excessive brightness of the light reflected by some structural elements located on the central island. Unfortunately, these problems were only identified after the in-field surveys and during the post-processing phase. The authors decided against repeating the surveys due to the relatively high cost of the installation used. This decision was also influenced by the level of satisfaction with the high quality results obtained with the first three roundabouts.

In the paper, the strengths and weaknesses of the five installations are described in detail in order to determine the optimal set-up. Each installation exhibited a different behaviour under the effects of wind, cloud cover, shadows, perspective deformation and obstructions. Two additional aspects, namely ease of perspective correction and synchronization between video cameras, were also investigated. Furthermore, an in-depth evaluation of vehicular features was conducted to establish any correlations between speed and deviousness of trajectory.

# METHODOLOGY

## Survey technique

The instrumentation used to collect and evaluate data consists of a vision system and a RTK-GPS system both connected to a dedicated PC (Mussone et al., 2011a).

The vision system is composed of one or three cameras with a resolution of 1360x1024 pixels. The optical lens of each video camera was adjusted in line with the application scenario. The vision system provided information on vehicular flow through the processing of images recorded by the video camera(s), while the RTK-GPS system was used to generate data useful for calibrating and evaluating the vision system.

The RTK-GPS system is composed of a base station equipped with a Trimble MS750 GPS and a Trimble Zephyr Antenna. A rover, made up of a Trimble 5700 GPS and a Trimble Zephyr Antenna, is placed on a probe vehicle and connected via radio link (DiGi XBee Pro modules in point to point mode) to the base station.

## Pre Processing

The data gathered need to be treated before their use. In particular, images require conversion, undistortion and rectification while RTK-GPS data need data conversion (for rover data) and synchronization between base station and rover timestamps.

The image analysis was carried out by VeTRA (Mussone et al. 2011a), which employs genetic algorithm optimization procedures to minimize the re-projection error of the central island onto the image plane, and provides a complete projective transformation from the 3D real world to the 2D image, by constraining world points to lie at ground level.

VeTRA was found to be particularly robust and accurate when subjected to the effects of changeable wind conditions, sudden changes in light conditions due to passing clouds, occlusions due to fixed objects (e.g. trees, poles) and moving vehicles, and perspective deformation (Mussone et al. 2011a).

The key tool in VeTRA is its tracking system which detects moving objects in the field through an adaptive background modelling and subtraction algorithm. The image areas representing the vehicles (known as "blobs" in information science jargon) are identified in the foreground through shadow and noise removal. The tracking system is capable of distinguishing between newly detected blobs and previously tracked vehicles. The trajectories of the tracked vehicles are continuously updated as new information is received. All these activities rely on a proper model of the background which has to be sufficiently robust to contend with changes in light conditions and minor camera movements.

When more than one video camera is used, two different strategies can be employed to consolidate the information. One strategy merges trajectories extracted from each separate video image (MT strategy), the second blends images from video cameras before extracting trajectories from the blended images (BI strategy).

## Trajectory reconstruction

Trajectories produced by the tracking system are processed in order to generate the E-E matrix, vehicle trajectories, speed profiles and the vehicle classification (Mussone et al., 2011b). The E-E matrix represents the matrix of all flow movements within the roundabout and, normally, some differences are to be expected between this and the corresponding matrix for other intersections since the U-turn manoeuvre is not possible.

Trajectories on pavement surfaces are easily calculated from trajectories between the entry and exit gates of the circulatory roadway on the image plane using RTK-GPS data collected by the rover on the probe vehicle. This was accomplished through a comparison of RTK-GPS and tracking system data, using the synchronization data to obtain the same amount of information. Extracted trajectories are then saved in a local system of coordinates.

Speed and curvature profiles are obtained from calculations based on vehicle position and time. Speed is calculated for two consecutive points by simply dividing the distance between them by the elapsed time (nearly equal to the frame rate of the camera). For the calculation of the local radius of the osculating circle, thirty-one consecutive points of the trajectory, corresponding to 1 second of records, were considered.

Classification of flow is necessary to improve the overall performance of VeTRA in flow count, speed diagram and trajectory path. A tentative classification was compiled with vehicles detected being assigned to the following three classes: (a) bikes and motorbikes, (b) light vehicles, vans and campers, and (c) heavy vehicles.

Since the algorithm for class recognition is based on a neural network model, both a learning data set and a minimum number of cases are required to work out the model. In some scenarios, as with Ghisalba and Poncarale, the number of bikes and motorbikes were so low that they proved insufficient for the purposes of the model and almost insignificant from a statistical point of view. Therefore, in these two cases this class was not used for performance comparison.

## Data treatment for speed analysis

The authors recently incorporated a filtering algorithm into VeTRA with the aim of rejecting trajectories for which the speeds are too low due to vehicle conflict both in the circulatory roadway and in the approaching and departure arms. As a result, trajectories with speeds lower than 10 km/h were discarded.

From those trajectories characterized by free-flow movements, three deviousness indexes ($D_1$, $D_2$, $D_3$), having as an objective the classification and characterization of the vehicle paths associated with specific manoeuvres (crossing, right, left and U-turn), have been derived by reference to general literature. The first index ($D_1$) considers the following formula:

$$D_1 = \frac{\sum_i |\alpha_i| \cdot R_i}{L} \qquad \text{(eq.1)}$$

in which the angle $\alpha_i$ is the angular deviousness between two successive recorded points ($P_i$ and $P_{i+1}$), $R_i$ is the radius of the osculating circle that is derived from thirty points across the considered one as previously indicated ($P_{i-15}$,…, $P_i$, $P_{i+1,}$ … $P_{i+15}$), and $L$ is the length of the trajectory between the entry and the exit gates.

The second deviousness index ($D_2$) is obtained with the equation:

$$D_2 = \frac{1}{L}\sum_i \frac{|\alpha_i|}{R_i} \qquad \text{(eq.2)}$$

while the third one ($D_3$), which is also known in literature as the curvature change ratio (CCR), is calculated as follows:

$$D_3 = \frac{\sum_i |\alpha_i|}{L} \qquad \text{(eq.3)}$$

The three indexes indicate the level of difficulty in negotiating the roundabout, which is higher when the sum of angles is high and the corresponding radii are small. The units of measurement for the three deviousness indexes are rad, rad/m$^2$ and rad/m respectively.

As previously indicated, the speed at each of the $P_i$ points along a generic trajectory is calculated by simply dividing the distance between every point $P_i$ and the consecutive point $P_{i+1}$ by the elapsed time (equal to the frame rate of the video camera).

# INVESTIGATION

With a view to establishing the optimal camera configuration and the performance of VeTRA, in-field research activities were undertaken at five roundabouts in Northern Italy (Piedmont and Lombardy regions). Table 1 reports a synthesis of the geometric characteristics and the most significant survey data, while Figure 1 contains the three general video camera configurations used for the surveys. Images were recorded for about 1.5-2 hours to obtain at least one hour of actual flow; the recording period was around the peak hour of midday and, in all cases, the weather conditions were dry and sunny. As mentioned previously, videos were recorded and successfully elaborated for only three of the five case studies due to unexpected difficulties encountered in two case studies.
The first roundabout is located near the urban limits of the city of Biella (Figure 2), and connects two arterials composed of two lanes per direction with separated carriageways.
Pedestrian crossings are provided at three of the four arms. The external diameter is 50 m, the circulatory roadway is 13 m in width, while the central island diameter is equal to 24 m including a surmountable curb of 1.5 m. The approaching arms are composed of two lanes with an average width of 8 m, while 6 m is the width of the single lane departure arms. The roundabout is equipped with a lighting tower headlight, while the water harvesting systems are located outside of the circulatory roadway. This signifies that the cross slope of the circulatory roadway is opposed to the curvature according to Italian standards (Ministero delle Infrastrutture e dei Trasporti, 2006).

Table 1 – Synthesis of information for survey activities (see Figure 1 to identify the configuration)

| **Roundabout →** | **Biella** | **Ghisalba** | **Poncarale** | **Chiari** | **Sarnico** |
|---|---|---|---|---|---|
| | **Geometric characteristics of roundabouts** | | | | |
| Latitude | 45°33’12”.39 | 45°35’32”.21 | 45°27’29”.99 | 45°32’00”.27 | 45°40’02”.79 |
| Longitude | 8°04’21”.85 | 9°46’19”.75 | 10°12’09”.66 | 9°55’23”.39 | 9°57’30”.80 |
| External diameter [m] | 50 | 50 | 71 | 21 | 28 |
| Central island diam. [m] | 24 | 26 | 56 | 3 | 14.7 |
| Circ. roadway width [m] | 13 | 10 | 7 | 9 | 6.7 |
| Number of arms | 4 | 4 | 4 | 5 | 3 |
| | **Survey data synthesis** | | | | |
| Configuration # | 1 | 2 | 3 | 2 | 3 |
| Number of cameras | 1 | 3 | 3 | 3 | 3 |
| Number of survey points | 1 | 1 | 3 | 1 | 3 |
| Video camera position | External | Internal | External | Internal | External |
| Horizontal angle (°) | - | 90 | 120 | 120 | 90, 110, 160 |
| Vertical angle (°) | 55 | 40 | 72 (1 camera)<br>55 (2 cameras) | 55 | 78, 72, 51 |
| Camera height [m] | 22 | 22 | 32 | 12 | 6, 9, 23 |

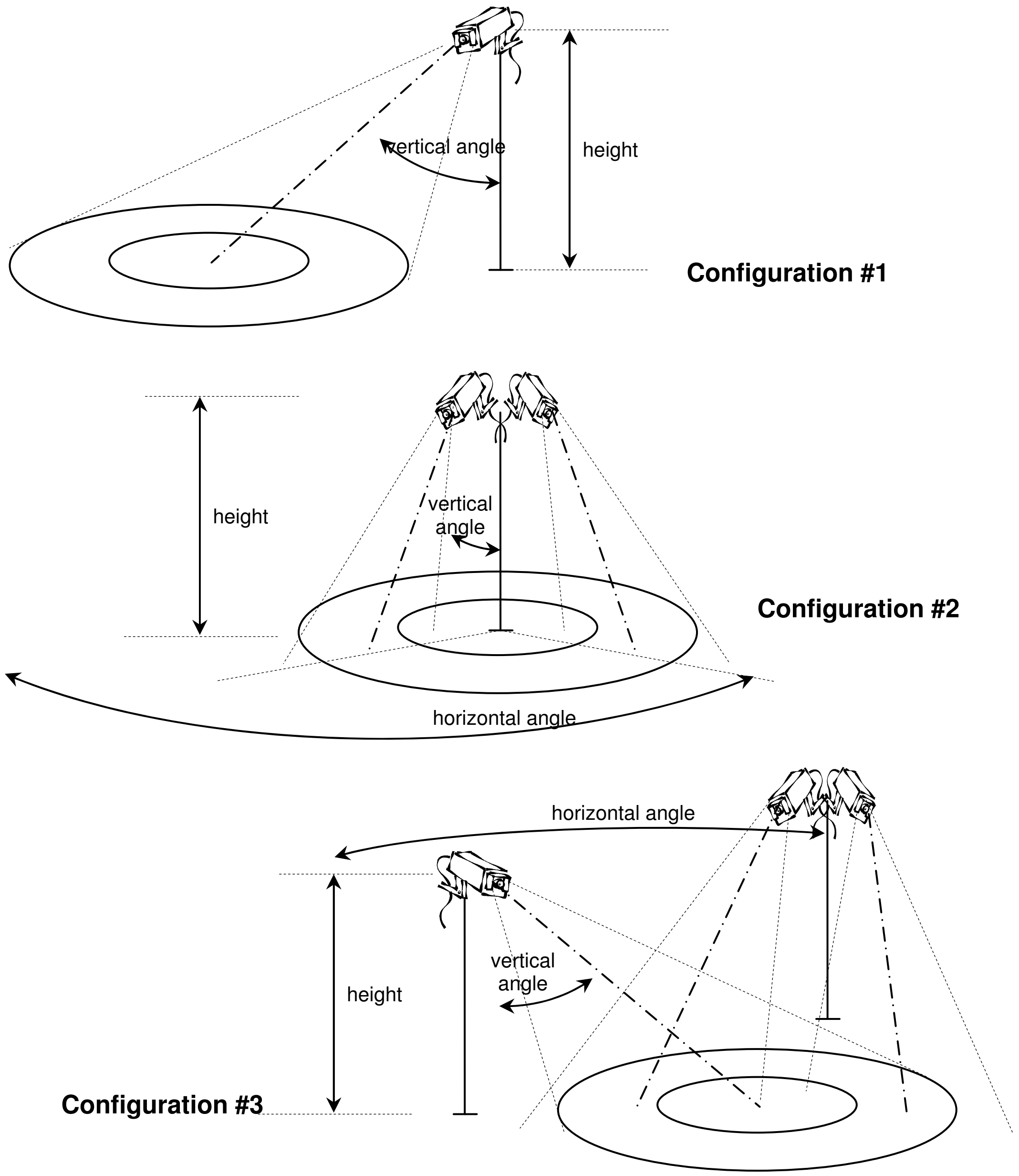


Figure 1 – Schema of the three camera configuration adopted for the survey

During the investigations, the detection system was placed on a moveable rack placed near the edge of the South East corner. The video camera, pointing towards the centre of the roundabout, was placed at a height of about 22 m at an angle of approximately 55° with respect to the rack axis.

The second roundabout is located in a rural area near Ghisalba (Figure 3) at the intersection of two single-carriageway rural highways with no pedestrian crossings. The external diameter is 50 m, the circulatory roadway is 10 m, and the central island diameter is equal to 26 m with a surmountable curb of 2 m. The roundabout is furnished with a central lighting tower headlight. During the investigations, the detection system, consisting of three cameras, was placed on the lighting pole in the centre of the central island at a height of about 21 m above the roundabout plane; with the three cameras facing East, North and West respectively and placed at vertical angles of approximately 40° with respect to the pole.

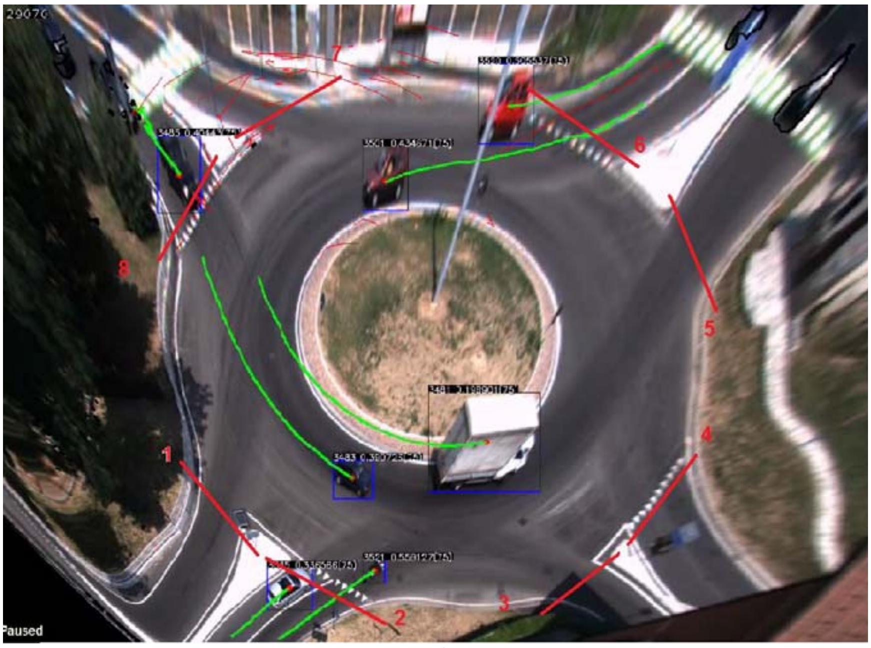


Figure 2 – Aerial view of the Biella roundabout

The third roundabout lies outside the urban area of Poncarale (Figure 3) at the intersection of two main highways, both of which are single carriageway with two-way traffic and no pedestrian crossings. The external diameter is equal to 71 m and the circulatory roadway is only 7 m. As a result the roundabout has a wide central island (56 m in diameter) that includes a surmountable curb of 2.5 m. In contrast with the two previous roundabouts, the approaching and departure arms of the Poncarale roundabout are tangent to the circulatory roadway. The lighting is provided by two lighting towers, located on two divisional islands at the North and South, distant 81 m and 28 m respectively from the roundabout. The measurements were taken with three cameras installed at a height of 32 m, two of which were located on the southern lighting pole at an angle of approximately 55° and the third on the northern lighting-pole at an angle of approximately 72°.

In Chiari (Figure 4) three video cameras were placed on a support beam held directly over the central island at a height of about 12 m by a crane arm. The crane was positioned just outside one side of the roundabout so that the angle set by video cameras with the vertical axis was approximately 55°. This set-up proved very effective in reducing perspective distortion, preventing occlusions, and in facilitating the detection of vehicles on the entry and exit arms. Unfortunately, the cameras were not adequately secured so they tended to sway in the wind.

Despite the relatively minor nature of these oscillations, they fatally compromised the performance of the background recognition algorithm included in VeTRA. A great deal of effort, ultimately unsuccessful, was dedicated to the recovery of the survey. This experience, it should be said, provided the authors with an opportunity to seek out different approaches to the recognition problem.

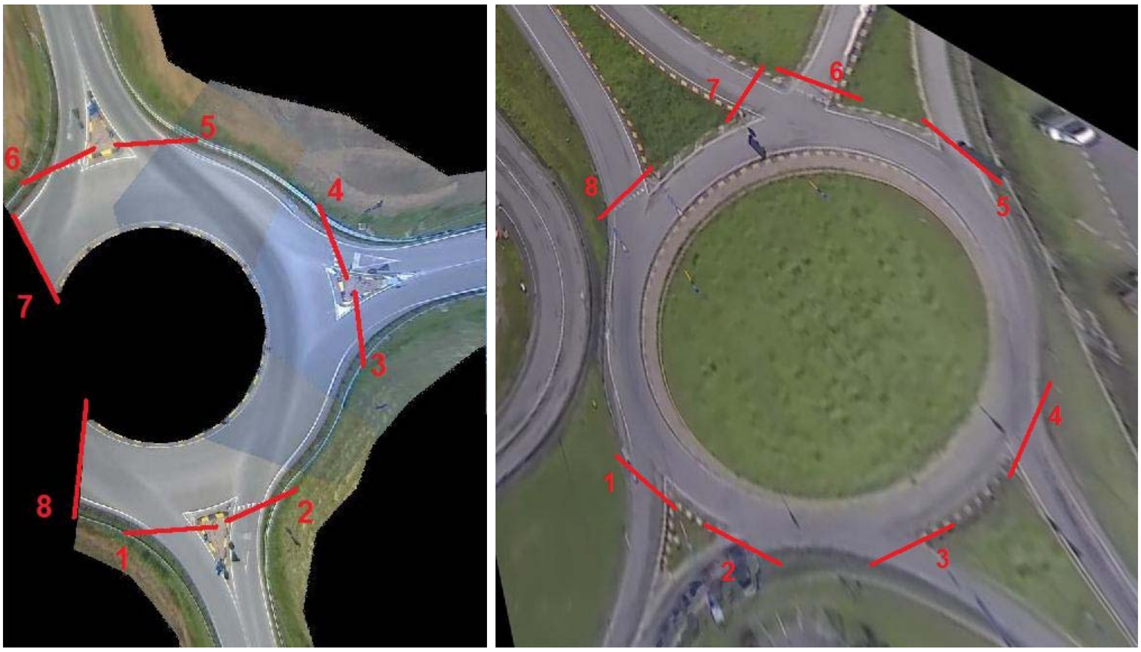

Figure 3 – Aerial view of the Ghisalba and Poncarale roundabouts


Figure 4 – Aerial view of the Chiari and Sarnico roundabouts

In Sarnico (Figure 4), the three video cameras were located atop secure buildings at heights of 6 m, 9 m and 23 m. Unfortunately, for a combination of reasons, the resulting video images proved to be of inferior quality. The images from one camera were corrupted by over exposure due to light-reflecting elements on steel torus around the central island. In the other two cases the camera vantage point was either too high or too low, creating difficulties at the image processing stage due to the low resolution of images, to obstructions and to difficulties in merging images resulting from such diverse vantage points. Consequently, the authors decided to reject the results obtained from these last two surveys and to focus instead on the results from the first three roundabouts. It should be added that the difficulties encountered represent a learning curve and a source of invaluable experience which can be capitalized on in future surveys.

# RESULTS AND ANALYSIS

## Vehicle classification and Entry–Exit matrix

As explained before, the classification of vehicles has been limited to two classes of vehicles (light and heavy) which, when combined, represent more than 95% of the total observed flow for the three investigated case studies. From the incomplete combination of the two aforementioned strategies (merged trajectories – MT, blended images – BI), with the number of video cameras (from one – 1C – to three – 3C), and configuration (from 1 to 3), five different cases have been considered and reported in Table 2, in which the results are shown for all the possible sixteen movements into a 4-arm roundabout.

The data elaborated by VeTRA were compared with those obtained from video observation by a number of operators. These observations, reported in Table 2 under the column "Operators", were repeated until the average values between observations were significantly stable and could be considered a "true" reference. It should be noted that the total number of vehicles observed in one hour of survey was high falling into a range of 1500 to 2500 veh/h. In this phase the authors focused mainly on error evaluation rather than on absolute values; Table 2 reports the percentage values for each movement with respect to the total number of movements.

Three different types of errors were obtained from Table 2 and listed in Table 3: the sum and average of absolute differences between percentages, and the average of percentage values (the last calculated as (A-B)/A, where A is the operator estimate and B is the VeTRA value).

It must be stressed that operators represent the way to obtain the true result by application of the central limit theorem. In this experiment, since an infinite number of operators is not possible, the calculated averages may be considered a good estimate of the true result. VeTRA results are, nonetheless, unavoidably affected by deterministic errors that cannot be completely cancelled since they are intrinsic to the system.

Values for the average of the absolute differences between operators and VeTRA are less than 5% and are compatible with traffic analysis resolution. This also holds true, albeit to a lesser extent, for the average of percentage differences. In contrast, the sum of percentage differences is generally very high even with the best strategy (see Ghisalba-BI, and Biella-1C in Table 2).

This fact evidences the existence of a bias due to the general environmental conditions during the survey (sunny conditions and resulting shadows, or pole oscillations due to the wind factor). The positive bias indicates that VeTRA has generally estimated a lower percentage value for each movement than the operators. In the cases of Biella and Poncarale the bias is positive while in Ghisalba it is negative.

On examination of the five analyses carried out with VeTRA (Table 2 and 3), the best results were obtained with configuration #1 of Figure 1. In fact, the performance obtained with the use of one video camera is similar to that of configuration #2 in which three cameras are employed but which has lower costs and requires less effort. Moreover, in the latter case at least four video cameras would be necessary to ensure coverage of the entire surface of the roundabout (see Figure 3).

Table 2 – Percentage values of Entry-Exit matrix for Biella, Ghisalba and Poncarale for different strategies (merged trajectories - MT, blended images - BI) and number of video cameras (from one – 1C – to three – 3C)

| E-E Movement | Biella (configuration #1) | | Ghisalba (configuration #2) | | | Poncarale (configuration #3) | | |
|---|---|---|---|---|---|---|---|---|
| | Operators | VeTRA 1C | Operators | VeTRA | | Operators | VeTRA | |
| | | | | 3C - MT | 3C - BI | | 1C | 2C-BI |
| 2-1 | 0.40 | 0.59 | 0.00 | 0.00 | 0.00 | 0.14 | 0.00 | 0.10 |
| 2-3 | 2.93 | 3.37 | 2.98 | 4.72 | 3.56 | 7.14 | 4.70 | 12.02 |
| 2-5 | 20.96 | 20.33 | 26.46 | 23.29 | 25.89 | 7.24 | 3.65 | 0.10 |
| 2-7 | 0.47 | 0.44 | 1.08 | 1.15 | 1.47 | 3.48 | 1.05 | 6.11 |
| 4-1 | 3.26 | 2.49 | 0.00 | 0.00 | 0.00 | 5.43 | 5.89 | 7.46 |
| 4-3 | 0.20 | 0.26 | 0.00 | 0.10 | 0.05 | 0.28 | 0.07 | 0.10 |
| 4-5 | 4.64 | 4.80 | 0.66 | 1.20 | 0.95 | 4.64 | 7.36 | 0.10 |
| 4-7 | 7.82 | 6.87 | 2.53 | 2.45 | 2.61 | 17.76 | 18.58 | 30.05 |
| 6-1 | 19.79 | 21.13 | 0.00 | 0.00 | 0.00 | 9.60 | 12.90 | 0.00 |
| 6-3 | 4.66 | 2.60 | 0.00 | 0.14 | 0.00 | 4.08 | 4.84 | 0.00 |
| 6-5 | 0.29 | 0.00 | 0.00 | 0.05 | 0.00 | 0.09 | 0.07 | 0.00 |
| 6-7 | 7.07 | 8.68 | 31.22 | 30.46 | 29.98 | 0.19 | 0.84 | 0.21 |
| 8-1 | 2.05 | 2.71 | 30.60 | 31.95 | 31.54 | 7.79 | 8.27 | 9.12 |
| 8-3 | 11.90 | 13.27 | 2.03 | 2.26 | 2.19 | 19.67 | 27.70 | 34.09 |
| 8-5 | 13.22 | 12.24 | 2.40 | 2.17 | 1.71 | 12.29 | 3.86 | 0.00 |
| 8-7 | 0.33 | 0.23 | 0.04 | 0.05 | 0.05 | 0.19 | 0.21 | 0.52 |

Table 3 – Performance indicators (errors) between operator and VeTRA computed values for each movement in E-E matrixes for the three roundabouts and five strategies

| Roundabout and image treatment strategies | Sum of absolute differences (%) | Average of absolute differences (%) | Average of percentage differences (%) |
|---|---|---|---|
| Biella (1C) | 11.64 | 0.72 | 3.6 |
| Ghisalba (3C-MT) | 8.47 | 0.53 | -10.0 |
| Ghisalba (3C-BI) | 5.03 | 0.31 | -6.0 |
| Poncarale (1C) | 34.52 | 2.15 | 6.0 |
| Poncarale (2C-BI) | 75.88 | 4.74 | 10.0 |

The problems resulting from the blending of sequences obtained from three video-cameras located at 32 m from the roundabout (configuration #3 of Figure 1) led to the necessity of considering two different strategies in the analysis of the Poncarale roundabout. Although the performance indicators in the case of a single camera (1C) configuration are close to those established in the Biella case study, the use of a two camera (2C) configuration with blended images results in the worst performance observed (Table 3).

## Deviousness and speeds

The analysis of deviousness and related speeds was performed on the class of light vehicles. For each trajectory, VeTRA derives the previously mentioned three deviousness indexes and associates each point of the trajectory with the local speed value. All the trajectories are grouped under the same E-E manoeuvre and the software can elaborate the requested statistical output selected by the operator.

Table 4 contains the synthesis of the 15$^{th}$ percentile of the three deviousness indexes ($D_1$, $D_2$ and $D_3$) calculated for those parts of the trajectories including the entry and exit gates of the roundabouts, and the 85$^{th}$ percentile of related speeds at the entry gate (1), at the midpoint of the trajectory inside the circulatory roadway (2), and at the exit gate (3).

The choice of the two percentiles is based on the supposition that aggressive drivers, whose speeds exceed $V_{85}$, tend to follow the fastest path which should be characterized by the lowest deviousness (Rodegerdts et al., 2007 and 2010). The authors associated the 15$^{th}$ percentile of deviousness indexes with the fastest path so as to define correlations between trajectory and speeds. In fact, plotting all the speed data contained in Table 4 as a function of the $D_{2,15}$ index, a general trend becomes evident and it confirms that lower speeds are related to higher values of deviousness (Figure 5).

Table 4 – 15th percentile of deviousness and 85th percentile of operating speed on trajectories recorded for several manoeuvres and certain strategies

| Roundabout | E-E | Manoeuvre | $D_{1,15}$ | $D_{2,15}$ | $D_{3,15}$ | $V_{1,85}$ | $V_{2,85}$ | $V_{3,85}$ |
|---|---|---|---|---|---|---|---|---|
| | | | [rad] | [rad/m$^2$] | [rad/m] | [km/h] | | |
| Biella 1C | 2-3 | right turn | 0.958 | 0.00124 | 0.0311 | 32.27 | 34.07 | 39.37 |
| | 2-5 | crossing | 0.821 | 0.00015 | 0.0096 | 33.88 | 39.00 | 44.11 |
| | 4-1 | left turn | 0.938 | 0.00200 | 0.0372 | 29.58 | 27.75 | 40.55 |
| | 4-5 | right turn | 0.972 | 0.00129 | 0.0330 | 29.33 | 30.44 | 33.62 |
| | 4-7 | crossing | 0.920 | 0.00069 | 0.0216 | 30.61 | 36.09 | 41.38 |
| | 6-1 | crossing | 0.930 | 0.00094 | 0.0255 | 32.71 | 33.43 | 42.68 |
| | 6-3 | left turn | 0.950 | 0.00207 | 0.0383 | 33.70 | 29.52 | 42.43 |
| | 6-7 | right turn | 0.918 | 0.00064 | 0.0218 | 34.63 | 34.66 | 37.27 |
| | 8-1 | right turn | 0.931 | 0.00054 | 0.0207 | 31.89 | 33.08 | 37.88 |
| | 8-3 | crossing | 0.901 | 0.00041 | 0.0163 | 36.11 | 35.51 | 44.56 |
| | 8-5 | left turn | 0.875 | 0.00179 | 0.0336 | 33.56 | 27.81 | 39.64 |
| Poncarale 1C | 4-1 | left turn | 0.960 | 0.00094 | 0.0267 | 40.31 | 38.31 | 47.53 |
| | 4-7 | crossing | 0.920 | 0.00037 | 0.0158 | 39.60 | 39.37 | 50.90 |
| | 2-3 | right turn | 1.000 | 0.00150 | 0.0380 | 28.31 | 30.97 | 31.24 |
| | 8-3 | crossing | 0.930 | 0.00050 | 0.0191 | 38.51 | 37.41 | 44.14 |
| | 8-1 | right turn | 0.750 | 0.00008 | 0.0065 | 38.02 | 40.96 | 47.37 |
| Ghisalba BI | 2-3 | right turn | 0.980 | 0.00047 | 0.0204 | 34.15 | 36.27 | 35.52 |
| | 2-5 | crossing | 0.930 | 0.00070 | 0.0224 | 36.70 | 35.80 | 40.07 |
| | 4-5 | right turn | 0.980 | 0.00032 | 0.0168 | 35.25 | 38.66 | 40.76 |
| Ghisalba MT | 2-3 | right turn | 0.970 | 0.00050 | 0.0203 | 30.70 | 32.90 | 33.67 |
| | 2-5 | crossing | 0.930 | 0.00067 | 0.0221 | 36.41 | 35.83 | 40.22 |
| | 4-5 | right turn | 0.970 | 0.00037 | 0.0182 | 31.57 | 34.61 | 39.18 |

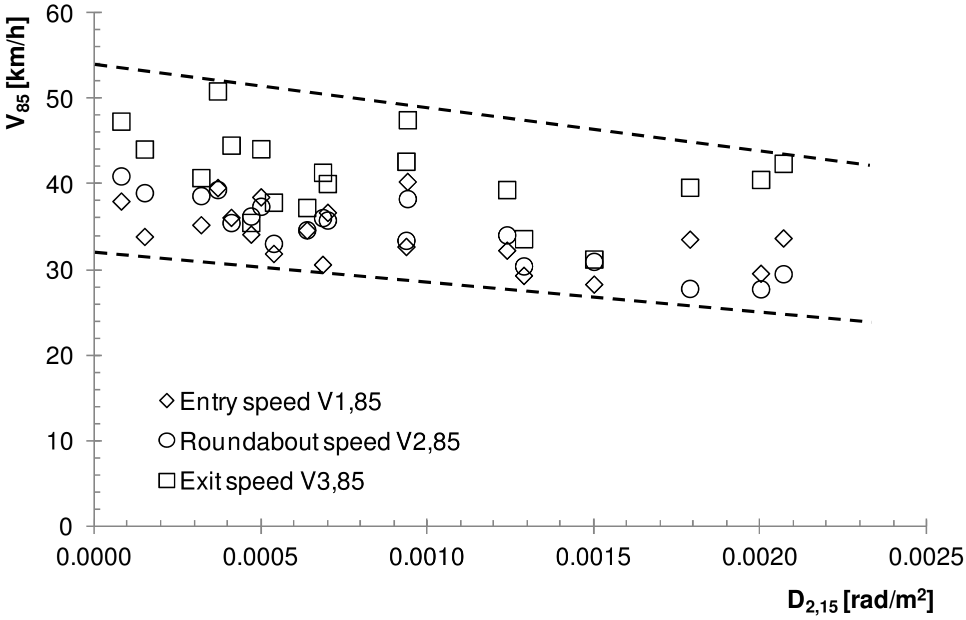


Figure 5 – Relationship between $V_{85}$ and $D_{2,15}$ index

When the analysis is restricted to a part of the speed data, the most significant relationships between the values reported in Table 4 are limited to the 85$^{th}$ percentile of speeds calculated at the middle point of trajectories ($V_{2,85}$) and the 15$^{th}$ percentile of the last two deviousness indexes $D_{2,15}$ and $D_{3,15}$. The results are reported in Figure 6 and Figure 7, and demonstrate that $D_{2,15}$ has a greater correlation with respect to $D_{3,15}$.

Figure 6 and Figure 7 also report the data generated with the MT strategy in the case of the Ghisalba roundabout. These data are more dispersed when compared to the corresponding data derived with the BI strategy. As a consequence, they were not taken into account in the two models (linear and exponential) plotted in both figures.

Very low correlations were found between the 85$^{th}$ percentile of entry ($V_1$) and exit ($V_3$) speeds. This is due to the fact that the entry speed depends on factors such as visibility on the circulatory roadway and the horizontal alignment of the approaching arm. Similarly, the exit speed depends on the geometry of departure lanes which does not affect the deviousness indexes.

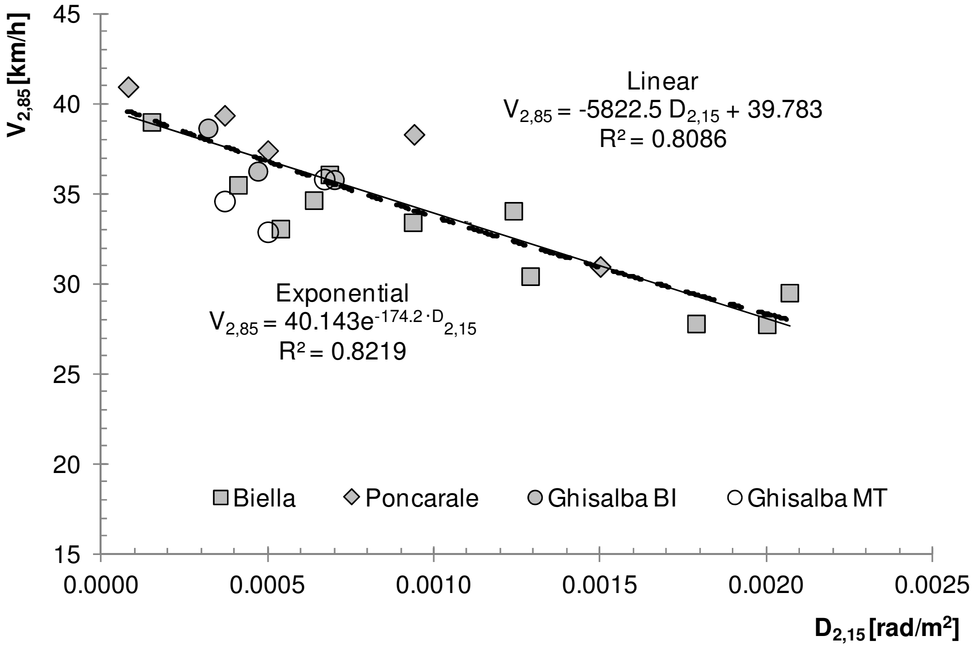


Figure 6 – Relationship between $V_{2,85}$ and $D_{2,15}$ index

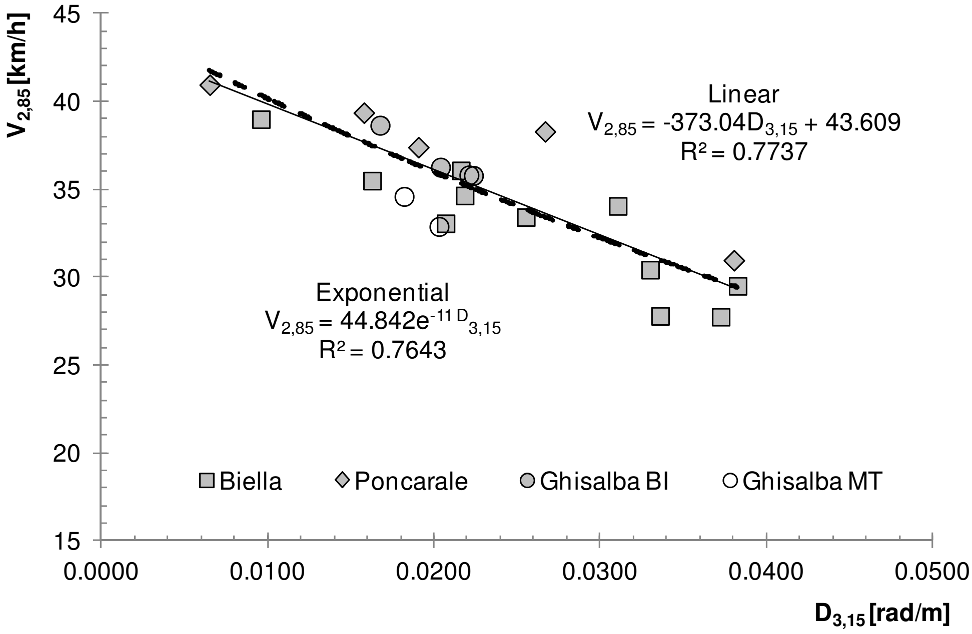


Figure 7 – Relationship between $V_{2,85}$ and $D_{3,15}$ index

Finally, the speed data show no correlation with $D_{1,15}$ demonstrating that such a parameter fails to explain the difficulties in negotiating the roundabout as a consequence of the product between angle and radius (see eq.1). In fact, speeds are limited only when high angles and small radii occur in the same manoeuvre. Figure 8 testifies to the fact that no correlation exists between $D_{1,15}$ and operating speeds.

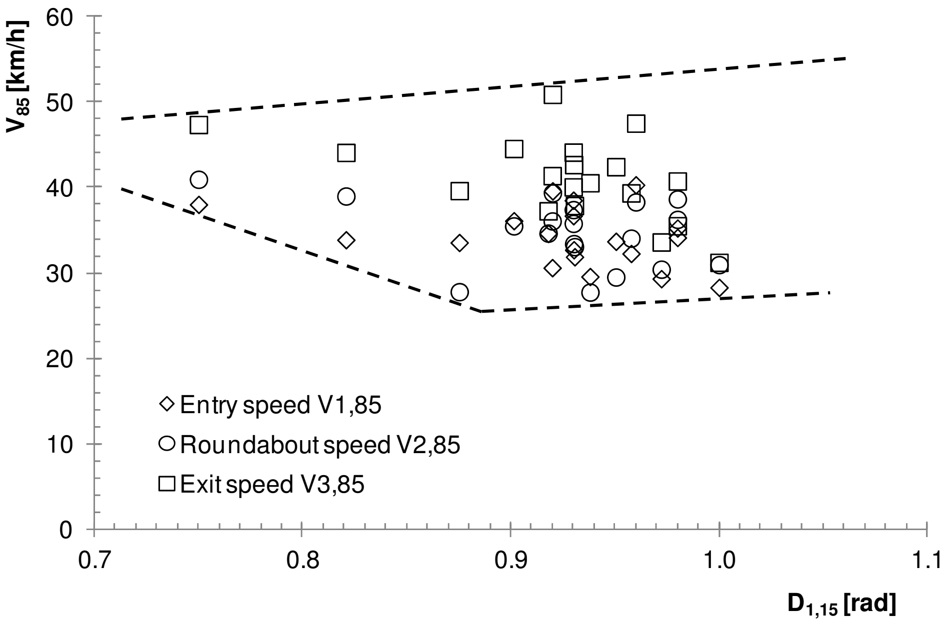


Figure 8 – Relationship between $V_{85}$ and $D_{1,15}$ index

# DISCUSSION AND CONCLUSIONS

The paper presents the results of several activities undertaken involving extensive use of the VeTRA software which the authors developed for the specific purpose of carrying out operational analyses of roundabouts. The software is able to operate on video recordings from one or more cameras, and was tested using both the one and three camera configurations.
In the paper ongoing activities have been described with reference to previous works by the authors (Mussone et al., 2011a and 2011b) in which they focused their attentions on the following two main objectives:

- the selection of the optimal set up for a video survey in terms of the ideal number of video cameras and their positioning relative to the roundabout;
- the reliability of the tracking systems in the survey of trajectories with the aim of deriving the E-E matrix and the geometric effects on speeds.

Previous works and the results reported in this paper testify to the fact that the video survey system and the processing code are both robust and reliable, despite some difficulties encountered with the video image acquisition and pre-processing in two particular surveys where poor wind and light conditions had an effect on and, indeed, compromised the processing of video images. As documented in this paper, the authors are aware that further work is required to mitigate the effects produced by wind and thus obtain more stable images.
Five different roundabouts and set-ups were considered. The results showed the strengths and weaknesses associated with each set-up.
In the three cases of Biella, Ghisalba and Poncarale small camera oscillations, clouds and flying objects (i.e., birds) affecting image quality were easily identified and corrected. In the two cases of Sarnico and Chiari, as a consequence of greater oscillations due to wind and over exposure and distortion due to the different height of the cameras from the plane of the roundabout, this task was not successful.

On examination of the three configurations presented in Figure 1, it is clear that the central position of the video cameras facilitates a reduction in perspective distortion but, as in the case of Ghisalba (configuration #2 in Figure 1 with three cameras), a relatively high number of video cameras is required given the dimensions of the circulatory roadway. The blending of images becomes more complicated with an increase in the number of video cameras installed on the roundabout. Moreover, synchronization between cameras becomes crucial: with the loss of only one frame of a video camera necessitating a challenging task of realignment between video frames.

Elevated vantage points on poles or buildings introduce high distortions especially in the case of heavy and long vehicles, as in the case of Poncarale (configuration #3 in Figure 1 with three cameras). Furthermore, the height of vantage points have a detrimental impact on image quality since the cameras and their supports are exposed to stronger winds, which can produce oscillations that cannot be corrected during the image treatment phase. From an analysis of the data collected at the Poncarale roundabout, it would appear that the merging of trajectories extracted from different images (MT strategy) seems to be less effective than the blending images (BI) technique. In this case, the only one where this comparison has been carried out, the performance indicators associated with the evaluation of the E-E matrix indicate a greater dispersion of data in the case of the merged trajectory technique (see Table 3).

Whereas the blending of images is essentially a straightforward task when video cameras have viewing angles of less than 90 degrees, it tends to prove problematic with wider angles (especially those close to 180°) as a consequence of the different perspective distortions of moving elements. Of the five strategies considered in this research, the use of a single video camera mounted on a pole located outside the roundabout, as in the case of Biella, would appear to offer the best compromise in terms of survey costs, pre-processing work, and quality of results.

From the image analysis of videos, VeTRA is able to collect spatial and temporal data for a large number of points along each trajectory, thus deriving local speeds. The authors decided to consider speeds at the entrance gate, at the central point and at the exit of the roundabout with the aim of reducing this amount of data into a smaller representative sample. With the same aim, three different deviousness (D) indexes were calculated for each trajectory by combining angular deviation and the distance between two successive recorded points, and the radius of the local osculating circle in different ways.

As a result, some robust linear and exponential relationships between the 85$^{th}$ percentile of speeds and the 15$^{th}$ percentile of deviousness indexes have been derived. The observations confirm that an effective speed control into the circulatory roadway is possible only when high horizontal curvatures of vehicle paths (i.e., high values of deviousness) are achieved as a consequence of the combination of the geometric characteristics of roundabout elements. In particular, as highlighted in Chen et al. (2012), the most influential geometric variables are the diameter of the internal circle, the width of the circulatory roadway, and the width of the entry lanes.

The regression equations presented here were obtained from the observation of just three roundabouts with each exhibiting a different geometry in terms of external and central island diameters, circulatory roadway width, number and geometry of entry and exit lanes. The high coefficient of one of the four proposed equations ($R^2$ = 0.821 for the exponential relationship

between $V_{2,85}$ and the $D_{2,15}$) allows its use in the estimation of the circulating operating speed ($V_{2,85}$) in the analysis and design of new roundabouts.
The use of this new survey system for roundabout data collection leads to a more reliable analysis of the operational effects of roundabout geometrics with respect to other techniques considered in literature (Rodegerdts et al., 2007 and 2010). As a consequence, the authors are confident that VeTRA can be successfully employed in the acquisition of operational data for research as well as for the design or redesign of intersections.

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