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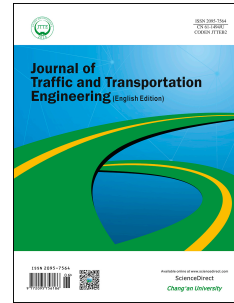
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1 Original research paper

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3 **Experimental analysis of operational data for** 4 **roundabouts through advanced image processing**

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11 **Highlights**

- 12 • An investigation carried out to survey vehicle movements at roundabouts was presented.
- 13 • O/D matrix, classification, trajectories tracking, speed and acceleration from video images
14 analysis.
- 15 • A number of camera set-up configurations were adopted.
- 16 • Performance of installation set-ups with different vehicle tracking strategies has been evaluated.

17

18 **Abstract**

19 Roundabout is still the focus of several investigations due to the relevant number of variables affecting
20 their operational performances (i.e., capacity, safety, emissions). To develop reliable models,
21 investigations should be supported by devices and related sensors to extract variables of interest (i.e.,
22 flow, speed, gap, lag, follow-up time, vehicle classification and trajectory). Notwithstanding that
23 several sensors and technologies are currently used for data collection, most of them present
24 limitations. The paper presents the investigation carried out to survey vehicle movements at
25 roundabouts as a comprehensive video image analysis system is able to derive the origin/destination

26 (O/D) matrix, compile a vehicle classification, track individual vehicle trajectories together with
27 corresponding speeds and accelerations along paths. To this end, the authors collected video-
28 sequences that were analyzed with a piece of software developed for that task. To minimize the
29 problems due to perspective distortion, environmental effects, and obstructions, a number of camera
30 set-up configurations were adopted with equipment being placed on central or external poles, and on
31 permanent fixtures such as raised working platforms outside the confines of the intersection area.
32 Performance of those installation set-ups with different vehicle tracking strategies has been evaluated.
33 Particularly, speed has been successfully related to trajectory tortuosity, the result of which
34 emphasizes the tremendous potential of image analysis and opens up to further studies on the
35 evaluation of the operational effects of roundabout geometrics.

36 **Keywords:**

37 Transportation; Roundabout; Image analysis/processing; Vehicle tracking and classification; Operating
38 speed; Trajectory.

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50 1 Introduction

51 In many countries, roundabouts have increasingly become the intersection of choice due to the
52 positive and acknowledged operational benefits deriving from their geometrics as reported in literature
53 (Curti et al., 2008; Rodegerdts et al., 2010, 2014). Nevertheless, operational performance in terms of
54 capacity, speed, and safety still remains a focus of investigation due to the number of variables, apart
55 from geometric ones, affecting trajectories and speeds of crossing vehicles (Sacchi et al., 2011), and
56 emissions (Fernandes et al., 2015; Salamati et al., 2013).

57 With the objective of developing reliable models, investigations should be conducted using
58 robust tools and with attention being paid contextually to the circulating roadway and all the legs.
59 Such tools have to be able to: (a) extract traffic variables of interest such as flow, speed, gap, lag,
60 follow-up time, vehicle length and weight, as well as vehicle position in time (i.e., vehicular
61 trajectory); (b) ensure that the recording video system is not visible to drivers so as to avoid any
62 behavioural effects; and (c) contribute to a reduction in the resources needed to run the system, also
63 in terms of operator time.

64 Although several sensors and technologies are currently used for traffic data collection in
65 roundabout, most of them are limited in their ability to survey traffic variables, a point which is
66 discussed in the paper. In order to avoid the limitations associated with their use, video recording
67 surveys and related image processing techniques can be successfully employed (Messelodi et al.,
68 2005; Migliore et al., 2006; Mussone et al., 2013).

69 The paper proposes a methodological contribution to analyse speed and trajectories of vehicles
70 through roundabouts. It presents the activities undertaken by the authors in the development and use
71 of a video recording system in conjunction with a software developed for the derivation of: (a) the
72 origin/destination (O/D) flow matrix, (b) the vehicle classification, and (c) the trajectories and
73 associated speeds and curvature diagrams along the paths traversing a roundabout.

74

75 2 Background

76 2.1 Vehicle position data collection tools

77 At present, many multi-purpose detectors for traffic data collection are available at affordable prices.
78 Laser, radar, microwaves, infrared, acoustic, ultrasonic, capacitive, piezoelectric, magnetometric, and
79 magnetic loops are the technologies employed in sensors. With more or less similar levels of
80 efficiency and precision, all the above-mentioned technologies allow for the collection of macroscopic
81 variables such as flow, speed, density (or occupancy) and vehicle specific variables such as headway,
82 gap, lag, follow-up time and vehicle length and weight.

83 Their main disadvantage (apart from the fact that they sometimes need to be physically supported
84 or that, in some cases, their installation can occasionally lead to an intrusion into the traffic circulation
85 area) is that their measurements refer to a single road section or linear segment, and therefore
86 multiple measurement points require an array of collection tools. None of them, in fact, may be
87 employed for vehicle tracking, especially in situations where vehicles move along inflected trajectories
88 (e.g., in case of roundabouts). This would not be a serious problem unless it is strictly necessary that
89 information gathered by detectors relates uniquely to each individual vehicle. This task is particularly
90 crucial at roundabouts where the construction of the O/D matrix is very challenging (Grenard and Wei,
91 2012).

92 One possible way to track vehicles could be the floating car data method that, however, requires
93 that a statistically significant number of vehicles are equipped with positioning sensors i.e., global
94 positioning system-global navigation satellite system (GPS-GNSS), inertial measuring unit (IMU) or
95 combined sensors, with data recorded on board and/or transferred to a central system. With this
96 method, installations and experiments are expensive and complicated since it (the method) needs a
97 large number of vehicles together with the participation of the general public to be of any use in a
98 realistic setting. However, the current wide diffusion of navigation systems working in real time and
99 connected to a central unit makes this feature of increasing interest for the near future, at least for
100 transport planning purposes (average speed prediction and O/D matrix reconstruction). Other
101 emerging survey technologies, such as the 3D light detection and ranging (LiDAR), facilitate the

102 collection of clouds of data and could be used to track vehicles. At present, however, they are more
103 expensive than video-image technology and entail a higher level of complexity and effort in the
104 collection and modelling of a large quantity of data.

105 Consequently, the most promising methodology available at present for the tracking of vehicles is
106 certainly represented by the video analysis technique. Several contributions have demonstrated that it
107 may be employed in a variety of applications from simple vehicle detection (Messelodi et al., 2005;
108 Wei et al., 2005) to the gathering of comprehensive data for trajectories in both time and space
109 domains, thus allowing a complete reconstruction of movements along sections (Beymer et al., 1997)
110 and at vehicle intersections (Alhajyaseen et al., 2013; Apeltauer et al., 2015; Datondji et al., 2016;
111 Dinh and Tang, 2017; St-Aubin et al., 2013) or cyclist behaviour trajectory analysis (Sakshaug et al.,
112 2010; Zaki et al., 2013).

113 With the aim of providing information useful for the calibration of microscopic simulation models,
114 Alhajyaseen et al. (2013) analysed the relationship between speed and trajectory at at-grade urban
115 intersections. Adopting the survey technique described in Suzuki and Nakamura (2006), those authors
116 demonstrated the effect on vehicle trajectory of geometry (angles between legs, corner radii, number
117 of exit lanes, and positions of hard noses of the medians) for different vehicle types negotiating the
118 intersection at different speeds, confirming the potential of the image analysis technique when
119 conducting surveys to gather positioning data at road junctions. In Mussone (2013), the question of
120 visibility on roundabouts was faced by using real trajectories extracted from video image records.

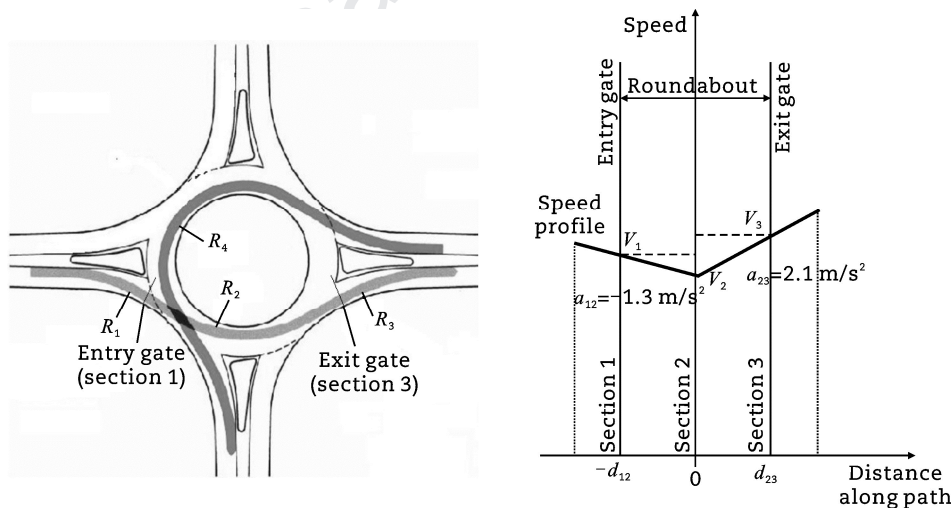
121 Finally, the possibility to track vehicles in roundabouts by video cameras mounted on drones has
122 raised a certain interest. Guido et al. (2016) used them to detect and compare tracking data with GPS-
123 equipped vehicles only. According to the authors, the methodology is promising but needs to be
124 improved for removing noise and inaccuracies due to uncontrolled movements and vibrations of
125 drones under the effects of wind.

126 *2.2 Position and speed data modelling at roundabouts*

127 Operational data for modern roundabouts were investigated for the first time in the National
128 Cooperative Highway Research Program (NCHRP) Project 3-65, when a comprehensive inventory of

129 103 US roundabouts with geometric, operational, and safety data was carried out (Rodegerdts et al.,
 130 2007). Of these, 31 roundabouts were the focus of video recordings in the spring and summer of 2003,
 131 with 34 h of traffic operation data accumulated (i.e., flow measurements, gaps, delays and travel times,
 132 turning movement proportions, and vehicle types). For this purpose, a video recording system
 133 consisting of analogic and digital video cameras was used. Operational data were recorded making
 134 use of "event recording" software (Rodegerdts et al., 2006). In the same study, sixteen single-lane and
 135 eleven multi-lane roundabouts were considered for the operating speed surveys (Fig. 1).

136 In Rodegerdts et al. (2007), speed data were collected through the use of radar guns only at four
 137 specific locations: one outside (i.e., at 60 m from the yield line) and three inside the roundabouts. In
 138 particular, as seen in Fig. 1, they were collected at the yield line (section 1), at the midpoint of the
 139 adjacent splitter island (section 2), and at the exit (section 3), with a minimum number of speed data
 140 per section greater than 30 to achieve a statistical significance. Speed data collected at the
 141 roundabouts were differentiated both by movement type (i.e., left, through or right turn), and by vehicle
 142 type (i.e., passenger cars, trucks), and only passenger car data were used for that analysis.



143

144 **Fig. 1** Layout of the operating speed surveys (Rodegerdts et al., 2010). (a) Geometric characteristics of trajectories. (b) Schematic speed
 145 profile.
 146

147 Starting from the elementary arc with the minimum radius on which the minimum speed is reached
 148 in the circulatory roadway (V_2), speeds at the entry (V_1) and exit (V_3) gates can be derived under the

149 hypothesis of naturally decelerated/accelerated motion and adopting average deceleration (a_{12}) and
 150 acceleration (a_{23}) values from observational data (Robinson et al., 2000).

151 The predictive speed equations (Rodegerdts et al., 2007) for the through movement for entry (V_1)
 152 and exit (V_3) speeds in km/h (Fig. 1) are

$$153 \quad V_1 = \min \left\{ V_{1\text{base}}; 3.6 \sqrt{\left(\frac{V_2}{3.6}\right)^2 - 2a_{12}d_{12}} \right\} \quad (1)$$

$$154 \quad V_3 = \min \left\{ V_{3\text{base}}; 3.6 \sqrt{\left(\frac{V_2}{3.6}\right)^2 + 2a_{23}d_{23}} \right\} \quad (2)$$

155 where a_{12} is the deceleration between the point of interest of the entry path and the midpoint of the
 156 path (assumed equal to -1.3 m/s^2), a_{23} is the acceleration between the midpoint of the path and the
 157 point of interest of the exit path (assumed equal to 2.1 m/s^2), and d_{12} and d_{23} are the distances
 158 between the points of interest along the entry and exit paths, and the midpoints of these paths
 159 respectively, which are measured along the vehicle trajectory. In Eqs. (1) and (2), $V_{1\text{base}}$, V_2 and $V_{3\text{base}}$
 160 represent the predicted speeds at the entry, midpoint and exit points based on path radii R_1 , R_2 and R_3
 161 (Fig. 1) using the basic formula of vehicle equilibrium on curves (Eq. (3)).

$$162 \quad \begin{cases} V_{1\text{base}} = \sqrt{gR_1(f+q)} \\ V_2 = \sqrt{gR_2(f+q)} \\ V_{3\text{base}} = \sqrt{gR_3(f+q)} \end{cases} \quad (3)$$

163 where g is the acceleration of gravity (equal to 9.81 m/s^2), f is the side friction factor, and q is the
 164 super-elevation, which is normally -2% in the case of modern roundabouts (Rodegerdts et al., 2007).

165 Eq. (3) may also be used to evaluate the speed along a left turn movement, using the value of R_4
 166 indicated in Fig. 1 as a radius.

167 A comparison between the 85th percentile speed observed in the field and the corresponding
 168 values predicted using Eqs. (1) and (2) demonstrated that the proposed model was applicable to
 169 those maneuvers in which vehicles interact with the central island (left turn and through movements),
 170 and that it was considered conservative because it tends to overestimate the operating speed. The
 171 regression analyses performed on these models with available data showed the coefficients of
 172 determination to be too low, thus indicating that the variables considered could not provide a reliable

173 prediction of speed on the circulatory roadway. This leads to the conclusion that the evaluation of
174 operating speed at roundabouts still remains a challenge at both the analysis level and design stage
175 (Šurdonja et al., 2018; Perco et al., 2012).

176 Currently, TORUS (Transoftsolutions, 2018) and CIVIL 3D (Autodesk, 2018) software packages
177 consider the fastest path analysis according to literature (Robinson et al., 2000; Rodegerdts et al.,
178 2007). These programs calculate the expected speed on the circulatory roadway along the minimum
179 radius along the “fastest vehicle path”, which represents the smoothest possible trajectory of a vehicle,
180 in the absence of other vehicles and ignoring all lane markings, from the entry to the exit gates (Ahac
181 et al., 2016; Rodegerdts et al., 2006).

182 **3 Methodology**

183 Starting from this literature review, the authors proposed a comprehensive methodology to collect
184 video records from existing roundabouts and derive information useful to model the relationship
185 between speeds and trajectories of vehicles. The tracking of trajectories gives also the possibility for
186 the derivation of trajectory tortuosity parameters, as well as the reconstruction of O/D matrix. From the
187 length of moving objects in the road scene, a neural network was trained to classify vehicles along
188 each movement.

189 To minimize the problems due to perspective distortion, environmental effects, and obstructions, a
190 number of camera configurations were adopted with equipment being placed on central or external
191 poles (with respect to central island), or on permanent fixtures such as raised working platforms
192 outside the confines of the intersection area. Strengths and weaknesses of the selected installations
193 are described in order to determine the optimal set-up. Three case studies in Northern Italy were
194 considered. Up to three video cameras were used in different set-ups. Each installation exhibited a
195 different behaviour under the effects of wind, cloud cover, shadows, dazzle, perspective deformation,
196 and obstructions. Two additional aspects, namely ease of perspective correction and synchronization
197 between video cameras, were also investigated and solved.

198 An important issue faced in the paper is the synchronization of recorded images when using more
199 than one video camera. This was achieved by inserting a timestamp for every recorded stream. This

200 task is easier when cameras are mounted on the same pole and camera output can be connected
201 directly to the same computer. More demanding is the case when several cameras on different poles
202 are involved and a wireless connection is needed to link the computers together to use the same
203 timestamp. Besides this, the authors experimented two different strategies in order to build trajectories:
204 by merging trajectories extracted by separated images (MT) and blending images before extracting
205 trajectories (BI).

206 Finally, the data collected from image analysis in the three case studies have provided general
207 relationships between speeds and trajectories as affected by roundabout geometrics. Differently from
208 the approach of Robinson et al. (2000) and Rodegerdts et al. (2007), continuous speed and trajectory
209 data help the authors in the development of a new model able to relate speeds to trajectory tortuosity.
210 The possibility to work out such a model can be considered by analysts and designers as an
211 opportunity to predict speed behaviour of drivers along their path on the basis of roundabout
212 geometrics.

213 *3.1 Survey tools and methodology*

214 The instrumentation used to collect and evaluate data consists of a vision system and a real time
215 kinematics-global positioning system (RTK-GPS), both connected to a dedicated PC (Fig. 2). In
216 Mussone et al. (2011, 2013), a more detailed description of the system, including details of both
217 hardware and software characteristics, can be found. Images from video cameras must not have blind
218 spots and this condition can be achieved through a planned set up of optics and video camera
219 orientation.

220 The vision system (Fig. 2(a)) consists of one to three cameras with a resolution of 1360 x 1024
221 pixels. The optical lens of each video camera was adjusted in line with the application scenario by
222 remote control. The vision system provided information on vehicular flow through the processing of
223 images recorded by the video camera(s), while the RTK-GPS system was used to generate data
224 useful for calibrating and evaluating the vision system.

225 The RTK-GPS system (Fig. 2(b)) is composed of a base station equipped with a Trimble MS750
226 GPS and a Trimble Zephyr Antenna. A rover, made up of a Trimble 5700 GPS (working at 5 Hz) and a

227 Trimble Zephyr Antenna, is attached to a probe vehicle and connected via radio link (DiGi XBee Pro
 228 modules in point to point mode) to the base station.

229

230 (a)



(b)



231

232 **Fig. 2** Data collection and evaluation instrumentation. (a) Vision system placed upon a raised working platform. (b) The probe vehicle
 233 with the rover system.

234

235 In order to improve the process of matching video camera data with GPS data, a series of marked
 236 points visible in video images were drawn on the pavement surface of the roundabout (four points on
 237 each leg, and from four to eight points on the circulatory roadway depending on the dimension(s) of
 238 the central island). The exact positions of these points were, then, attained by both GPS (with an
 239 accuracy ranging from 2 to 15 cm) and by video recording. The matching of vehicle coordinates (and
 240 then speed) data calculated by image processing with the data gathered by GPS was then a relatively
 241 straightforward task.

242 Calibration of the vision system was carried out for image rectification, thus tuning the Bouguet
 243 camera model of the vision system. Image rectification aims at achieving homogeneity in terms of
 244 corresponding pixels in the image plane, and the ratio between lines lengths and angles in a specific
 245 plane of the observed world (i.e., the central islands is circular but it appears an ellipse in the
 246 perspective projection). This requires a proper image transformation, i.e., a homography between the
 247 road surface and the image plane. Vehicle tracking on the transformed plane turns out to be quite

248 effective and more accurate than when carried out on the original image. The homography is known
249 when the size and the position of some specific elements of the observed scene are available.

250 3.2 *Pre processing*

251 The images gathered require conversion, undistortion, and rectification, while RTK-GPS data need
252 data conversion (for rover data) and synchronization between base station and rover timestamps.

253 The image analysis was carried out by a software (developed at Politecnico di Milano and based on
254 MATLAB platform) named Vehicle Tracking for Roundabout Analysis (VeTRA), which employs genetic
255 algorithm optimization procedures to minimize the re-projection error of the central island onto the
256 image plane, and also provides a complete projective transformation from the 3D real world to the 2D
257 image, by constraining world points to lie at ground level.

258 The current version of VeTRA has further improved performance in blob recognition with respect to
259 the original version used in Mussone et al. (2011). Improvements to the algorithms have now limited
260 the negative effects of some environmental factors (i.e., wind, sudden changes in light conditions due
261 to clouds), occlusions due to fixed objects (i.e., trees, poles) and moving vehicles (Oh et al., 2012), as
262 well as perspective deformations.

263 The key tool in VeTRA is its tracking system, which detects moving objects in the field through an
264 adaptive background modelling and subtraction algorithm. The image areas representing the vehicles
265 (known as “blobs” in information science jargon) are identified in the foreground through shadow and
266 noise removal. The tracking system is capable of distinguishing between newly detected blobs and
267 previously tracked vehicles between three types of vehicles as explained in the next paragraph. The
268 blobs are continuously updated as new information is received. All these activities rely on a proper
269 model of the background, which has to be sufficiently robust to contend with daily changes in light
270 conditions and camera oscillations. Although the tracking system detects the movements of objects in
271 the background, it is able to filter and hence exclude from computation all the small movements of any
272 objects (i.e., trees, sheets on the pavement, etc.) affected by wind.

273 When more than one video camera is used, two different strategies can be employed to consolidate
274 the information. One strategy merges the blob trajectories extracted from each separate video image

275 (here called Merging Trajectory (MT) strategy), the second blends images from video cameras before
276 extracting trajectories from the blended images (here called Blend Images (BI) strategy). There are a
277 number of problems and advantages associated with each strategy that were tested in this experiment.

278 With the MT strategy, the trajectory of the same vehicle is extracted from video cameras (two or
279 more) as in the approach with one camera only. After that, trajectories of the same vehicle are
280 associated and superimposed in order to obtain only one trajectory. The challenging activity is the
281 association of trajectories avoiding strong discontinuities between them.

282 With the BI strategy, a new image is generated from the blending of all images collected to exclude
283 the portions of images affected by distortion. Then, blended images are analysed as in the one
284 camera approach to extract trajectories.

285 The MT strategy makes it easier to extract blob trajectories separately from each video camera but
286 does not guarantee a perfect continuum (in the sense of function derivability) of single trajectories. On
287 the other hand, the BI strategy allows a final complete trajectory which is perfectly continuous but
288 requires considerable effort due to merging images. In fact, isomorphic transformation and
289 perspective correction must be applied to each image to maintain the same scale over the trajectory.

290 It is worth noting that new set-ups with a different number of video cameras required an
291 improvement of the original version of VeTRA (Mussone et al., 2013). The new images produced by
292 blending separate images, or the new trajectories derived from mixing the trajectories given by each
293 video camera, are significant results for the post processing phase.

294 3.3 *Post processing I – trajectory reconstruction*

295 For each video survey, the blob trajectories produced by the tracking system are processed and
296 stored in a database in order to generate the O/D matrix, vehicle trajectories, speed profiles and the
297 vehicle classification.

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

302 then saved to a system of local coordinates. Speed and curvature profiles are obtained from
303 calculations based on vehicle position and time. Speed is calculated for two consecutive points by
304 simply dividing the distance between them by the elapsed time (equal to the frame rate of the camera,
305 except in those very rare cases where some frames have been lost).

306 The tracking system used in VeTRA follows two different procedures. The first one is less
307 sophisticated and is employed for flow classification purposes as it distinguishes between (a) bikes
308 and motorbikes, (b) light vehicles, vans and campers, and (c) heavy vehicles. It detects the blob for
309 each vehicle, which is then tracked from the entry to the exit section. In this paper, only classes (b)
310 and (c) were used for performance comparison since too few bikes and motorbikes were observed
311 during the survey.

312 Classification is based on vehicle dimension, particularly on its length, which is derived from blob
313 length. Since blob dimension generally changes according to its position inside the image (that is, the
314 position inside the circulatory roadway) due to perspective distortion, a neural network (NN) was used
315 to classify vehicle length by using for training some images sampled from vehicle trajectory,
316 accurately divided by movements. The NN must be trained in every location because it needs to learn
317 the effect of perspective distortion along the circulatory roadway. The accuracy of NN recognition was
318 high with an error lower than 3% for trajectories closer to video camera; higher errors were observed
319 for short trajectories, and for those farther from the video camera where perspective distortions may
320 create difficulties in recognition.

321 The second tracking procedure is more accurate and is employed for trajectory and speed analysis.
322 It recognizes the barycentre (or centroid) of each blob in 2D and produces a continuous curve formed
323 by points that are known in the space and time domains. More details on tracking procedures are
324 available in Mussone et al. (2013).

325 *3.4 Post processing II – data treatment for speed analysis*

326 A filtering algorithm in VeTRA was included to reject trajectories in which the speeds are too low due
327 to vehicle conflict both in the circulatory roadway and in the approaching and departure legs. More
328 specifically, vehicles that stopped before entering or reduced the speed to give priority to circulating

329 ones were excluded from the speed analysis to obtain free flow speeds only. As a result, trajectories
 330 with average speeds between entry and exit lower than 10 km/h were discarded. Filtering was also
 331 necessary to exclude stationary vehicles in the circulating roadway, or affected in trajectory by
 332 conflicting vehicles. In fact, in some cases, very low speeds were the result of superimposition of
 333 trajectories (and blobs) of two or more vehicles.

334 When available in time and space domains, the trajectory of any isolated vehicle traversing the
 335 roundabout in free-flow conditions contains all the information necessary for an assessment of how
 336 the said vehicle trajectory was affected by the geometry of the roundabout. Tortuosity indexes may be
 337 used to characterize curved trajectories. In this paper, two tortuosity indexes, having as an objective
 338 the characterization of the vehicle paths associated with specific maneuvers (crossing, right, left and
 339 U-turn), have been derived by reference to general literature. It is obvious that these indexes cannot
 340 capture all aspects of driver behaviour but they are helpful in understanding whether the trajectory
 341 itself and related vehicular speed are confined to a range within recommended operating intervals.

342 According to Fig. 3, the first index (T_1) (a derivation of index T_2 , presented hereafter) is shown as
 343 follow

$$344 \quad T_1 = \sum_i (|\alpha_i|/R_i)/L \quad (4)$$

345 where $|\alpha_i|$ is the absolute value of the angle between the tangents passing from two successive
 346 recorded points (P_i and P_{i+1} , P_{i+1} and P_{i+2}), R_i is the radius of the osculating circle that is derived from
 347 thirty points around the considered one (15 before $-P_{i-15}$, ..., P_i , and 15 after $-P_{i+1}$, ..., P_{i+15}), L is the
 348 length of the trajectory between the entry and the exit gates, and i is one of the considered points. The
 349 sum over i includes all the points between the entry and the exit gates. Thirty-one points allow to
 350 manage a set of images of one second duration (at the current frame rate), which can be considered
 351 long enough to smooth peaks due to random noise effects in blobs.

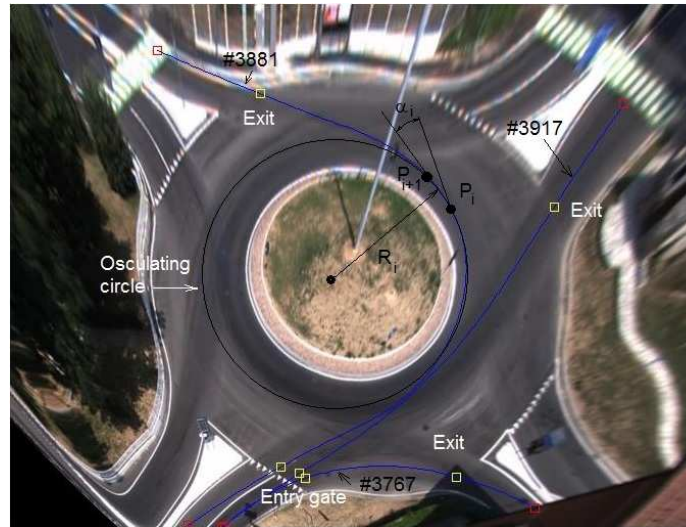
352 The second tortuosity index (T_2) is obtained with the Eq. (5).

$$353 \quad T_2 = \sum_i (|\alpha_i|/L) \quad (5)$$

354 Eq. (5) is also known in literature as the curvature change ratio (Yasser and Mohamed, 2011).

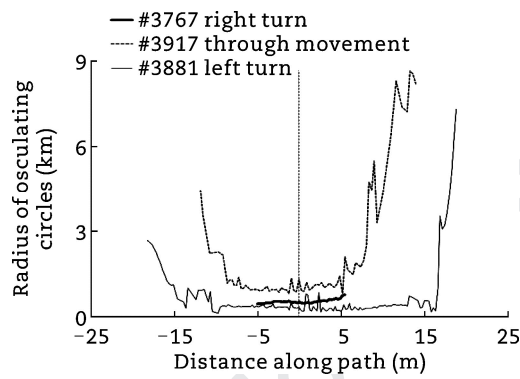
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356 (a)

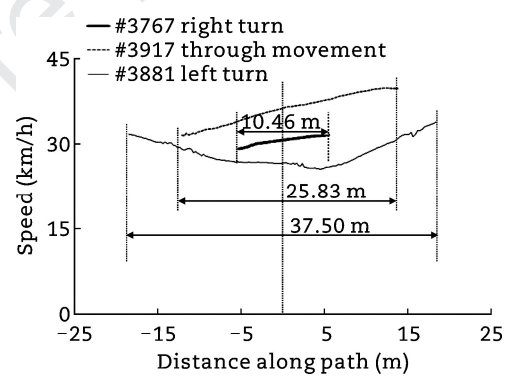


357
358

(b)

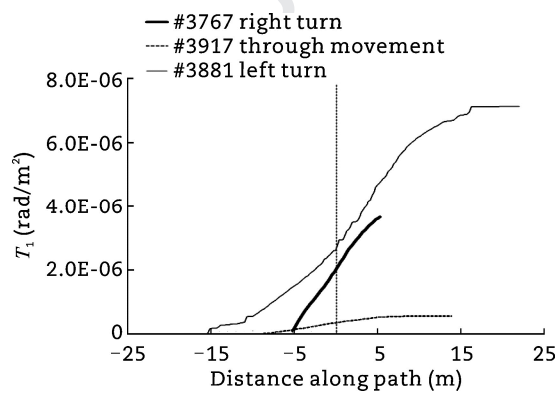


(c)

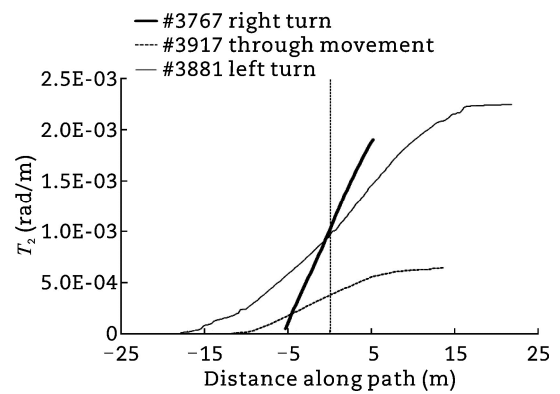


359
360

(d)



(e)



361
362
363
364
365

Fig. 3 Trajectory analysis. (a) Typical curves for parameter analysis. (b) Trajectory radius. (c) Speed. (d) T_1 . (e) T_2 .

366 Fig. 3 shows the typical curves for the four parameters extracted from trajectory analysis (trajectory radius, speed, and two tortuosity indices) for three main movements: right, through and left turn (U-

367 turn was not considered due to the paucity of data examples). In the same Fig. 3, the cumulated
368 values of these two indexes from the initial point at the entry gate ($i = 1$) to the generic points (i) along
369 the trajectory is also plotted.

370 The two indexes indicate the level of difficulty in negotiating the roundabout, which is higher when
371 the angles are high and the corresponding radii are small. The units of measurement for the two
372 tortuosity indexes are rad/m^2 and rad/m , respectively. In Fig. 3(d) and (e), they have been plotted
373 according to the formulas with values that increase along the travelled path, for three trajectories
374 selected from the Biella roundabout database (each identified with a 4-digit code). In Fig. 3(b) and (c),
375 for the same three trajectories, the radius of the osculating circles and the speed profile are plotted. It
376 is worth noting that in Fig. 3, the central point of the path has a reference station equal to 0.

377 As previously indicated, the speed at each of the P_i points along a generic trajectory is calculated by
378 simply dividing the distance between every point P_i and the consecutive point P_{i+1} by the elapsed time
379 (equal to the frame rate of the video camera that was equal to 0.0333 s). For the radius diagram,
380 thirty-one consecutive points of the trajectory (resulting in 1 s of images) have been considered for the
381 estimation of R_i values.

382 4 Investigation

383 With a view to establishing the optimal camera configuration and assessing the performance of
384 VeTRA, in-field research activities were initially undertaken at five roundabouts in northern Italy
385 (Piedmont and Lombardy regions), chosen for their geometrical characteristics and environment (rural
386 and urban). Table 1 reports a synthesis of the geometric characteristics and the most significant
387 survey data, while Fig. 4 illustrates three general video camera configurations used for the surveys.

388 Unfortunately, two other sites with different set-ups and in urban environment were investigated but
389 recorded images were unusable due to the effects of a strong wind in one case and to a reflected
390 dazzle in the latter that were not possible to remove.

391 Images were recorded for between 1.5 and 2 h to obtain at least one hour of actual flow. The
392 recording period was in and around the peak hour of midday and, in all cases, the weather conditions
393 were prevalingly dry and sunny with occasional passing clouds.

394 The first roundabout is located near the urban limits of the city of Biella (Fig. 5, with the identification
 395 of tracked vehicles, entry and exit gates, and video camera direction (arrow)), and connects two
 396 arterials with two lanes per direction and separated carriageways.

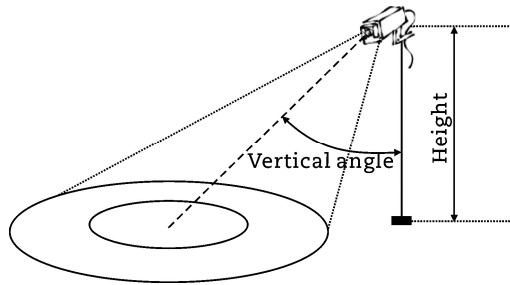
397 Pedestrian crossings are provided at three of the four legs. The external diameter is 50 m, the
 398 circulatory roadway is 13 m in width, while the central island diameter is equal to 24 m including a
 399 truck apron of 1.5 m. The approaching legs have two lanes with an average width of 8 m, while 6 m is
 400 the width of the single lane departure legs. The roundabout is equipped with a lighting tower headlight,
 401 while the water harvesting systems are located outside the circulatory roadway. During the study, the
 402 detection system was placed on a moveable rack near the edge of the southwest corner. The video
 403 camera, pointing towards the centre of the roundabout, was placed at a height of about 22 m at an
 404 angle of approximately 55° with respect to the rack axis.

405 **Table 1** Synthesis of information for survey activities.
 406

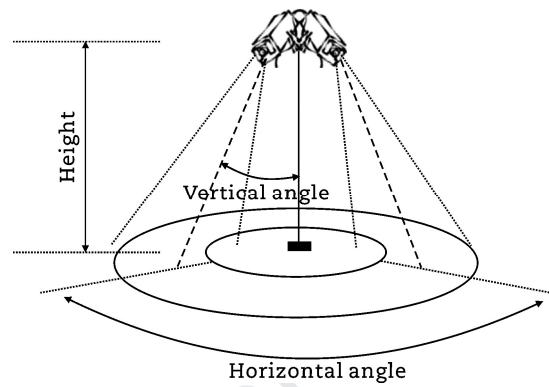
Roundabout	Biella	Ghisalba	Poncarale
Latitude	45°33'12".39	45°35'32".21	45°27'29".99
Longitude	8°04'21".85	9°46'19".75	10°12'09".66
Inscribed diameter, D_{INS} (m)	50	46	70
Inner island diameter, D_{INT} (m)	24	26	56
Circulatory roadway width, W_{CR} (m)	13	10	7
Number of legs	4	4	4
Configuration # (Fig. 4)	1	2	3
Number of cameras	1	3	3
Manufacturer	Goyo GM12314S	No.2 Goyo GM12314S (2.30 mm, 94°)	Goyo GM12314S
(focal length, FOV)	(2.30 mm, 94°)	No.1 Theia MY125M (1.43 mm, 125°)	(2.30 mm, 94°)
Number of survey points	1	1	2
Video camera position	External	Internal	External
Horizontal angle (°)	-	90	120
Vertical angle (°)	55	40	72 (1 camera) 55 (2 cameras)
Camera height (m)	22	22	32

407 Note: FOV is field of view.
 408
 409

410 (a)



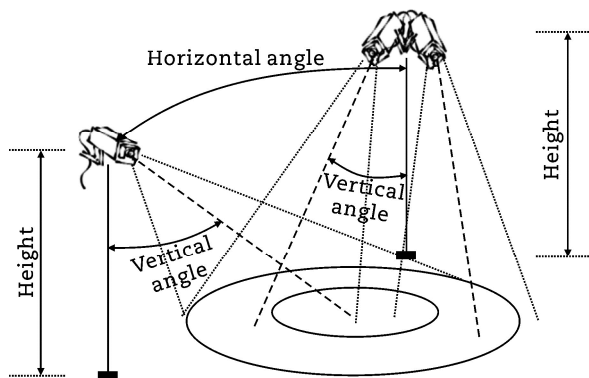
(b)



411

412

413 (c)



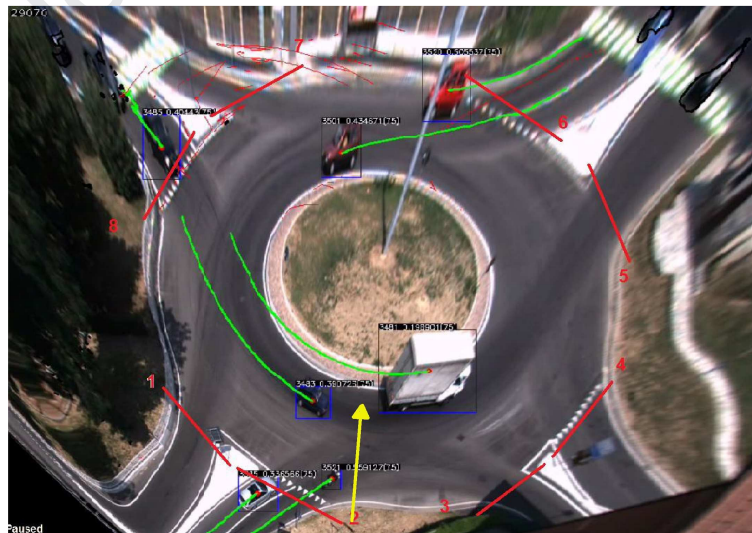
414

415

416

417

Fig. 4 Scheme of the three video camera configurations adopted for the survey. (a) Configuration #1. (b) Configuration #2. (c) Configuration #3.



418

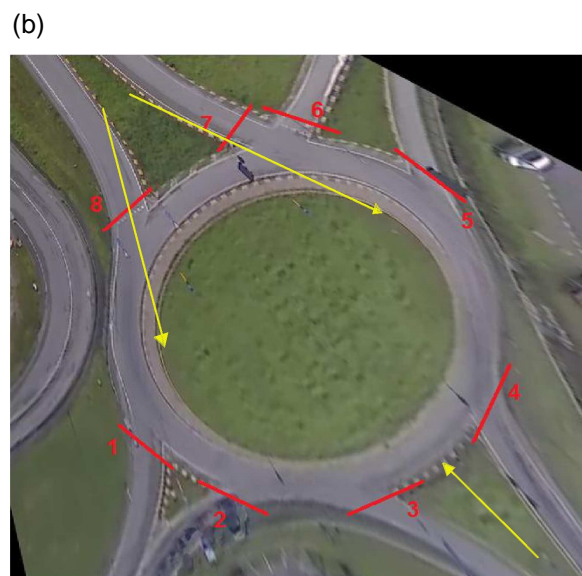
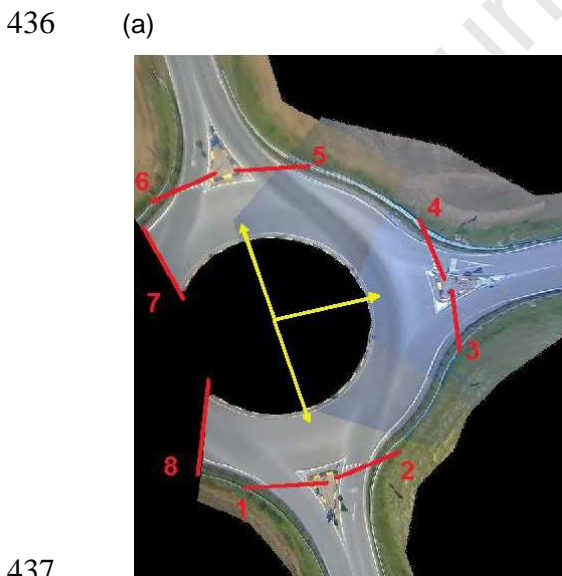
419

420

Fig. 5 Aerial view of the Biella roundabout.

421 The second roundabout is located in a rural area near Ghisalba (Fig. 6(a)) at the intersection of two
 422 single-carriageway rural highways with no pedestrian crossings. The external diameter is 46 m, the
 423 circulatory roadway is 10 m, and the central island diameter is equal to 26 m with a truck apron of 2 m.
 424 The roundabout is furnished with a central lighting tower headlight. The detection system, consisting
 425 of three cameras, was placed on the lighting pole in the centre of the central island at a height of
 426 about 21 m above the roundabout plane, with the three cameras facing east, north and west
 427 respectively and placed at vertical angles of approximately 40° with respect to the pole.

428 The third roundabout lies outside the urban area of Poncarale (Fig. 6(b)) at the intersection of two
 429 main highways, both of which are single carriageway with two-way traffic and no pedestrian crossings.
 430 The external diameter is equal to 70 m and the circulatory roadway is only 7 m. As a result, the
 431 roundabout has a wide central island (56 m in diameter) that includes a truck apron of 2.5 m. In
 432 contrast with the other two roundabouts, the approaching and departure legs of the Poncarale
 433 roundabout are tangent to the circulatory roadway. The lighting is provided by two lighting towers,
 434 located on two divisional islands to the north and south, distant 81 and 28 m respectively from the
 435 roundabout.



437
 438 **Fig. 6** Aerial view of roundabouts. (a) Ghisalba roundabout. (b) Poncarale roundabout. (Arrows indicate video-camera direction).

439 The measurements were taken with three cameras installed at a height of 32 m, two of which were
 440 located on the southern lighting pole at an angle of approximately 55° and the third on the northern

441 lighting pole at an angle of approximately 72°. The cameras were attached to the lifting system to
442 which the lamps of the central pole are fixed. This system is lifted and lowered whenever lamp
443 maintenance is conducted. Since the video cameras were close to the lamps, it is reasonable to
444 assume that they were not seen by drivers and so did not influence their behaviour. Survey vantage
445 points were determined according to the particular set-up adopted (Fig. 4), with video cameras able to
446 cover the entire roundabout.

447 **5 Results and analysis**

448 *5.1 Vehicle classification and O/D matrix*

449 As explained before, the classification of vehicles has been limited to two classes of vehicles (light
450 and heavy) which, when combined, represent more than 95% of the total observed flow for the three
451 investigated case studies. Classification is worked out by a neural network previously trained through
452 a sample of cases which are manually extracted.

453 Using different combinations of the two strategies cited previously (merged trajectories (MT) and
454 blended images (BI)), the number of video cameras (from one to three (1C–3C)) and configurations
455 (from #1 to #3), five different cases have been considered and reported in Table 2 to validate the
456 estimates produced by VeTRA. In Table 2, the results are shown for all the possible sixteen
457 movements into a 4-leg roundabout, with the last row containing the total number of movements
458 recorded by VeTRA and the corresponding average values counted by the operators (specifically,
459 three people who manually counted vehicles looking at the videos and subdividing such counts by
460 movements).

461 The data elaborated by VeTRA and expressed in percentage terms (v_i), calculated on the total
462 collected flow, were compared with those obtained from video observation by a number of operators.
463 These measurements are reported in Table 2 in percentage under the column “Operator” (o_i), and
464 were repeated until the average values between observations were significantly stable (i.e., the mean
465 did not change anymore with the addition of new observations, according to the central limit theorem),
466 and could be considered a “true” reference. Assuming application of the central limit theorem,

467 repeated extractions (analysis of same video images by the same operator) lead to a reduction in
 468 error when estimating the mean. It should be noted that the total number of vehicles observed in one
 469 hour of survey time was high (1500–2500 veh/h).

470 **Table 2** Comparison of percentage values of the O/D matrixes for Biella, Ghisalba and Poncarale roundabouts.
 471

O/D movement	Biella (configuration #1)		Ghisalba (configuration #2)			Poncarale (configuration #3)		
	Operator (%)	VeTRA (%)	Operator (%)	VeTRA (%)		Operator (%)	VeTRA (%)	
		1C		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
Total flow (veh)	2002	2060	2415	2078	2105	2156	1706	1154

472
 473 In this phase, the authors focused mainly on error evaluation rather than on absolute values, so
 474 Table 2 reports the percentage values for each movement with respect to the total number of
 475 movements.

476 Bernardin and Stiefelhagen (2008) suggested the use of clear multiple object tracking (MOT)
 477 metrics to measure the performance of video image processing. It is made up of two indexes: (a) the
 478 total error value averaged by the number of matches made when estimating position (indicated as
 479 MOTP–multiple object tracking precision–and discussed in the next subparagraph), and (b) the
 480 tracking accuracy (MOTA–multiple object tracking accuracy), estimated using the following equation.

481
$$\text{MOTA} = 1 - (\sum_t (m_t + fp_t + mmc_t)) / (\sum_t g_t) \quad (6)$$

482 where for any time t , m_t is the number of misses, fp_t is the number of false positives, mmc_t is the
 483 number of mismatches, and g_t is the number of objects.

484 In this application, we calculated MOTA using all data collected by operator but only data for
 485 completely detected trajectories by VeTRA (since partially revealed trajectories are not of interest in
 486 this context and then the number of objects, g , is lower), thus leading to possible worse performance.
 487 Therefore, the subscript t (usually the index of each frame) is here assumed to be linked to a whole
 488 trajectory. This index varies from 1 to 0 (from best to worst performance). Besides, differences
 489 between operator and VeTRA are firstly calculated for each movement and then summed up. Three
 490 other different error types were also calculated from Table 2 and listed in Table 3 according to
 491 performance indexes used in technical literature: the sum of absolute differences (E_1), the average of
 492 absolute differences (E_2), and the average of differences (E_3). E_1 , E_2 , and E_3 are calculated according
 493 to the following equations.

$$494 \quad E_1 = \sum_i |v_i - o_i| \quad (7)$$

$$495 \quad E_2 = \sum_i |v_i - o_i|/n \quad (8)$$

$$496 \quad E_3 = \sum_i (v_i - o_i)/n \quad (9)$$

497 where n represents the number of movements considered in the analysis.

498 Difference between E_1 and E_2 depends only on the number of movements n taken into
 499 consideration but this number may change from site to site. Hence, when comparing performance of
 500 two sites, it may be useful to use both indexes. Besides the indexes, their percentages were also
 501 taken into consideration. They were calculated considering $v_i / \sum_i v_i$ instead of v_i for E_1 , and
 502 $o_i / \sum_i o_i$ instead of o_i for E_2 . For E_3 , the average percentage is always nil.

503 It must be stressed that operators represent the way to obtain the true result by application of the
 504 central limit theorem. In this experiment, since an infinite number of operators is not possible, the
 505 calculated averages may be considered a good estimate of the true result. VeTRA results are,
 506 nonetheless, affected by deterministic errors that cannot be completely avoided since they are
 507 intrinsic to the system (i.e., video cameras and lenses).

508 Values for the average of the absolute differences (Table 2) between operator and VeTRA
 509 generated data are less than 5% and are compatible with traffic analysis resolution. This also holds
 510 true, albeit to a lesser extent, for the average of percentage differences (considering all movements).

511 In contrast, the sum of percentage differences is generally very high even with the best strategy (see
512 Ghisalba-BI and Biella-1C in Table 2).

513 This last result shows the existence of a bias due to the general set-up conditions during the survey.
514 The fact that bias is positive indicates that VeTRA has generally estimated a lower percentage value
515 for each movement than that obtained by the operators. In the cases of Biella and Poncarale, the bias
516 is positive, while in Ghisalba, it is negative.

517 On examination of the five analyses carried out with VeTRA (Tables 2 and 3), the best results were
518 obtained with configuration #1 in Fig. 4, in particular when considering the MOTA index. In fact, the
519 performance obtained with the use of one video camera, which has lower costs and requires less
520 effort, is quite similar to that of configuration #2 in which three video cameras are employed. Moreover,
521 in the latter case at least four video cameras would be necessary to ensure adequate coverage of the
522 entire surface of the roundabout (Fig. 6).

523 The problems resulting from the blending of sequences obtained from three video cameras located
524 at 32 m from the roundabout (configuration #3 of Fig. 4) led to the necessity of considering two
525 different strategies in the analysis of the Poncarale roundabout. Although the performance indicators
526 (in Table 3) in the case of three-camera (Ghisalba-3C) and also a single camera (1C) configurations
527 are still quite close to those established in the Biella case study, the use of a two-camera (2C)
528 configuration with blended images results in the worst performance observed.

529 The use of additional cameras can result in operating problems related to factors such as
530 synchronization between frames from different cameras, different orientations and separated
531 communication wires. Synchronization is an acute problem that can be exacerbated by the loss of
532 some frames. In addition, the different orientation of video cameras requires different isomorphisms,
533 that is, different camera calibrations and homography transformations. The result obtained for E_3 of
534 Biella, which is indeed very low, is not surprising since Eq. (9) does not use absolute values and
535 therefore errors, which are not very biased in this case, cancel each other.

536

537

538

539
540**Table 3** Performance indicators (errors) between operator and VeTRA computed values according to Eqs. (6)-(8).

Roundabout and image treatment strategy	E_1		E_2		E_3	MOTA (%)
	(sum of absolute differences)		(average of absolute differences)		(average of differences)	
	Percentage	Value	Percentage	Value	Value	
	(%)	(veh)	(%)	(veh)	(veh)	
Biella (1C)	11.64	58	0.72	4	0.89	88
Ghisalba (3C-MT)	8.47	419	0.53	26	21.00	82
Ghisalba (3C-BI)	5.03	336	0.31	21	19.00	86
Poncarale (1C)	34.52	643	2.15	41	28.00	70
Poncarale (2C-BI)	75.88	1006	4.74	63	63.00	53

541 *5.2 Positions and speeds validation*

542 Since the distances between the RTK-GPS data and the VeTRA probe vehicle obtained data are not
543 Gaussian distributed, the MOTP index (Bernardin and Stiefelhagen, 2008) is split into three other
544 indexes – the median, median of absolute deviations (MAD), and inter-quartile range (IQR) (Table 4).

545 The results are available for the six different analyses carried out on the three roundabouts and the
546 different strategies of image processing. Furthermore, Table 4 lists the average and the standard
547 deviation of the speed differences recorded by both the on-board RTK-GPS system and by the
548 tracking process, for the same combination of roundabout and image processing strategies.

549 The results show that differences in positions and speed occur when different configurations and
550 processing strategies are adopted. The best performances in terms of tracking were observed in the
551 following cases: single camera configuration (Biella), two cameras with image blending (2C-BI) and
552 merged trajectory (2C-MT) strategy (Poncarale). Greater distances between tracked points were
553 measured when configuration #2 of Fig. 4 with three central cameras was adopted, and in the case of
554 the survey carried out at Poncarale, where only one camera was used to analyse vehicle movements
555 at a roundabout with the largest diameter (70 m) between the three here investigated.

556 As regards speeds, the best results in terms of average and standard deviation were noted in the
557 Biella survey, while the worst performances were those in the Poncarale survey in which the image
558 analysis procedure was conducted with one camera only. This would suggest the necessity to use
559 more than one camera for surveys of roundabouts larger than the Poncarale one.

560
561**Table 4** Distribution of errors in distance and speed difference between VeTRA and RTK-GPS data.

Roundabout	Distance (m)			Speed difference (km/h)	
	Median	MAD	IQR	Average	Standard deviation
Biella (1C)	0.375	0.179	0.399	0.11	2.71
Ghisalba (3C-MT)	0.651	0.457	0.863	0.12	7.31
Ghisalba (3C-BI)	0.272	0.743	0.619	3.06	8.87
Poncarale (1C)	0.576	0.250	0.576	11.46	23.66
Poncarale (2C-MT)	0.383	0.191	0.436	1.06	8.64
Poncarale (2C-BI)	0.384	0.173	0.397	7.58	18.71

562

563 In the case of Poncarale with the strategy 2C-MT, data analysis was limited to speed analysis and
 564 not extended to the whole set of analyses due to difficulties in building the whole trajectory. In too
 565 many cases, the continuity of the trajectory curve was not achieved.

566 5.3 Tortuosity and speeds analysis

567 An analysis of tortuosity and related speeds was performed on the class of light vehicles only. For
 568 each trajectory and at each point (i), VeTRA derives the two tortuosity indexes and local speeds from
 569 the recorded positions and times when the centre of the vehicle occupies the points $i+1$, i and $i-1$. All
 570 the trajectories are grouped under the same O/D maneuver and the software can elaborate the
 571 requested statistical output selected by the operator.

572 Table 5 contains the synthesis of the 15th percentile of the two tortuosity indexes ($T_{1,15}$ and $T_{2,15}$)
 573 calculated for those parts of the trajectories including the entry and exit gates of the roundabouts, and
 574 the 85th percentile of corresponding speeds at: (1) the entry gate ($V_{1,85}$), (2) the midpoint of the
 575 trajectory inside the circulatory roadway ($V_{2,85}$), and (3) the exit gate ($V_{3,85}$) as indicated in Fig. 1. The
 576 data in Table 5 was evaluated on the base of 2208 measurements of light vehicles operating in free-
 577 flow conditions. According to Fig. 6(a), in the case of Ghisalba, only three maneuvers were completely
 578 measured; in the case of Biella and Poncarale, the number of performance measures per O/D was
 579 lower than sixteen (four origins per four destinations) since the number of vehicles recorded for certain
 580 maneuvers (typically the U-turn) was too low.

581
582**Table 5** Filtered trajectory data for 15th percentile of tortuosity and 85th percentile of operating speed.

Roundabout	O/D	Maneuver	No. of data	$T_{1,15}$ (rad/m ²)	$T_{2,15}$ (rad/m)	$V_{1,85}$ (km/h)	$V_{2,85}$ (km/h)	$V_{3,85}$ (km/h)
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Biella 1C	2-3	Right turn	20	0.00124	0.0311	32.27	34.07	39.37
	2-5	Crossing	185	0.00015	0.0096	33.88	39.00	44.11
	4-1	Left turn	21	0.00200	0.0372	29.58	27.75	40.55
	4-5	Right turn	50	0.00129	0.0330	29.33	30.44	33.62
	4-7	Crossing	73	0.00069	0.0216	30.61	36.09	41.38
	6-1	Crossing	185	0.00094	0.0255	32.71	33.43	42.68
	6-3	Left turn	42	0.00207	0.0383	33.70	29.52	42.43
	6-7	Right turn	83	0.00064	0.0218	34.63	34.66	37.27
	8-1	Right turn	20	0.00054	0.0207	31.89	33.08	37.88
	8-3	Crossing	72	0.00041	0.0163	36.11	35.51	44.56
Ghisalba 3C-BI	8-5	Left turn	97	0.00179	0.0336	33.56	27.81	39.64
	2-3	Right turn	33	0.00047	0.0204	34.15	36.27	35.52
	2-5	Crossing	364	0.00070	0.0224	36.70	35.80	40.07
Ghisalba 3C-MT	4-5	Right turn	9	0.00032	0.0168	35.25	38.66	40.76
	2-3	Right turn	33	0.00050	0.0203	30.70	32.90	33.67
	2-5	Crossing	364	0.00067	0.0221	36.41	35.83	40.22
Poncarale 2C-BI	4-5	Right turn	9	0.00037	0.0182	31.57	34.61	39.18
	4-1	Left turn	42	0.00077	0.0241	43.60	37.70	47.02
	4-7	Crossing	183	0.00035	0.0152	40.26	39.59	46.31
	2-3	Right turn	22	0.00100	0.0298	32.43	32.71	38.91
	2-7	Left turn	28	0.00075	0.0233	34.67	35.47	44.92
	8-3	Crossing	226	0.00048	0.0177	37.76	38.03	45.25
	8-1	Right turn	47	0.00007	0.0065	39.09	44.88	49.48

583

584

The 85th percentile of speed distribution is widely considered in the geometric design of highways.

585

It is compared with the design speed to assess speed consistency between the hypothesis of

586

designer and driver behaviour. It reflects the movement of isolated vehicles (i.e., free-flow conditions),

587

and separates the population of prudent drivers from the group of more aggressive ones (Yasser and

588

Mohamed, 2011).

589

The choice of the two percentiles is based on the supposition that aggressive drivers, whose

590

speeds exceed the 85th percentile, tend to follow the fastest path that should be characterized by the

591

lowest tortuosity (as also suggested in Rodegerdts et al., 2007, 2010). The authors associated the

592

15th percentile of tortuosity indexes with the fastest path so as to establish correlations between

593

trajectory and speeds.

594

When the analysis is confined to a part of the speed data, the most significant relationships

595

between the values reported in Table 5 are limited to the 85th percentile of speeds calculated at the

596 middle point of trajectories ($V_{2,85}$) and the 15th percentile of the two tortuosity indexes $T_{1,15}$ and $T_{2,15}$.
 597 The results are reported in Figs. 7 and 8, and demonstrate that $T_{2,15}$ rather than $T_{1,15}$ has a rather good
 598 correlation to $V_{2,85}$ as confirmed by the statistics of the two models summarized in Table 6.

599 Figs. 7 and 8 also report the data generated with the MT strategy in the case of the Ghisalba
 600 roundabout. These data are more dispersed when compared to the corresponding data derived with
 601 the BI strategy, and, as a consequence, they were not taken into account in the exponential model
 602 which was plotted in both figures, and which exhibited the highest coefficient of determination for both
 603 tortuosity indexes.

604 Very low correlation values were found between the 85th percentile of entry (V_1) and exit (V_3)
 605 speeds. This may be attributed to the fact that the entry speed largely depends on driver behaviour in
 606 the approaching leg, while the exiting speed depends more on the specific shape of curbs around the
 607 exit lane.

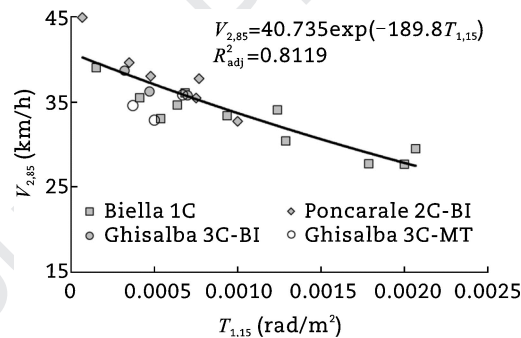


Fig. 7 Relationship between $V_{2,85}$ and $T_{1,15}$ index.

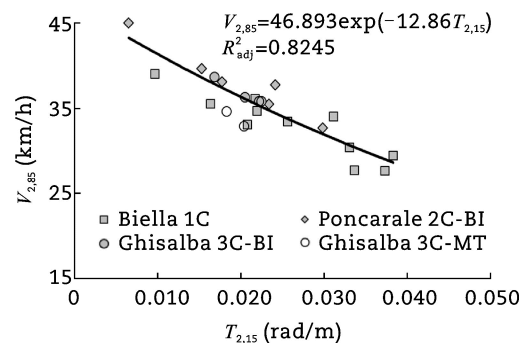


Fig. 8 Relationship between $V_{2,85}$ and $T_{2,15}$ index.

Table 6 Output of statistics for model reported in Figs. 7 and 8.

Model	$V_{2,85} = 40.735\exp(-189.8T_{1,15})$	$V_{2,85} = 46.893\exp(-12.86T_{2,15})$
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R^2		0.8218	0.8337
R^2 adjusted		0.8119	0.8245
Standard error		0.0520	0.0510
F value		83.0259	90.2644
		(F critical = 2.17, p = 0.05)	(F critical = 2.17, p = 0.05)
p value	Intercept	1.27×10^{-30}	2.90×10^{-27}
	Variable	3.66×10^{-8}	1.95×10^{-8}

618

619 It must be stressed that we limited the study of correlation between speed and tortuosity only to
620 three points (entry, middle and exit) as reproduction of the approach proposed by Rodegerdts et al.
621 (2007).

622 5.4 Acceleration analysis

623 Table 7 shows the statistics for acceleration and deceleration measured on the circulatory roadway for
624 the Ghisalba and Poncarale roundabouts (trajectory data are the same of Table 5). It should be
625 highlighted once again that the data considered here pertain to vehicles that were not affected by
626 other vehicles when negotiating the roundabout, thus all the data can be considered to be that of
627 isolated vehicles and drivers affected by the roundabout geometrics only.

628 According to the speed variation model depicted in Fig. 1, the deceleration from sections 1 to 2 is
629 indicated as a_{12} , while the acceleration from the central point of the trajectory (section 2) to the exit
630 section (section 3) is indicated as a_{23} .

631
632

Table 7 Statistics for vehicular acceleration and deceleration at the Ghisalba and Poncarale roundabouts.

Roundabout	Ghisalba 3C-BI				Poncarale 2C-BI					
	Right turn		Through		Right turn		Through		Left turn	
Acceleration	a_{12}	a_{23}	a_{12}	a_{23}	a_{12}	a_{23}	a_{12}	a_{23}	a_{12}	a_{23}
No. of objects	42	42	364	364	69	69	409	409	70	70
Mean (m/s^2)	-0.614	0.116	-0.063	0.409	-0.674	0.719	-0.264	0.468	-0.051	0.358
Standard deviation (m/s^2)	0.601	0.499	0.370	0.273	1.030	0.660	0.555	0.616	0.312	0.204
15th percentile (m/s^2)	-1.241	-0.556	-0.378	0.142	-1.724	0.117	-0.831	0.141	-0.371	0.205
85th percentile (m/s^2)	-0.038	0.606	0.281	0.676	0.132	1.261	0.235	0.744	0.257	0.543
Max (m/s^2)	0.213	1.075	1.160	1.204	3.037	2.796	2.228	11.141	0.838	0.739

Min (m/s ²)	-1.901	-0.721	-1.948	-0.793	-3.201	-1.474	-2.156	-0.832	-0.895	-0.518
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633

634 Per each vehicle traversing the roundabout, these two values were computed with the following
635 equations.

$$636 \quad a_{12} = (v_{22} - v_{12}) / (2d_{12}) \quad (10)$$

$$637 \quad a_{23} = (v_{32} - v_{22}) / (2d_{23}) \quad (11)$$

638 where d_{12} and d_{23} have the same meaning of Eqs. (1) and (2). Data have also been distinguished for
639 left turn, right turn, and through movements.

640 The mean and the standard deviation of acceleration values indicate that entering vehicles in
641 deceleration (a_{12}) and exiting vehicles in acceleration (a_{23}) exhibit large variations as a result of the
642 roundabout layout and geometrics, and type of maneuvers. The 15th percentiles of deceleration (a_{12}),
643 listed in Table 7, are only higher in the case of right turn movements than the absolute value of 1.3
644 m/s² suggested in Rodegerdts et al. (2007), and reflect the behaviour of aggressive drivers. In all
645 other cases, the statistics for a_{12} indicate that lower values are observed.

646 Regarding the acceleration variable (a_{23}), a large difference is evident between the observed values
647 and the value of 2.3 m/s² proposed again in Rodegerdts et al. (2007), thus suggesting the need for an
648 extended investigation into a greater number of roundabout geometry types. In fact, the two
649 roundabouts considered here yield different results as a consequence of the significant difference in
650 their layout.

651 **6 Discussion**

652 The results illustrated in previous paragraphs outlined the strengths and weaknesses associated with
653 each set-up for the three different roundabouts considered in the investigation. In the three cases,
654 small camera oscillations, clouds, and flying objects (i.e., birds) affecting image quality were easily
655 identified and corrected.

656 On examination of the three configurations presented in Fig. 4, it is clear that the central position of
657 the video cameras facilitates a reduction in perspective distortion but, as in the case of Ghisalba
658 (configuration #2 in Fig. 4 with three cameras), a relatively high number of video cameras is required

659 given the dimensions of the circulatory roadway. The blending of images becomes more complicated
660 with an increase in the number of video cameras installed at or around the roundabout. Moreover,
661 synchronization between cameras becomes crucial: with the loss of only one frame of a video camera
662 necessitating a challenging task of realignment between video frames.

663 Elevated vantage points on poles or buildings introduce high levels of distortion especially in the
664 case of heavy and long vehicles, as in the case of Poncarale (configuration #3 in Fig. 4 with three
665 cameras). Furthermore, the height of vantage points has a detrimental impact on image quality since
666 the cameras and their supports are exposed to stronger winds, which can produce oscillations that are
667 hard to correct during the image treatment phase. From an analysis of the data collected at the
668 Poncarale roundabout, it would appear that the merging of trajectories extracted from different images
669 (MT strategy) seems to be less effective than the blending images (BI) technique. In this case, the
670 only one for which this comparison has been made, the performance indicators associated with the
671 evaluation of the O/D matrix indicate a greater dispersion of data in the case of the merged trajectory
672 technique (Table 5).

673 Whereas the blending of images is essentially a straightforward task when video cameras have
674 viewing angles of less than 90° , it tends to prove problematic with wider angles (especially those
675 closer to 180°) as a consequence of the different perspective distortions of moving elements. Of the
676 three configurations considered in this research, the use of a single video camera mounted on a pole
677 located outside the roundabout, as in the case of Biella (with the camera located at the external side
678 of the circulatory roadway), would appear to offer the best compromise in terms of survey costs,
679 pre-processing work, and quality of results. However, this is not a definitive conclusion, since the
680 number of experiments carried out to date is not considered comprehensive from a technological point
681 of view. In this study, the authors focused primarily on a general evaluation of the methodology and
682 the estimation of technical problems to be solved for each specific configuration. In fact, while the
683 results here have been used to assess the survey methodology, they cannot be considered
684 statistically significant in terms of the performances of the investigated roundabouts or, indeed,
685 roundabouts in general.

686 In all the three configurations depicted in Fig. 4, VeTRA has been able to collect spatial and
687 temporal data for a large number of points along each trajectory, thus deriving local speeds. The
688 authors decided to consider speeds at the entry gate, at the midpoint and at the exit of the roundabout
689 to compare results with those in Rodegerdts et al. (2007). Two different tortuosity indexes were
690 calculated for each trajectory by combining angular deviation and the distance between two
691 successive recorded points, and the radius of the local osculating circle in different ways.

692 As a result, some linear and exponential relationships between the 85th percentile of speeds and
693 the 15th percentile of tortuosity indexes have been derived. The observations confirm that an effective
694 speed control within the circulatory roadway is possible only when high horizontal curvatures of
695 vehicle paths (i.e., high values of tortuosity) are achieved as a consequence of the combination of the
696 geometric characteristics of roundabout elements.

697 The regression equations presented here were obtained from 2208 speed data (Table 5) of just
698 three roundabouts with each exhibiting a different geometry in terms of external and central island
699 diameters, circulatory roadway width, number and geometry of entry and exit lanes. The high
700 coefficient of determination of one of the four proposed equations ($R^2 = 0.8337$ for the exponential
701 relationship between $V_{2,85}$ and the $T_{2,15}$) facilitates its use in the estimation of the circulating operating
702 speed ($V_{2,85}$) in the analysis and design of roundabouts.

703 Acceleration and deceleration values on the circulatory roadways exhibit large variations as a
704 consequence of roundabout layout and geometrics, maneuver type, and driving attitudes and styles.
705 In light of the observation data, the suggested values of -1.3 m/s^2 in deceleration and 2.1 m/s^2 in
706 acceleration included in the NCHRP Reports 572 and 672 (Rodegerdts et al., 2007, 2010) seem to be
707 questionable, thus new research is necessary to obtain better design-operating speed and
708 acceleration distribution on the circulatory roadway. This paper has demonstrated that image analysis
709 has the potential to achieve such objectives.

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711

712

713 7 Conclusions

714 The paper presents the results of several activities undertaken involving extensive use of the VeTRA
715 software and acquisition tools, which the authors developed for the specific purpose of carrying out
716 operational analyses of roundabouts through the use of video-tracking technology.

717 At present, the comprehensive gathering of operational data at roundabouts necessitates the use of
718 non-integrated acquisition systems and prolonged data analysis times. Since 2010, the authors have
719 worked on the development of an integrated system (specifically designed for roundabouts)
720 composed of a hardware system for data acquisition and collection, and software for data analysis.

721 The system and some data analysis have already been presented in previous referenced works
722 (Mussone et al., 2011, 2013), in which the system included one video camera only.

723 In this paper, the authors focused their attention on an extended use of the software with the aims
724 of solving issues related to the survey configuration used with more than one video camera and their
725 positioning inside or around the roundabout, and improving the tracking system of vehicles and
726 deriving the O/D matrix and trajectories (i.e., position and time of tracked vehicles).

727 Two possible strategies consisting in (a) the merging of trajectories extracted from each separate
728 video, and (b) the image blending from different video cameras before extracting trajectories were
729 investigated. Results suggest that the second is more effective than the first one. Furthermore, of the
730 three configurations considered, the one consisting in a single video camera mounted on a pole
731 outside the roundabout appeared to be the optimal in terms of costs, processing work, and quality of
732 results. However, this solution may imply large perspective distortion of the tracked vehicles in
733 locations far from the camera, especially in case of roundabout with large diameters. To limit
734 perspective distortion, the vantage point must be raised up as much as possible.

735 From the data collected from case studies, one further result concerns the correlation between
736 speed and tortuosity of vehicle trajectories, which could be used by designers in the estimation of
737 vehicle performance when negotiating a roundabout. This result emphasizes the tremendous potential
738 of the image analysis in capturing position and kinematic of vehicles, and opens up to further studies
739 on the evaluation of the operational effects of roundabouts.

740 In conclusion, previous works by the authors, together with the results reported in this paper, testify
741 to the fact that the video survey system and the processing code are both robust and reliable. As
742 documented in this paper, the authors are aware that further work is necessary to improve the
743 performance of the tracking system of VeTRA in all possible set-up configurations.

744 With this objective in mind, a new version of the software is under development. It will include a set
745 of 3D models of vehicles that differ in terms of dimensions and that can be associated with each blob.
746 In this way, trajectories will be derived with reference to the geometric centre of the model rather than
747 to the centre of the blob. This approach, already adopted by some authors but in different road
748 scenarios (Kim et al., 2005; Koller et al., 1993; Messelodi et al., 2005), can lead to better vehicle
749 recognition, which is considerable when high perspective distortions are present (like in Poncarale),
750 together with even more precise localization and tracking. The authors are confident that the use of
751 vehicle models will reduce the negative effect of video camera oscillations and will enable the
752 separation of the shadows (of vehicles) from the actual vehicles in blobs, thus reducing the impact of
753 shadows on the quality of collected data. Finally, to extend the possibility of data collection to night-
754 time conditions, new research will also be carried out assessing how to use videos from thermal
755 and/or infra-red video cameras.

756 **Conflict of interest**

757 The authors do not have any conflict of interest with other entities or researchers.

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