



ESTIMATING TRAFFIC OPERATIONS AT MULTI-LANE ROUNDABOUTS: A CASE STUDY

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ABSTRACT

This paper addresses traffic modeling issues at urban multi-lane roundabouts where, despite circulating vehicles have priority, negotiation of the right-of-way can occur between antagonist traffic flows, as a result of minor drivers' failing to obey the nominal operating rule (stop or yield control). Existing models for the estimation of operational performances have the shortcoming of not representing the interdependencies between entering and circulating vehicles at multi-lane roundabouts. An analytical capacity model derived from field observations was developed for this kind of intersections in a previous study. The complexity of the model lies in the difficulty of observing the behavioral parameters which are needed to implement the model. A procedure to get unknown behavioral parameters from traffic surveys is here proposed. This concerns saturation headways, often eluding direct observations due to rare occurrences of traffic conditions in which they can be observed. The unknown parameters were estimated through a regression model using on-field data collected at a multi-lane roundabout. The presence of data correlation within a cluster of observations required the estimation of the regression parameters through a generalized estimating equation model. Results gave insight into the analysis of operations at multi-lane roundabouts, containing evidence to support assumptions made for the estimation of unobservable parameters.

Keywords: traffic, roundabout, headway, operational analysis, performance estimates, regression model.

INTRODUCTION

Despite traffic circles are precursor of the modern roundabouts and now rarely installed, several examples of them still operate especially in Italian urban areas. The reason for this is that the two types of intersections share some characteristics such as the central island and the circular shape with multiple entries and exits. Moreover, Italian design guidelines for road intersections have been in force since 2006, but many schemes of roundabouts were already operating. Thus not all roundabouts were created equal due to differences in design practices adopted in the national territory of Italy. To date, despite circular intersections are widespread within the road network, the process of conversion of schemes with old design into modern roundabouts cannot be considered yet fully completed.

Moreover, conditions under which such intersections can be installed are related to a great variety of traffic situations from low- to high-traffic-volume. By way of example, the high volume circular intersections are integrated into arterial interchanges to serve at-grade traffic and, differently from freeways, are often directly accessed from side roads; then roundabouts are used within the context of through roads (that also perform as urban main streets) to mitigate the impact of rural or suburban traffic flowing through the cities. In these cases roundabouts are often intersections with circular shape, having a large diameter of the central island and more circulating and entering lanes; moreover, their installation has been conditioned by different constraints (e.g., physical, topographical, architectonic, etc.), so roundabouts result characterized by compromise solutions

related to one or more constituent components and geometric aspects of their layout. It follows that the great variety of geometric layouts non-referable to modern roundabouts can make difficult the conceptual framework of operational conditions; thus uncertainty in the estimations of capacity and quality-of-service measures can increase and adequacy of the entire roundabout design or the single design change cannot be assessed. Indeed usual models based on gap-acceptance theory, either as they are specified for modern roundabouts, or for stop-controlled intersections, cannot be applied to analyze operating conditions and estimate behavioral parameters at circular intersections not-consistent to standard layouts, because they can lead to rough results. Moreover, operating conditions in the urban context can be characterized by a highly random component due to unconventional user behaviors, i.e., users giving their priority, or users entering into the roundabout and ignoring the give-way sign. As a consequence, despite the priority rule for circulating vehicles, operating performances of such not-conforming intersections may be very far from those of modern roundabouts.

Based on the examination of a sample of intersections with circular shape installed in road network of Palermo, Italy, and characterized by geometric characteristics intermediate between unsignalized (stop-controlled) intersections and modern roundabouts, the possibility to propose a reference framework for understanding operations was explored (Giuffrè *et al.*, 2008).

This paper addresses the theoretical and empirical issues in modeling operational patterns at urban multi-lane



roundabouts where, despite vehicles on circulatory roadway have priority, negotiation of the right-of-way can occur among antagonist traffic flows; this happens because drivers disregard the nominal operating rule (i.e., stop or yield control). Existing models for performance estimations have the shortcoming of not representing the interdependencies between entering and circulating vehicles at multi-lane roundabouts. In a previous study an analytical capacity model for multilane roundabouts with negotiation of the right-of-way between antagonist traffic flows was derived from field observations (Giuffrè *et al.*, 2012a). The complexity of this model lies in the difficulty of observing the behavioral parameters which are needed to implement the model.

A procedure to estimate unknown behavioral parameters from traffic surveys is here proposed. This concerns saturations headways, often eluding direct observations because traffic conditions in which they can be observed rarely occur. The unknown parameters were estimated through a regression model derived from data observed at a multi-lane roundabout. The presence of response correlation requested the use of Generalized Estimating Equations (GEEs) for the estimation of the regression parameters (Zeger *et al.*, 1988).

The paper is organized as follows; the first section provides a brief background about existing models for capacity evaluations at modern roundabouts as developed in Europe and elsewhere. Section 2 describes research assumptions to model operating conditions at the multi-lane roundabouts with negotiation of the right-of-way between antagonist traffic flows here examined. Section 3 presents the methodology used for estimating saturation headways with reference to the case study. Section 4 summarizes the modeling results. The last section provides a summary of the work accomplished so far in this research and its main findings.

A REVIEW OF CAPACITY MODELS FOR MODERN ROUNDABOUTS

The methods for capacity evaluations at existing or planned roundabouts were initially based on the old-style scheme of circular intersection with successive weaving sections between the legs. However, the length of the weaving section determined design solutions characterized by large diameters and high circulating speeds, making maneuvers within the circle more challenging.

In literature reviews on models for capacity estimations at roundabouts, reference is made to roundabouts where priority is given to entering vehicles. Wardrop (1957) developed an empirical formula to estimate the capacity of a roundabout based on the weaving section in the ring as the critical area that may limit roundabout capacity, namely that the latter is dependent on the capacity of the weaving section. According to Wardrop (1957), as cited by Chik *et al.* (2004), this capacity estimation relied on the geometric parameters including the shape and the size of the roundabout; the formula also includes the proportion of

traffic requiring to weave in the weaving section and the heavy good vehicles. Thus the capacity based on an isolated weaving section is a function of the width and the length of the weaving section, the average effective entry width, the proportion of the weaving traffic and the proportion of heavy vehicles.

Subsequent capacity formulations began to address together both specific geometric design aspects (width of lanes and weaving section length) and aspects relating to traffic regulation (such as prohibiting the stop on the ring, roundabouts located in flat areas, etc.).

The introduction of modern roundabouts where vehicles travel counterclockwise around the central island and entering vehicles must yield to circulating vehicles, led to criteria for calculating capacity based on the concept that the roundabout is composed by a set of T-intersections, following each other along the circulatory roadway; thus, the capacity of an entry opposed by conflicting traffic streams can be estimated as though the entry approach was isolated, i.e. performances of each leg are analyzed independently from other legs.

Entry capacity formulations for modern roundabouts have evolved in relation to roundabout categories (single-, double-, multi-lane roundabouts) progressively introduced; each roundabout category is identified by the number of circulating lanes, the increase of which requiring wider circulatory roadways to accommodate the vehicles traveling side-by-side (Rodegerdts *et al.*, 2010). Moreover, the roundabout capacity, as for two-way-stop-controlled intersections, is an input required by the delay and queuing models.

Methods for analyzing operations generally include linear/exponential empirical regression models (Al-Madani, 2013; Brilon and Vandehey, 1998; Kimber and Coombe, 1980; Kyte *et al.*, 1991), and analytical gap-acceptance models (Brilon *et al.*, 1997; HCM, 2010). A summary of international capacity models for modern roundabouts is reported by Rodegerdts *et al.* (2007) and Yap *et al.* (2013). New forms of roundabouts have been recently developed in Europe; they include the turbo roundabouts and the flower roundabouts (Fortuijn, 2009; Tollazzi *et al.*, 2011). However, specific models for estimating capacity are not yet available for roundabouts with innovative layout, but current approaches are inspired to those of modern roundabouts (Giuffrè *et al.*, 2012b; Guerrieri and Corriere, 2013a & b; Mauro and Branco, 2010; Mauro and Guerrieri, 2013; Yao *et al.*, 2013).

THE PROPOSED METHOD: RESEARCH ASSUMPTIONS

Driving behaviors able to affect traffic conditions at multi-lane roundabouts have been highlighted just from the field observations. More specifically traffic patterns in which the right-of-way alternates between entering and circulating vehicles were observed; then they inspired the method for capacity estimates as proposed hereinafter.

The following considerations will focus on the general case of a multi-lane roundabout with three lanes at entries and three circulating lanes, where both subject



approach vehicles and conflicting vehicles move along one-way directions. Based on the negotiation of the right-of-way between circulating and entering vehicles, one can consider that the conflicting approach is the circulating roadway when the entry is the subject approach; on the contrary, one can consider that the entry is the conflicting approach when the circulating roadway is the subject approach. Each subject approach vehicle can face different degree-of-conflict cases with the conflicting vehicles; thus, the probability of each degree-of-conflict case must be determined.

At multi-lane roundabouts with three entering and three circulating lanes where negotiation of the right-of-way can occur between circulating and entering vehicles, analogy can be established with all-way-stop-controlled intersections.

More specifically, for a three-lane approach, eight possible degree-of-conflict cases and the corresponding probability of occurrence have to be determined depending on the number of conflicting vehicles by lane. Thus the departure headway at each subject approach lane L_1, L_2, L_3 is the expected value of the saturation headway distribution and is expressed as follows (Kyte *et al.*, 1997):

$$h_d = \sum_{i=1}^n P(C_i) \cdot h_{si} \quad (1)$$

where $P(C_i)$ is the probability of the degree-of-conflict case i and h_{si} the saturation headway for the case i (Giuffrè *et al.*, 2007).

At a three-lane entry approach of roundabouts with three circulating lanes only two degree-of-conflict cases can be faced by entering (or circulating) vehicles: the first (case 1) occurs under the condition of no vehicle on the conflicting approach (that is the entry or the circulating lanes depending on which is the subject approach); the second case is structured in different sub-cases (from 2 to 8) which occur under the condition of one, two or three vehicles on the conflicting approach (i.e., the entry or the circulating lanes), depending on how many lanes are involved. Thus in total eight degree-of-conflict cases can be observed, each of them with a probability of occurrence as showed in the following box:

No.	Doc case	Probability of occurrence
1	1/0	$P(C_{1-0}) = (1-x_{L1}) \cdot (1-x_{L2}) \cdot (1-x_{L3})$
2	3/1 _a	$P(C_{3-1})_a = x_{L1} \cdot (1-x_{L2}) \cdot (1-x_{L3})$
3	3/1 _b	$P(C_{3-1})_b = (1-x_{L1}) \cdot x_{L2} \cdot (1-x_{L3})$
4	3/1 _c	$P(C_{3-1})_c = (1-x_{L1}) \cdot (1-x_{L2}) \cdot x_{L3}$
5	3/2 _a	$P(C_{3-2})_a = x_{L1} \cdot x_{L2} \cdot (1-x_{L3})$
6	3/2 _b	$P(C_{3-2})_b = x_{L1} \cdot (1-x_{L2}) \cdot x_{L3}$
7	3/2 _c	$P(C_{3-2})_c = (1-x_{L1}) \cdot x_{L2} \cdot x_{L3}$
8	3/3	$P(C_{3-3}) = x_{L1} \cdot x_{L2} \cdot x_{L3}$

where x_{L1}, x_{L2}, x_{L3} are the degree of utilization (x) of each lane (L_1, L_2, L_3) in the conflicting approach, computed as a

function of the arrival rate v , veh/s, in the considered lane and the departure headway, s :

$$x = (v \times h_d) / 3600 \quad (2)$$

where x denotes presence of vehicles whereas $(1-x)$ denotes absence of vehicles; the departure headway required for the calculation above can be surveyed directly on the basis of the service time t_s , s , i.e., the waiting time at the stop line, and the move-up time m , s , i.e., the time necessary to the driver for arriving at the stop line from the second position of the queue:

$$h_d = t_s + m \quad (3)$$

Operating traffic conditions at three-lane approaches of roundabouts with three circulating lanes allow to observe easily the departure headways h_d at each lane; on the contrary, traffic conditions in which saturation headways are observed rarely occur, due to saturation headways often elude direct surveys. Starting from these considerations a procedure to estimate saturation headways has been developed (see next section). A regression analysis based on data of departure headways was implemented in GenStat. The presence of response correlation required the estimation of h_s through a marginal model by using Generalized Estimating Equations models (GEEs).

ESTIMATING SATURATIONS HEADWAYS BY GEES

A generalized model based on the degree-of-conflict faced by the subject approach driver was developed for the estimation of saturations headways.

At roundabouts with three entering and three circulating lanes one can consider just two degree-of-conflict cases 1/0 and 3/*; the latter, in turn, is divided into 8 sub-cases, each depending on the number of vehicles being on the lanes of the conflicting approach. Then, for each lane of the subject approach the departure headway is defined as:

$$(h_d)_{Lz} = \sum_{i=1}^8 P(C_i) \cdot (h_{si})_{Lz} = P(C_{1/0}) \cdot (h_{s1/0})_{Lz} + \sum_{i=2}^4 P(C_{3/1})_i \cdot (h_{s3/1})_{Lz,i} + \sum_{i=5}^7 P(C_{3/2})_i \cdot (h_{s3/2})_{Lz,i} + P(C_{3/3}) \cdot (h_{s3/3})_{Lz} \quad (4)$$

Real-world surveys confirmed that the saturation headways can be measured in the degree-of-conflict cases 1/0, 3/1_a, 3/1_b and 3/1_c. Thus the procedure assumes that the saturation headways for degree-of-conflict cases 3/2 and 3/3 are the parameters which must be estimated by the generalized model.

The generalized model can be put then in the form:

$$(h_d)_{Lz} = P(C_{1/0}) \cdot (h_{s1/0})_{Lz} + (h_{s3/1})_{Lz} \cdot \sum_{i=2}^4 P(C_{3/1})_i + (h_{s3/2})_{Lz} \cdot \sum_{i=5}^7 P(C_{3/2})_i + P(C_{3/3}) \cdot (h_{s3/3})_{Lz} \quad (5)$$



in which one can see the unknown parameters denoted by a star symbol; the unknown saturation headways can be estimated using a regression model where $(h_d)_{Lz}$ represents the response variate whereas the probability of occurrence for the degree-of-conflict cases 3/2 and 3/3 represent the covariates. Assuming the variable $(h_d)_{Lz}$ normally distributed, one can write:

$$(h_d)_{Lz,k} \sim N(\mu, \sigma^2) \text{ and } \mu = \mathbf{E}[(h_d)_{Lz,k} / \mathbf{P}_k] = o_k + \mathbf{P}'_k \cdot (\mathbf{h}_s^*)_{Lz} \quad (6)$$

where:

$$o_k = P(C_{1/0})_k \cdot (h_{S1/0})_{Lz} + (h_{S3/1})_{Lz} \cdot \sum_{i=2}^4 P(C_{3/1})_i$$

$$\mathbf{P}'_k = \left[\sum_{i=5}^7 P(C_{3/2})_i, P(C_{3/3}) \right]$$

$$(\mathbf{h}_s^*)_{Lz} = [(h_{S3/2}^*)_{Lz}, (h_{S3/3}^*)_{Lz}]$$

The intrinsic correlation of h_d observations at entering lanes and circulating lanes within each operational condition suggested that regression parameters were estimated by using quasi-likelihood methods (Fitzmaurice *et al.*, 1993; McCullagh and Nelder, 1989); thus Generalized Estimating Equations (GEE) were employed (Zeger *et al.*, 1988). Field observations and exploratory data analysis are reported by Giuffrè *et al.* (2007) and briefly summarized in the next section in which the sample correlation analysis, the functional form selection between the response variate and the explanatory variate, and model validation will be also described.

MODELING RESULTS

In order to illustrate the proposed procedure a multi-lane roundabout where negotiation of the right-of-way occurs between circulating and entering vehicles was selected as a case study; this roundabout has three entering lanes and three circulating lanes; all entry approaches share similar traffic demands, roadway geometry, and surrounding environments.

Traffic operations were recorded during daylight hours in two working days (see Giuffrè *et al.*, 2007); two minutes were the length of time for each observation recorded by lane for 20 operating conditions. To explain the proposed method the eastbound entry of the roundabout was selected (see Figure-1).

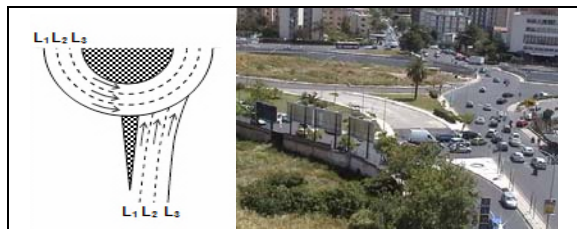


Figure-1. A view of the Eastbound entry at the selected roundabout and lanes scheme.

Numbering for entering and circulating lanes is as follows: L_1 is the inner lane at the entry approach, whereas L_1 is the outer lane on the circulatory roadway used by vehicles to travel counterclockwise around the central island.

Mean values of the departure headways observed at circulating lanes were equal to 6.63 s, 4.83 s, 3.16 s for L_1, L_2, L_3 , respectively; mean values of the departure headways observed at entering lanes were equal to 5.64 s, 3.38 s, 2.25 s for L_1, L_2, L_3 , respectively. Mean values of conflicting volumes for circulating lanes were equal to 348 veh/h, 574 veh/h, 576 veh/h for L_1, L_2, L_3 , respectively; mean values of the departure headways observed at entering lanes were equal to 321 veh/h, 462 veh/h, 643 veh/h for L_1, L_2, L_3 , respectively.

First, saturation headways h_s for the degree-of-conflict cases 1/0 and 3/1 were estimated; since h_s estimations did not show any significant difference between the cases 1/0 and 3/1, the same mean value was considered for them (see Table-1); moreover, the marginal effect produced by the vehicle position and the subject approach (time to time considered as such) were also estimated.

The sample correlation analysis was then used to reveal if the data came from a bivariate normal distribution.

Table-1. Estimations of saturation headways for degree-of-conflict cases 1/0 and 3/1.

h_s	Estimation (s.e.)
base (L_1)	0.75 (0.07)
L_2	-0.57 (0.08)
L_3	-0.86 (0.06)
Circulatory roadway (cr)	1.25 (0.14)
Entry	0.99 (0.16)

For this purpose the departure headways at entering lanes ($h_{d,e}$) and circulating lanes ($h_{d,cr}$) were considered as two s-dependent random variables normally distributed; $h_{d,cr}$ and $h_{d,e}$ were referred to Cartesian coordinate system, with axis lines X and Y, and centered on their mean values (variances σ^2 for $h_{d,cr}$ and $h_{d,e}$ were 6.02 and 7.52, respectively).

The joint probability distribution function of $h_{d,cr}$ and $h_{d,e}$ will result as follows:

$$z = f(h_{d,cr}, h_{d,e}) = \frac{1}{\sigma_{h_{d,cr}} \cdot \sigma_{h_{d,e}} \sqrt{1 - \rho^2} \sqrt{2\pi}} \cdot \exp \left[-\frac{1}{2 \cdot (1 - \rho^2)} \cdot \left(\frac{h_{d,cr}^2}{\sigma_{d,cr}^2} - \frac{2 \cdot \rho \cdot h_{d,cr} \cdot h_{d,e}}{\sigma_{h_{d,cr}} \cdot \sigma_{h_{d,e}}} + \frac{h_{d,e}^2}{\sigma_{h_{d,e}}^2} \right) \right] \quad (7)$$

with ρ representing the correlation coefficient equal to:



$$\rho = \frac{\text{Cov}\{h_{d,cr}, h_{d,e}\}}{\sigma_{h_{d,cr}} \cdot \sigma_{h_{d,e}}} = 0.86$$

Figure-2 shows the sample correlation analysis ($h_{d,e}$ vs $h_{d,cr}$).

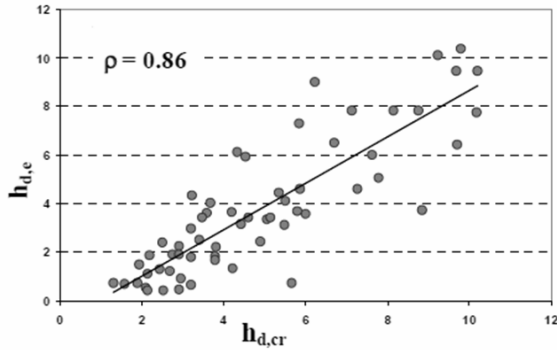


Figure-2. Sample correlation analysis.

Figure-3 shows the sample data and the horizontal section of the joint pdf at $z = 0.01$, where one can find 99% of the bidimensional pdf.

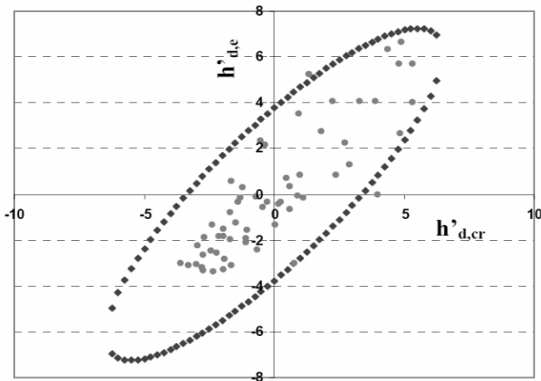


Figure-3. Horizontal section of the joint pdf ($z = 0.01$).

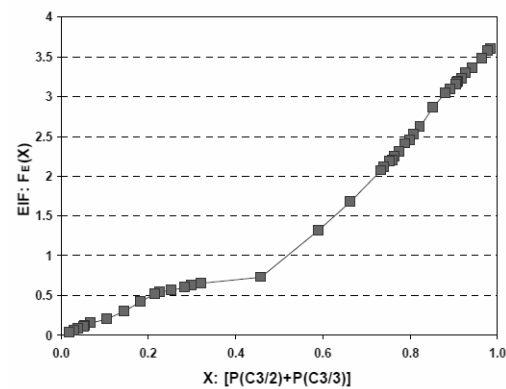
Results of this analysis highlighted that data were consistent with the hypothesis of bivariate normal distribution. Moreover, the correlation of the responses led us to exclude likelihood-based methods, since they cannot account for the correlation; thus, the quasi-likelihood methods based on Generalized Estimating Equations (GEE) were used for estimating unobserved saturation headways (h_s^*).

The functional form selection between the response variate ($h_{d,cr}$, $h_{d,e}$) and the explanatory variate (i.e., the probability of degree-of-conflict cases 3/2 and 3/3), was identified using the well-known Integrate-Differentiate method (see Hauer and Bamfo, 1997). Based on the ID method, the dependence of the response variate on regressors was tested. Assuming a function $y = f(x)$ linking the response variate and the explanatory variate, the ID method suggests how to estimate the Integral

Function $F(X)$, namely the definite integral of $f(x)$ from $x = 0$ to $x = X$. Thus, the estimate $F_E(X)$ of the Integral Function $F(X)$ represents the Empirical Integral Function of $f(x)$; $F(X)$ and $f(x)$ are recognized by deriving $F(X)$.

In order to test the linear link between the response variate and the assumed covariate, EIFs were fitted by a quadratic function written in the form $F(X) = aX + bX^2$, where X was represented by $[P(C_{3-2})]$, $[P(C_{3-3})]$ and $[P(C_{3-2})+P(C_{3-3})]$.

The best data fitting was obtained considering together the probability of occurrence $[P(C_{3-2})+P(C_{3-3})]$ for all the data (circulating lanes plus entering lanes); this covariate, indeed, had a major influence on the response variate (see Figure-4).



F(X) Parameters	Estimate (s.e.)
Lin	0.94 (0.14)
Quad	2.74 (0.17)
R ²	0.994

Figure-4. Empirical Integral Function (EIF).

The results of the analysis conducted up to this point showed that saturation headways in degree-of-conflict cases 1/0 and 3/1 can be assumed having the same mean value; moreover, the unknown saturation headways h_s^* for the degree-of-conflict cases 3/2 and 3/3 can be considered to have the same effect on the response variate. The exploratory analysis also highlighted that drivers behave differently in relation to the approach from which they come and vehicle position in the carriageway can affect departure headways.

Starting from these considerations, a two level factor was introduced in the model to distinguish between the circulatory roadway and the entry, whereas a three level factor (L_1, L_2, L_3) was considered in the model fitting to account for vehicle position; an offset variate was also considered to estimate a fixed effect on the response h_d , representing the contribution of the probability of occurrence for doc 1/0 plus doc 3/1. A factor for through movements expressed by the proportion of these maneuvers by lane was included in the model since it had some influence on h_d . For estimating the unknown h_s^* , data were fitted with generalized estimating equations (GEEs), using GenStat package.



The generalized estimating equation approach facilitates the analysis of longitudinal data or repeated measures. GEEs use the generalized linear model to estimate the regression parameters in a more efficient way than ordinary least squares regression; indeed, it is possible to specify a working correlation matrix that accounts for the form of within-subject correlation of responses on dependent variables for different distributions (Ballinger, 2004). According to Ballinger (2004), two correlation structures that seemed to be appropriated to the case here studied were compared: i) an *exchangeable* correlation structure for the cases in which the within-subject observations are equally correlated and no logical order for observations within a subject can be observed; ii) an *unstructured* correlation matrix for the estimation of all possible correlations between within-subject responses, including them in the estimation of the variances. The statistical performance of the model was assessed by using the marginal R-square test:

$$R_m^2 = 1 - \frac{\sum_{Lz=1}^3 \sum_{i=1}^{20} (h_{di,Lz} - \hat{h}_{di,Lz})^2}{\sum_{Lz=1}^3 \sum_{i=1}^{20} (h_{di,Lz} - \bar{h}_{di,Lz})^2} \quad (8)$$

where i represents each operating conditions (20 in total). R_m^2 provides an estimate similar to R^2 used in linear regression but it is not appropriate for GLMs and is calculated from the sum of squared residuals against the squared deviations of the observations from mean values for the response variables. The statistics represents the amount of variance in the response variable which is explained by the fitted model (Hardin and Hilbe, 2003).

For model testing the quasi-likelihood under the independence model information criterion was also used (Pan, 2001); it allows the selection of the appropriate correlation structure and it is useful to compare covariance matrices under GEE models with the covariance matrix generated under the independence hypothesis. The correlation structure with the QIC score closest to zero is judged to be the best. At last, the cumulative residuals method was applied to confirm (or not) the accuracy of the model in data fitting and evaluate the consistency of the assumptions made in the model built for the estimation of unobserved parameters (Hauer and Bamfo, 1997).

Table-2 shows the estimates of the parameters and s.e. obtained in GLM and in GEE contexts. The correlation structures are also compared through QIC measures. Reductions in standard errors and QIC measures show an improved efficiency in estimation (i.e., when the correlation structure is closer to that correct than another structure). The cumulative residuals were then produced for GEE model with unstructured correlation matrix which showed the best data fitting (see Figure-5).

SUMMARY AND CONCLUDING REMARKS

Modeling traffic operations at roundabouts with large diameter of central island and two or more entering and/or circulating lanes is complex both for vehicles disregarding the priority rule and for free vehicular movements not conditioned by conflicting streams.

The paper shows that a generalized model for traffic operations can be developed starting from probability of occurrence of degree-of-conflict cases faced by a subject approach driver.

Table-2. Estimations of unknown saturation headways.

	GLM	GEE	
		Unstructured	Exchangeable
	Estimate (s.e.)	Estimate (s.e.)	Estimate (s.e.)
base L ₁	6.12 (1.24)	6.04 (0.56)	6.53 (0.17)
L ₂	-2.96 (0.44)	-2.99 (0.36)	-2.76 (0.13)
L ₃	-4.41 (0.64)	-4.41 (0.26)	-4.431 (0.112)
c.r.	1.86 (0.35)	1.81 (0.36)	2.003 (0.24)
e	-	-	-
.TR	2.62 (1.31)	2.79 (1.36)	1.73 (0.28)
R_m^2	0.79		
QIC		78.5	75.4
(-) estimates for which the null hypothesis could not be rejected			

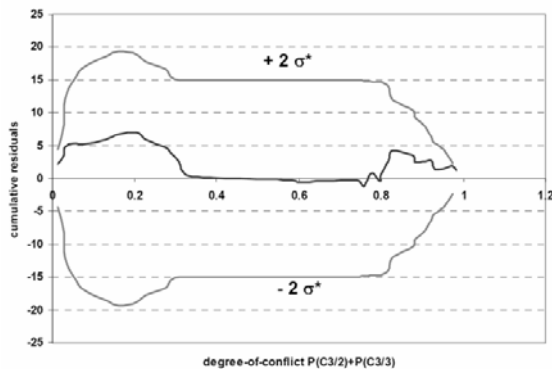


Figure-5. Cumulative residuals and the $\pm 2\sigma^*$ band.

The procedure, based on quasi-likelihood methods, allowed obtaining efficient estimates of the unobserved behavioral parameters that are necessary to implement the model. This represents the preliminary step for delay estimations at not-conventional roundabouts, since gap-acceptance models cannot be applied.

The application to a case study of multi-lane roundabout allowed to illustrate how to derive the model specification from the exploratory analysis of on-field observations. Moreover, the proposed method can be adapted to specific intersection layouts to account for the factors affecting operations (lane occupied by vehicles at entries, presence of heavy vehicles, type of movement, etc.).

The practical interest of this topic is that the correct assessment of effects of geometric design on capacity can provide insight on the conception and the installation of a roundabout and/or minor geometric adjustments that can give significant safety and operational benefits.

At last, the proposed approach may be useful to analyze operational conditions at existing not-conventional roundabouts, basing on-field observations; this approach can be also employed to make decisions about the measures to be put into practice for improving performances of these installations when they are going to be upgraded or converted to other geometric schemes.

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