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Passenger car equivalent for heavy vehicles crossing turbo-roundabouts

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Abstract

Turbo-roundabouts represent an innovative scheme of modern roundabouts which provides a spiraling traffic flow and requires drivers to choose their direction before entering the intersection, since raised lane separators mark the lanes on the ring. The configuration of the turbo-roundabout makes that patterns of conflict at entries with one and two conflicting traffic streams can coexist.
This paper presents research efforts aimed at measuring quantitatively the effect of heavy vehicles on operational conditions of a turbo-roundabout. The study starts from the initial belief that the greatest constraints to the vehicular trajectories imposed by the turbo-roundabout necessarily imply that the impact of heavy vehicles on the quality of traffic flow is more unfavorable than on other modern roundabouts. Microsimulation revealed as a useful tool when the variation of the traffic quality in turbo-roundabouts should be evaluated in presence of mixed fleets, each having different percentages of heavy vehicles; indeed, it allowed to isolate traffic conditions difficult to observe on field and replicate them to have a number of data as much as possible numerous. Entry capacity values for each entry lane of the turbo-roundabout were obtained by microsimulation, varying the percentage of heavy vehicles for entering flows. Nonlinear regression analysis of simulation data allowed to derive the behavioral parameters for heterogeneous populations of users and, ultimately, composed exclusively of heavy vehicles. The capacity functions thus obtained allowed us to determine how the passenger car equivalent (PCE) varies with the percentage of heavy vehicles and circulating flows for each entry lane of the turbo-roundabout. The results of this study indicate that there is a need to distinguish the impact of heavy vehicles when analyzing the capacity of a turbo-roundabout. When the traffic stream contains a significant number of heavy vehicles, a larger PCE effect would be expected. This effect should be accounted for in the estimation of the turbo-roundabout

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capacity. Lastly it should be emphasized that an important aspect of the research consists in having identified a methodology for assessing the impact of heavy vehicles on the quality of traffic flow, that can be applied to different patterns of intersection.

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Keywords: Turbo-roundabouts; passenger car equivalent; heavy vehicles; critical headway; follow-up headway; microsimulation

1. Introduction

Despite roundabouts are a solution to safety concerns of other intersections and worldwide there has been an increase in conversion of problematic intersections to roundabouts to improve their safety performances, it is difficult to make these roundabouts, in particular multi-lane roundabouts, safe to all the users. Double-lane roundabouts are associated with larger traffic capacity compared with single-lane roundabouts; however, they also present some disadvantages: higher speeds as vehicles negotiate through the roundabout because of the wider traffic lanes, the possibility of lane changing and weaving (or cutting) at the circulating and exit areas, which can generate traffic conflicts, and longer crossing distances for mopeds, cyclists, and pedestrians (Rodegerdts et al., 2010). With the problems of a double-lane roundabout in mind, Fortuijn (2009a) revolutionized the roundabout design in the Netherlands, developing the turbo-roundabout concept and creating a roundabout with a same or a higher capacity than the double-lane roundabout, but with the same safety features as the single-lane roundabout. The first turbo-roundabouts were installed at the end of the 1990s in the Netherlands, where by the end of 2007 seventy turbo-roundabouts were built (CROW, 2008); at the end of 2013 more than 200 turbo-roundabouts were built. The turbo-roundabout has a spiral course of the circulatory roadway. The entry, the circulating and the exit lanes are usually physically-separated by raised curbs so that drivers choose the lane before entering the roundabout to get to the correct exit; moreover, such raised curbs allow eliminating the conflicting points caused by weaving manoeuvres and reduce vehicular speeds (Fortuijn, 2009a). In essence, no lane changing on the roundabout, no need to yield to more than two lanes and low driving speed characterize the turbo-roundabout.

Fortuijn (2009a) highlighted that the reduction in the number of conflicts on turbo-roundabouts answers a safety problem of the double-lane roundabouts, whereas the spiral lane marking, together with raised lane dividers, offers a positive effect: turbo-roundabouts allow the distribution of the traffic flow over the different lanes, which makes for a high capacity. Compared to a double-lane roundabout, a basic turbo-roundabout shows a visible reduction from 24 to 14 conflict points, indicating a global reduction in the crashes. However, noting that not only the number of conflict points, but also the type of conflict influences road safety performance, Silva et al. (2013) affirmed that a more in depth analysis should be performed by applying microsimulation techniques, especially in absence of historic crash data. Despite their advantages, turbo-roundabouts can represent an awkward traffic situation for heavy vehicles. The geometric design of turbo-roundabouts can impose greatest constraints to the vehicular trajectories; thus, one can expect a more unfavourable impact of heavy vehicles on the traffic conditions than on other types of roundabouts. Before introducing the specific objectives of the paper, a brief overview of the turbo-roundabout geometric design and issues in modelling the turbo-roundabout capacity will be presented.

1.1. The turbo-roundabout geometric design

Five types of four-leg turbo-roundabouts can be distinguished basing on differing number of entry and exit lanes and bypasses; six types of three-leg turbo-roundabouts can be also installed (Fortuijn, 2009a). These variations are mainly due to the different distribution of traffic volume over the legs of the roundabout. Fortuijn (2009a) also presented the various forms of turbo-roundabouts, approximated values of the capacity for each intersection and a schema of the traffic volumes for the chief movements affecting the roundabout design. It goes without saying that all the different variants of four-leg turbo-roundabouts (namely, the basic turbo-roundabout, the egg-roundabout, the knee-roundabout, the spiral-roundabout and the rotor-roundabout) share the same basic geometry or 'turbo block', which is a useful design tool in their geometric design (see Fig. 1, case a).

The geometric shape of the circulatory roadway on a turbo-roundabout consists of spirals which are composed of segments of circular arcs, with each arc having a larger radius than the previous arc. Since the radius of the arc changes, the centre of the arc also changes by a same amount so that the curve remains continuous. In the geometry of the basic turbo-roundabout, two nested spirals represent the lane boundaries. Three semicircles with successively larger radii compose each spiral; the semicircles meet at the translation axis along which the centres C_{right} and C_{left} of the arc segments lie (see Fig.1 – case a). The distance between C_{right} and C_{left} is called the shift along the translation axis; the distance from each centre to the overall centre, or half the shift, is called bias of an arc. The shift must equal the change in radius so that the spiral is continuous; moreover the shift is one roadway width, because the spiral moves out by one roadway width every 180 degrees. Fig. 1 (case b) shows the sketch of a basic turbo-roundabout in which the main traffic flow is east-west and the minor traffic flow is north-south; this layout is used later in the application of the methodology for the calculation of passenger car equivalents (PCEs) for heavy vehicles. The design of other types of turbo roundabouts is also presented in CROW (2008). The main dimensions of turbo-roundabouts and the calculation procedure can be also found in some general guidelines based on the Dutch and Slovenian manuals and practical experience (Tollazzi, 2015). However, some design software can help quickly transportation engineers and planners to evaluate the feasibility of implementing a roundabout design.

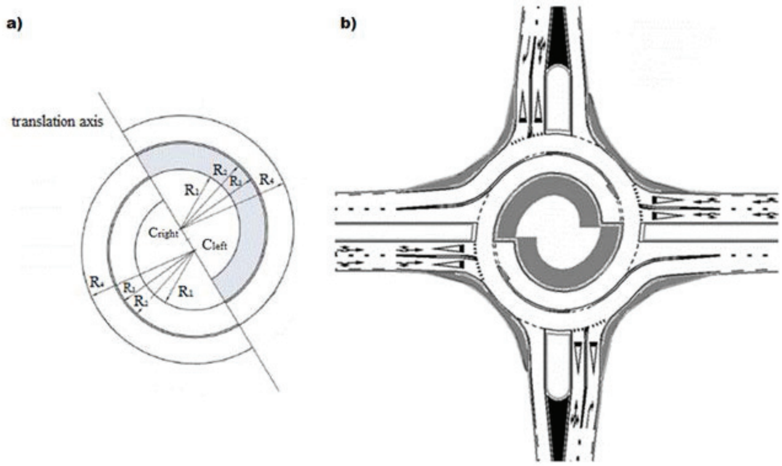

Fig. 1 (a) A turbo block with arcs of spirals representing the roadway edges; (b) A sketch of the basic turbo-roundabout.

1.2. Modelling the turbo-roundabout capacity

Fortuijn (2009b) initially estimated the capacity of the turbo-roundabout at steady-state conditions basing on a modification of the Bovy model. Further changes to such model allowed to take the diversification of circulating lanes into account based on the amount of traffic flow; the model calibration was determined from field observations at a turbo-roundabout built in the Netherlands (Fortuijn, 2009b); a tool to compare the various types of turbo-roundabouts, the 'multi lane roundabout explorer (in Dutch: Meerstrooksrotondeverkenner) was then developed. Subsequently Fortujin (2009b) remarked the drawback of a linear relationship between the circulating flow and the entry capacity and deemed most appropriate an estimation approach based on the theory of the gap-acceptance. This choice was supported by the results published by Brilon et al. (2014) and Grabowski (2012).

Developing suitability domains in undersaturated conditions, Giuffrè et al. (2012) also showed that in traffic situations where movements directed to major roads are prevalent over the other turning movements, the turbo-roundabouts can provide operating conditions advantageous compared to double-lane roundabouts under the same entering traffic volumes; in these cases, delays can be much shorter for turbo-roundabouts than for double-lane roundabouts. An interesting comparative analysis of the capacity performances between double-lane roundabouts and turbo-roundabouts was published by Vasconcelos et al. (2012). For an overview of entry capacity models whose formulation allows the use both for modern roundabouts and for turbo-roundabouts the reader is referred to Fortuijn (2009b) and Mauro (2010).

1.3. Motivation to the research and specific objectives of the paper

Despite accommodations for heavy vehicles at roundabouts is important from a geometric design perspective (Russell et al., 2013), there are few studies on the impact of heavy vehicles on roundabout performance from a traffic operational perspective (Lee, 2015). It is plausible, indeed, to suppose a more unfavorable impact of heavy vehicles on the traffic operations than on other types of intersections, due to the greatest constraints imposed to the vehicular trajectories by the geometric design of these multi-lane roundabouts.

The goal of this paper is to address the question of how to estimate passenger car equivalents (PCEs) for heavy vehicles driving turbo-roundabouts. The nature of the topic dictates the use of a microsimulation method to evaluate the variation of the traffic quality at turbo-roundabouts in presence of mixed fleets, each of them having different percentages of heavy vehicles. By executing the microsimulation model, traffic conditions difficult to observe on field can be isolated and replicated to have a number of data as much as possible numerous. Indeed, changing the percentage of heavy vehicles in entering flows, entry capacity values for each entry lane of the turbo-roundabout can be estimated. In order to attain the above mentioned objective, multiple runs of several simulation scenarios were executed in Aimsun; based on the output of these runs, capacity functions for each entry lane of the turbo-roundabout were developed and the effect of a single class of heavy vehicles on turbo-roundabout operations has been determined. Thus PCEs for heavy vehicles were calculated by comparing results for a fleet of passenger cars only with those of the mixed fleet scenarios. The following section 2 will present a brief literature review on PCEs, whereas the methodology of PCE estimation is described in section 3. At last modeling results will be presented in section 4 and conclusions in section 5.

2. Literature Review on PCEs

All PCEs for heavy vehicles allow to convert a mixed vehicle flow into an equivalent flow exclusively made of passenger cars. Since heavy vehicles differ from passenger cars for size and acceleration/deceleration abilities, these different characteristics result in driving behaviour different by each vehicle class in a traffic stream where the distribution of vehicles among the classes is influenced by location and time. Roess et al. (2014) also suggest that heavy vehicles impose a psychological and practical impact on drivers in adjacent lanes due to their larger size and manoeuvring difficulties. The impact of heavy vehicles on traffic operations has been an interesting topic since the first edition of the Highway Capacity Manual (HCM). However, the PCEs used in the HCM procedures account for the effect of dimensions and performance of heavy vehicles only under steady-state conditions; the inferior acceleration performance exhibited after the onset of congestion is not incorporated. Because capacity often is realized at saturated operations, the use of HCM PCEs for demand capacity analysis during queuing operations is expected to estimate improperly the effect of heavy vehicles. Some critical issues on using the HCM PCEs are reported by Al-Kaisy (2006) to which the reader is referred.

After the introduction of the PCE concept, many researchers have quantified the effect of heavy vehicles in a traffic stream both for uninterrupted flow and for interrupted flow; thus PCEs have been calculated through different methodologies and equivalency criteria. The determination of passenger car equivalents, indeed, include methods based on flow rates and density (Huber, 1982; Sumner et al., 1984), headways (Anwaar et al., 2011), queue discharge flow (Al-Kaisy et al., 2002), volume/capacity ratio (Linzer et al., 1979), platoon formation (Elefteriadou et al. 1997). Craus et al. (1980) considered the traffic delays caused by heavy vehicles and opposing traffic; they proposed a new set of PCEs which followed similar fluctuations of the HCM PCEs, but reported significantly lower values for slow heavy vehicle speeds. However, significant differences can be found among the values of PCEs derived from different methods especially in heterogeneous traffic environment (Adnan, 2014). In the process of developing PCEs, few studies have been based on field data (Carroll and Wiley, 1982) or have calibrated PCEs for a specific road infrastructure (De Luca and Dell'Acqua, 2014); thus, for some time most studies have resorted to traffic simulation techniques to obtain equivalent flows for a wide combination of flows and geometric conditions (Webster and Elefteriadou, 1999). Several investigations on performance of signalized and unsignalized intersections by different types of vehicles were also a special case of quantifying PCEs (see e.g. Branston and Gipps, 1981). However, technical literature still presents few studies related to the calculation of PCEs for heavy vehicles at roundabouts (see e.g. Macioszek 2012; Lee 2014). There is a gap in the current literature of assessment of PCEs on circular intersections and for turbo-roundabouts that this paper aims to address.

3. Methodology

In this section the proposed method of PCE estimation is presented; just after, the preliminary research activities in Aimsun, the issues tackled during the simulation study, and the nonlinear regression analysis for model parameters estimations will be described.

3.1. Method of PCE estimation

The process of developing PCEs for heavy vehicles at turbo-roundabouts can be articulated in the following steps. As a first step it is necessary to select the scheme of turbo-roundabout, as well as the length of the inner radius and the widths of the basic elements –the inside and outside roadways, the lane divider, and the offsets between the roadway edges and the lane lines, etc. Step 2 is to built the turbo-roundabout model in Aimsun, and to identify the origins and the destinations by centroids on the end of each leg. Step 3 is to perform the model calibration using Aimsun. In this view, the step is to carry out an iterative process which consists in changing and adjusting some model parameters and then comparing the model outputs with data that have been derived from measurements; the process will be held until a predefined level of agreement between the two data sets is reached. The choice of parameters in Aimsun should be carried out carefully for the purposes of calibration and their optimization. The fourth step is concerned with calculating the capacity values by simulating saturation conditions on each entry lane of the turbo-roundabout. Starting from O/D matrices assigned to reproduce the desired circulating flows, the calibration process can be conducted so that Aimsun gives capacity values comparable to measurements. In order to consider satisfactory the calibration phase, one or more statistics must be also selected to compare simulated and empirical data sets. The fifth step is to calculate the PCEs for heavy vehicles at turbo-roundabouts. Assuming a circulating flow made of passenger cars, the effect of a single class of heavy vehicles on turbo-roundabout operations can be determined. O/D matrices have to be assigned in Aimsun and saturation conditions at entries have to be reproduced so that the number of vehicles entering the intersection could represent the capacity for a given entry lane. For each entry lane of the turbo-roundabout, the PCE is estimated by comparing the capacity C_{car} that would occur in presence of a traffic demand of passenger cars only and the capacity C_p corresponding to a traffic demand characterized by a p percentage of heavy vehicles. This estimation can be developed considering the equation: $C_{car} = (1\text{-}p) \cdot C_p + p \cdot C_p \cdot E_t$, in which C_p is the entering heterogeneous flow in saturation conditions including both the share of passenger cars $(1\text{-}p) \cdot C_p$ and the share of heavy vehicles ($p \cdot C_p$), multiplied by the passenger car equivalent factor $E_t = (p \cdot C_p)^{-1} \cdot [C_{car} - (1\text{-}p)\, C_p]$ for reasons of homogeneity. In order to apply this criterion for calculating E_t, regressions on simulated data are necessary. Since mixed fleet depend on the circulating flow, E_t will depends on the whole circulating flow (Q_c) for left- and right-lane on major entries and right-lane on minor entries; in turn, for left-lanes on minor entries E_t will depend on two circulating flows (Q_{ce} and Q_{ci}).

3.2. Preliminary research activities

A scheme of basic turbo-roundabout was selected for this study; Fig. 1 (case b) exhibits the turbo-roundabout which complies with the recommendations by the Dutch guidelines in roundabout design. This layout was selected because in Italy turbo-roundabouts are not yet provided by guidelines as achievable schemes among the roundabouts. The Aimsun model of the turbo-roundabout was a 4-entry scheme with a diameter just over of 40 m. The turbo-roundabout characteristics selected for this case study such as lane, edge strip, and median strip widths, distances between edge lines and radii for roadway edges are summarized in Table 1.

It is noteworthy that the dimensions of the basic turbo-roundabout were obtained by the calculation procedure recommended by *Roundabouts: Application and design. A Practical Manual* (2009); the same manual, as well as Fortujin (2009b), highlights the standard values of capacity.

Table 1. The basic turbo-roundabout geometry for the selected case study.

Cross section elements	[m]	Roadway widths, shifts, and biases	[m]	Elements for roadway edges	[m]
inner radius R_1	12	inside roadway width	5.15	R_1 = inside roadway, inner edge	12
inner edge line offset	0.45	outsider roadway width	4.85	R_2 = inside roadway, outer edge	17
inside lane	4.50	shift1 (inside to middle)	5.20	R_3 = outside roadway, inner edge	17.30
divider inner/outer line offset	0.20	shift2 (middle to outside)	4.90	R_4 = outside roadway, outer edge	22.15
divider	0.30	bias 1 = shift1/2 (applies to R_1)	2.60	Arc centre bias (applies to R_1)	2.60
outside lane	4.20	bias 2 = shift2/2 (applies to all other radii)	2.45	Arc centre bias (applies to all other radii)	2.45
outer edge line offset	0.45	bias difference	0.15	shift difference	0.30

Note that $R_2 = R_1$ + inside roadway width - bias difference; $R_3 = R_2$ + divider width; $R_4 = R_3$ + outside roadway width

For the evaluation of the capacity values at each entry, it was decided to apply to the traffic demand the gap acceptance-based model developed by Hagring (1998), whose basic formulation allows its use also for turbo-roundabouts. In order to attain the objective of the paper, the model calibration was carried out by ensuring that Aimsun for each entry lane of the turbo-roundabout gave results close to those derived from the Hagring model (1998) using the critical and follow-up headways on-field surveyed by Fortuijn (2009b). Fortuijn (2009b) carried out experimental observations on turbo-roundabouts operating in the Netherlands. The collected values of the critical and follow-up headways were differentiated both by major and minor entries and by right- and left-entry lane; only for the left-lane at minor entries, Fortuijn (2009b) found two critical headways, one for the inner circulating lane and one for the outer circulating lane. Since critical headways (T_c) were obtained in different sites, each of them with a proper sample size, a weighted mean of these parameters by lane was introduced into the capacity model. Starting from data reported by Fortuijn (2009b), we assumed the gap-acceptance parameters as follows: i) on major entries, the critical headway is of 3.60 s for the left-lane and 3.87 s for the right-lane, whereas the follow-up headway is of 2.26 s for the left-lane and 2.13 s for the right-lane; ii) on minor entries, the critical headway is of 3.74 s for the right-lane, whereas the follow-up headway is of 2.13 s for the same lane. The critical headways for the left-lanes are of 3.19 s and 3.03 s for the inner and the outer circle lane respectively, whereas the follow-up headway is of 2.26 s.

We specified the Hagring model (1998) both in relation to the circulating flows in the circulating lanes as they are faced by entering drivers and in relation to the critical and follow-up headways. Thus, right- and left-lane capacities on major entries and right-lane capacity on minor entries were computed by the equation:

$$C_e = Q_c \cdot \left(1 - \frac{\Delta \cdot Q_c}{3600}\right) \cdot \frac{\exp\left(\frac{-Q_c}{3600} \cdot (T_c - \Delta)\right)}{1 - \exp\left(\frac{-Q_c}{3600} \cdot T_f\right)} \tag{1}$$

where Q_c is the whole (antagonist) circulating flow at the entry, T_c is the critical headway, T_f, is the follow-up headway and Δ is minimum arrival headway. Left-lane capacity on minor entries was computed by the equation:

$$C_e = (Q_{ce} + Q_{ci}) \cdot \left(1 - \frac{\Delta \cdot Q_{ce}}{3600}\right) \cdot \left(1 - \frac{\Delta \cdot Q_{ci}}{3600}\right) \cdot \frac{\exp\left(\frac{-Q_{ce}}{3600} \cdot (T_{ce} - \Delta) \frac{-Q_{ci}}{3600} \cdot (T_{ci} - \Delta)\right)}{1 - \exp\left(\frac{-(Q_{ce} + Q_{ci})}{3600} \cdot T_f\right)} \tag{2}$$

where Q_{ci} and Q_{ce} are the inner and the outer circulating flow respectively, T_{ci} is the critical headway for the inner circulating lane and T_{ce} is the critical headway for the outer circulating lane. According to literature, Δ was assumed equal to 2.10 s. For calibration purposes, the entry-lane capacities derived from the Hagring model (1998) were compared with simulated capacity values. O/D matrices were assigned in Aimsun to reproduce traffic demand as observed by Fortuijn (2009b); saturation conditions at entries were reproduced such as to derive the entry-lane capacities. After performing several iterations, manually adjusting different combinations of values of some default parameters in Aimsun, a minimum headway of 1.70 s was used instead of the default value of 0.00 s, whereas a reaction time of 1.00 s was used instead of the default value of 1.35 s. Then, the GEH index was used as criterion for acceptance, or otherwise rejection, of the model (see Barceló 2010, p. 46). Since the deviation of each simulated value with respect to the measurement for each entry lane was smaller than 5 in 100% of the cases, the model was accepted as significantly able to reproduce local conditions and traffic behaviour. For each entry lane, the normalized root-mean-square error also resulted less than 5 percent.

In order to estimate PCEs, the heavy vehicles mix included trucks with the following attributes: maximum length of 10 m, maximum desired speed of 85 km/h with a range 70 km/h-100 km/h, maximum acceleration of 1 m/s^2 with a range 0.6-1.8 m/s^2, maximum deceleration of 5 m/s^2 with a range 4-6 m/s^2. It was decided that the traffic demand was composed of different mixed fleets (100% passenger cars, 10%, 20% and 100 % heavy vehicles). Ten values of entry capacity for each lane on major entries and the right-lane on minor entries were obtained by simulation, for each mixed fleet at different values of circulating flow; in turn, ten capacity values for the left-lanes on minor entries were gained by simulation for each mixed fleet and for 7 combinations of circulating flows ($Q_{ci}=0$, $Q_{ce}=var$; $Q_{ci}/Q_{ce}=0.33$; $Q_{ci}/Q_{ce}=0.5$; $Q_{ci}/Q_{ce}=1$; $Q_{ci}/Q_{ce}=2$; $Q_{ci}/Q_{ce}=3$; $Q_{ci}=var$, $Q_{ce}=0$). Thus Aimsun gave 400 values of simulated capacity in total. It should be noted that each capacity value obtained during the data acquisition represented an average of the values obtained in 10 different simulations which Aimsun automatically calculates, for a total number of 4,000 outputs from simulation runs. For the left-lane on minor entries a greater capacity value was obtained for combinations of circulating flows characterized by a higher flow on the inner lane and a lower flow on the outer lane. In other words, denoting capacity with C^* and the ratios between the inner circulating flow and the outer circulating flow with Q_{ci}/Q_{ce}, the following relationship was always verified:

$$C^*\left(\frac{Q_{ci}}{Q_{ce}}=x\right) > C^*\left(\frac{Q_{ci}}{Q_{ce}}=\frac{1}{x}\right) \qquad \text{with} \quad x>1 \tag{3}$$

According to the criterion for calculating E_t as explained in section 3.1, simulation data were used to develop the C_{car} and C_p functions for each entry lane of the turbo-roundabout and for the different mixed fleets. Since we decided to adopt the Hagring model (see eqs 1 and 2) as the functional form best suited to perform regression on simulation data, nonlinear regressions were developed; more specifically the parameters of the regressions were the critical and follow-up headways for heterogeneous driver populations corresponding to the assumed traffic scenarios. Tables 2 and 3 show the results for major entries performed by Mathematica 9.0 software. For all the cases, increasing the percentages of heavy vehicles the parameter estimations increased. The capacity functions were then developed by each entry lane of the turbo-roundabout and for different options of mixed fleets. In all cases, the increase in the circulating flow corresponded to a reduction in the capacity values, especially when higher percentages of heavy vehicles characterized the traffic demand.

Table 2. Results of regressions for the right-lane on major entries.

fleet	parameter	est (s.e.)	R^2	t	p-value	confidence interval (α= 0.05)
10% hv	T_c	3.91 (0.0674)	0.99	57.93	8.75×10^{-12}	3.7543-4.0656
	T_f	2.31 (0.0191)		120.70	2.48×10^{-14}	2.2649-2.3531
20% hv	T_c	4.08 (0.0630)	0.99	64.83	3.56×10^{-12}	3.9394-4.2300
	T_f	2.35 (0.0177)		132.74	1.16×10^{-14}	2.3131-2.3948
100% pc	T_c	3.73 (0.0927)	0.99	40.25	1.59×10^{-10}	3.5176-3.9452
	T_f	2.27 (0.0264)		85.67	3.84×10^{-13}	2.2050-2.3270

Note: hv stands for heavy vehicles; pc for passenger cars; α= significance level

Table 3. Results of regressions for the left-lane on major entries.

fleet	parameter	est (s.e.)	R^2	t	p-value	confidence interval (α= 0.05)
10% hv	T_c	3.7778 (0.0516)	0.99	73.189	1.3530×10^{-12}	3.65874-3.89679
	T_f	2.3317 (0.0151)		154.24	3.4915×10^{-15}	2.2968-2.3665
20% hv	T_c	3.9991 (0.0245)	0.99	163.19	2.2236×10^{-15}	3.9426-4.05567
	T_f	2.3696 (0.0070)		336.31	6.8427×10^{-18}	2.3534-2.3858
100% pc	T_c	3.63 (0.0558)	0.99	64.98	3.4958×10^{-12}	3.4981-3.7554
	T_f	2.283 (0.0163)		139.79	7.6656×10^{-15}	2.2437-2.3189

Note: hv stands for heavy vehicles; pc for passenger cars; α= significance level

Fig. 2 shows the simulated points and the capacity functions for the right-lane on minor entries, whereas for the left-lane on minor entries, the capacity function is represented by a surface, since the capacity depends on the inner and the outer circulating flows. Fig. 2 (case b) shows the case of a mixed fleet of 20% heavy vehicles and 80% cars, where the simulated points corresponding to capacity values higher than those obtained by regression are visible.

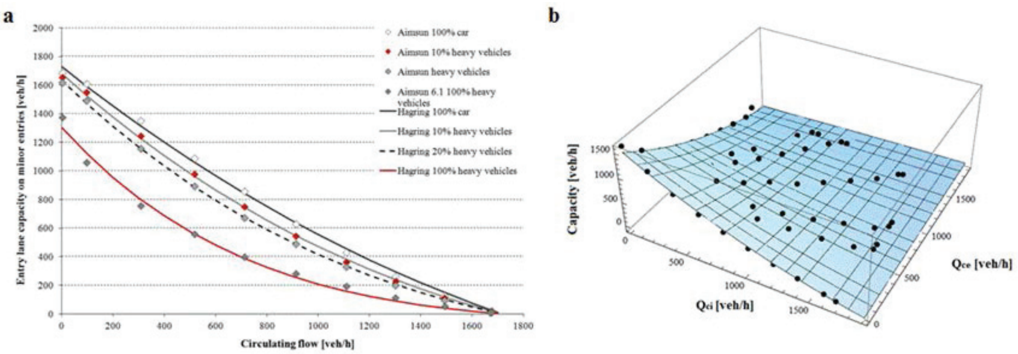

Fig. 2. The simulated points and the capacity functions for: (a) the right-lane on minor entries; (b) the left-lane on minor entries.

4. The PCE estimation for the basic turbo-roundabout

The estimation of PCEs was performed for the subject type of heavy vehicle and the explored mixed fleets at each entry lane of the turbo-roundabout as explained in section 3. Figure 3 shows the PCEs for the right- and the left-lane on major entries, whereas Figure 4 shows the PCEs for each lane on minor entries.

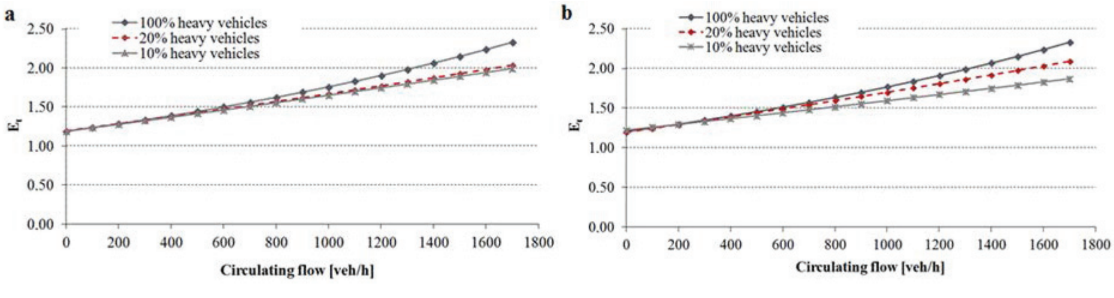

Fig. 3. PCE estimations: (a) the right-lane on major entries; (b) the left-lane on major entries.

We can observe that in operational conditions with 20% and 10% of heavy vehicles in the entry demand, E_t are below 2 for each lane on major entries (see Fig. 3); E_t reaches higher values for an (unrealistic) traffic demand made of 100 % heavy vehicles (or in traffic conditions saturated for the circulating flow). In turn, in operational conditions with 10% and 20% of heavy vehicles in the entry demand, an E_t of 4 is reached for the right-lane on minor entries (see Fig. 4a), whereas an E_t of 4.5 is reached for the left-lane on minor entries (see Fig. 4b). Compared to an E_t of 2 as suggested by HCM 2010 for roundabouts, in usual operational conditions (20% and 10% of heavy vehicles in the entry demand), overestimation of the impact of heavy vehicles on the quality of traffic flow can happen for left- and right-lane on major entries and underestimation of the impact of heavy vehicles may happen for the right- and the left-lane on minor entries.

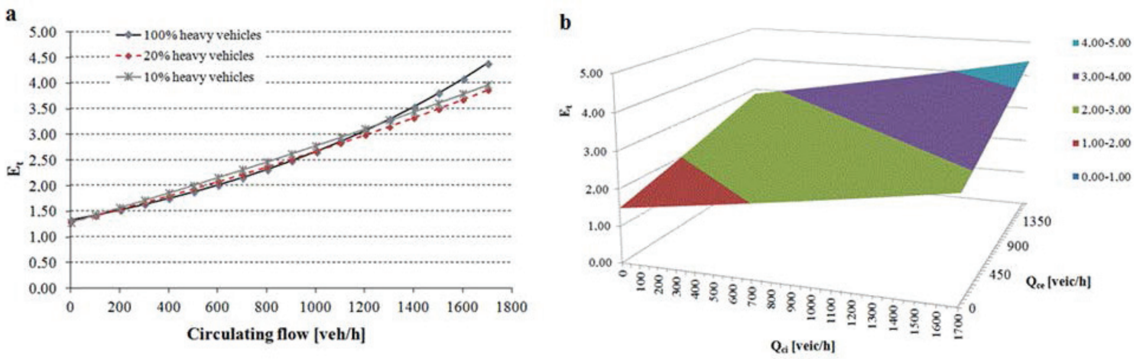

Fig. 4. PCE estimations: (a) the right-lane on minor entries; (b) the left-lane on minor entries (10% heavy vehicles and 90% cars).

5. Conclusions

The paper addresses the question of how to estimate passenger car equivalents (PCEs) for heavy vehicles driving turbo-roundabouts. This study starts from the belief that the greatest constraints to the vehicular trajectories imposed by the turbo-roundabout design imply a more unfavourable impact of heavy vehicles on the quality of traffic flow than on other roundabouts.

Estimations of capacity for each entry lane of the turbo-roundabout were obtained by microsimulation, varying the percentage of heavy vehicles in traffic demand. Within the boundaries of an exploratory study as the present one, the microsimulation technique was particularly suitable for the purposes of research, since it allowed to isolate traffic conditions that can hardly be observed directly on the road and to replicate many times as necessary to obtain sample sizes sufficiently representative. Nonlinear regression analysis of simulated data allowed to recalculate critical and follow-up headways for mixed fleets, up to 100% heavy vehicles. Capacity functions were developed for each entry lane on major and minor entries and then used to determine how the PCE varies with the percentage of heavy vehicles and the circulating flows (cars only).

Despite the obtained results are influenced by the assumptions adopted in the analyses, especially with regard to the user behaviour at turbo-roundabouts, they provide evidence that the analysis of the impact of heavy vehicles is an essential component in the estimation of the capacity of a turbo-roundabout. When the traffic stream contains a significant number of heavy vehicles, a larger PCE effect would be expected. This effect should be accounted for in the estimation of the turbo-roundabout capacity. Thus, assuming the values of passenger car equivalents as the HCM (2010) suggests for roundabouts, underestimation or overestimation of the effect of heavy vehicles on the quality of the traffic flow may happen. Some implications can be drawn from the application of the proposed procedure. In usual operational conditions (namely an entry demand with 20% and 10% of heavy vehicles), the values of E_t were below 2 for each lane on major entries; higher values were reached only for an unrealistic traffic demand made of 100 % heavy vehicles, or in saturated conditions for the circulating flow. In turn, a value of E_t twice that suggested by HCM 2010 for roundabouts is reached in usual operational conditions for the right-lane on minor entries. Thus assuming an E_t of 2 as suggested by HCM 2010 for roundabouts, the impact of heavy vehicles on the quality of traffic flow would be overestimated for left- and right-lane on major entries and underestimated for the right-lane on minor entries. For the left-lane on minor entries in operational conditions with 20% and 10% of heavy vehicles in the entry demand, an E_t value of 4.5 can be reached; as a consequence, a significant underestimation of the impact of heavy vehicles on the quality of traffic flow may happen when an E_t of 2, as HCM 2010 suggests for roundabouts, is selected. At last, it should be noted that an important aspect of the research consists in having identified a methodology for assessing the impact of heavy vehicles on the quality of traffic that can be also applied to different patterns of roads and intersections.

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