



# Estimation of Passenger Car Equivalents for Two-Lane and Turbo Roundabouts Using AIMSUN

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### Specialty section:

This article was submitted to  
Transportation and Transit Systems,  
a section of the journal  
Frontiers in Built Environment

**Received:** 05 December 2019

**Accepted:** 08 May 2020

**Published:** 09 June 2020

### Citation:

Granà A, Giuffrè T, Macioszek E and  
Acuto F (2020) Estimation of  
Passenger Car Equivalents for  
Two-Lane and Turbo Roundabouts  
Using AIMSUN.  
Front. Built Environ. 6:86.  
doi: 10.3389/fbuil.2020.00086

The paper addresses issues related to Passenger Car Equivalents (PCEs) at roundabouts. Compared to other road units, the curvilinear elements of roundabout geometric design may impose greater constraints on vehicular trajectories and have a significant effect on the swept envelope of heavy vehicles. Specifically, the aim of the paper is to present the methodological approach which used traffic microsimulation to estimate PCEs. Focus is made on a case study which considered the conversion of a two-lane roundabout into a basic turbo roundabout with comparable size. Empirical capacity functions for both roundabouts were derived as target values to which simulated capacities by lane were compared. In order to estimate the PCEs a criterion of equivalence based on the amount of capacity used by cars and heavy vehicles is presented. AIMSUN allowed to simulate traffic conditions with different percentages of heavy vehicles at both roundabouts. Thus, variation of traffic conditions where mixed fleets operate was explored. A comparison was made between the PCEs estimated for each entry lane characterized by similar mechanism of entry maneuver. The results indicated there is a need to distinguish the impact of heavy vehicles when operational performance of a two-lane roundabout or a turbo-roundabout should be examined. Especially when circulating flows increase, a higher PCE value is expected than the value that the Highway Capacity Manual proposes for roundabouts.

**Keywords:** two-lane roundabout, turbo roundabout, microsimulation, passenger car equivalent, capacity

## INTRODUCTION

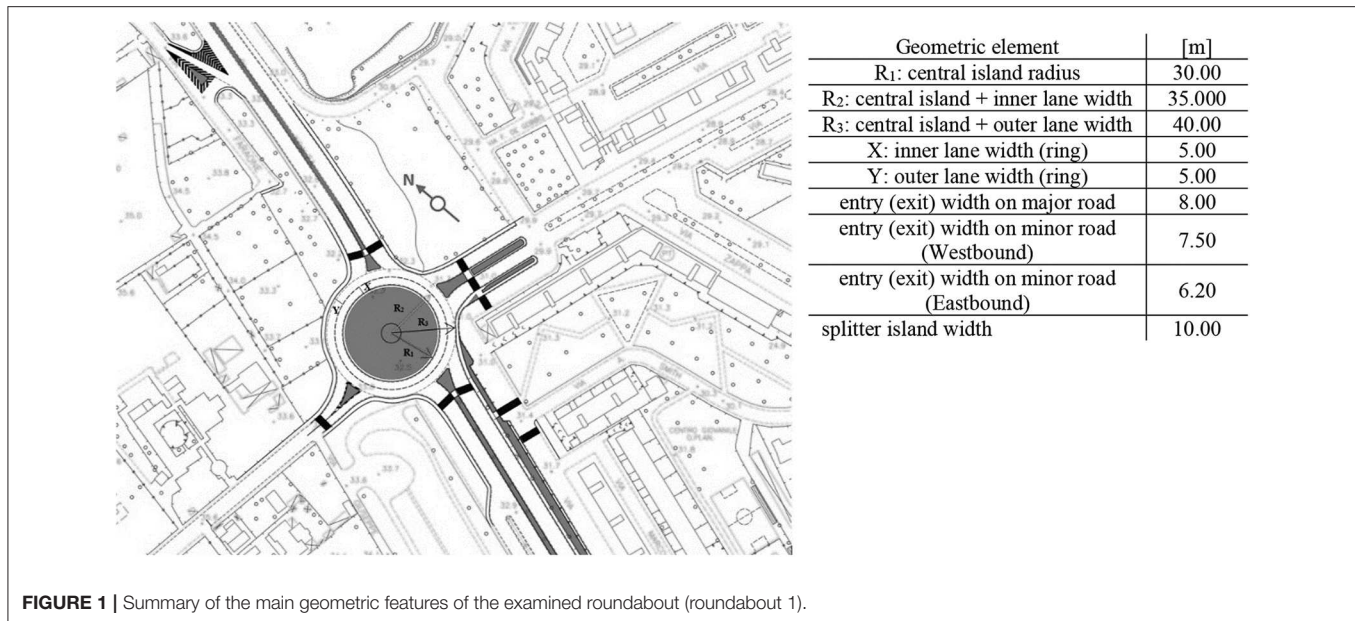
Heavy vehicles have a significant impact on operational performance of the traffic flow, particularly where the curvilinear elements of geometric design of a road unit may influence the vehicular trajectories and the swept path envelope of heavy vehicles. The last issue characterizes both standard roundabouts and alternative roundabouts such as e.g., turbo roundabouts, flower roundabouts, target roundabouts and so on, which have been introduced for enhancing some design and functional features (lane selection before entering to the desired destination, reduction in conflict points, or traffic calming). Alternative roundabouts could be an appropriate solution as existing similar-sized intersections or roundabouts should be reconstructed on condition that an additional circulating lane inwards or outwards could be introduced compatibly with the available space and costs to be incurred (Vasconcelos et al., 2014; Tollazzi, 2015; Tollazzi et al., 2016; Guerrieri et al., 2019).

Passenger Car Equivalents (hereinafter PCEs) express the impact of types of vehicles on traffic variables such as e.g., speed, headway, density and so on, compared to passenger cars. Traffic is made of various types of vehicles, whose range and composition within a traffic mix could vary from site to site, also in relation to the context of installation and territorial function of the road. Thus, the values of PCEs used within a capacity model have to reflect the characteristics of each type of vehicle, the road unit and (rural or urban) environment of insertion when on-street performance shall be assessed.

Various methods have been developed for determining PCEs based on type of road unit under mixed traffic conditions (see e.g., Raj et al., 2019). The main conclusions are that the parameters used to estimate PCEs under mixed traffic can vary for almost all the types of road units and the effects given by different factors on the PCE estimations can be mainly due to limitation of data collected in the field. In turn, simulation studies which have more recently been carried out to calculate PCEs, have attempted to better capture human factors that influence driving behavior (see e.g., Tran et al., 2017).

With specific reference to roundabouts it should be noted that little information from specialized sources and published studies is still available on calculation of PCEs; see e.g., Giuffrè et al. (2019), Pajecki et al. (2019), Macioszek (2012), (Fortuijn, 2009a), Brilon (2005). The Highway Capacity Manual (2000), Highway Capacity Manual (2010), and Highway Capacity Manual (2016) propose PCE values for heavy vehicles equal to two for all types of roundabouts. However, the equivalent factor for roundabouts fails to take account of the size and performance of heavy vehicles, and traffic demand level. In this regard, Lee (2015) estimated PCEs for heavy vehicles at three roundabouts and applied the PCEs to predict the entry capacity using the HCM 2010 model. The author argued that the prediction errors of the HCM model were lower when the critical and the follow-up headways were adjusted for heavy vehicles by different weights instead of the default PCE value of 2.0. However, Lee (2015) also determined a constant value of PCE at each roundabout and concluded that the PCEs could be considered valid only for the examined roundabouts, but not enough reliable to solve the problem of their generalization to other sites. Equivalent factors have been proposed only recently for turbo roundabouts. In this regard, Macioszek (2019) developed an empirical analysis to determine the numerical values of PCEs for various types of heavy vehicles on turbo roundabouts in Poland. The author examined the effect of heavy vehicles on (critical and follow up) headways and time gaps between the vehicles moving on the separated lanes of the turbo block, and concluded that higher headways could be observed when the percentages of heavy vehicles increased. Thus, PCE values were determined for each class of heavy vehicles differentiated by lane. In turn, Giuffrè et al. (2016a) also addressed the question of how to estimate PCEs for trucks driving turbo roundabouts, but analyzed both empirical data and microscopic traffic simulation. The results showed the dependence of PCEs on operational conditions which characterized turbo roundabouts. Similar results were obtained also for roundabouts. Giuffrè et al. (2017) proposed a microsimulation-based procedure to estimate the equivalent

factors for single-lane roundabouts and determined PCEs by comparing the capacity functions made of a fleet of passenger cars with the capacity functions calculated for different percentages of trucks. Differently from HCM 2010 which sets the PCE value of 2.0 for heavy vehicles at roundabouts, their results showed a greater PCE effect in presence of a high number of heavy vehicles in traffic; this effect should be accounted for calculating capacities and level-of-services. Thus, constant values of PCEs for roundabouts, as the HCM proposes, could misinterpret the effect of trucks on the quality of traffic depending on the entering demand level and the amount of circulating traffic. It should be noted that, among the alternative roundabouts, turbo roundabouts have been in operation for a long time and more of 300 turbo roundabouts have been installed worldwide (Fortuijn, 2009b; Tollazzi, 2015). Turbo roundabouts are characterized by physical separation of lanes so that traffic streams run along separated lanes before entering into the roundabout and throughout the roundabout up to the exit. Nevertheless, data are often unavailable for them and different possibilities are still open not only for safety evaluation but also for capacity and level-of-service determination. In this regard, Fortuijn and Harte (1997) proposed an empirical regression model for estimating entry capacity at turbo roundabouts which considered the lane separation in the turbo block; the authors modified the regression model developed by Bovy et al. (1991), in its turn used to estimate entry capacity at standard roundabouts. Fortuijn (2009a) adapted the Wiedemann model of car following to Dutch driver behavior and applied traffic microsimulation to calibrate parameters useful for the estimation of entry capacity by lane at turbo roundabouts. Since the split lane of the turbo block had to be more clearly understood, the Author applied the Hagring model (Hagring, 1998) which distinguishes traffic flows on the circulating lanes. A good agreement was obtained between observed and simulated capacities especially when the Hagring model (Hagring, 1998) was used. The application of the Hagring model to turbo roundabouts and efforts to calibrate the microsimulation model showed how better the inside lane could perform due to spiral marking and raised lane dividers compared to the inside lane at standard multi-lane roundabouts. Brilon (2011) also developed a method for estimating entry capacity at turbo roundabouts; his solution took into account the two different lane configurations at entries, i.e., two entering lanes and one circulating lane on major entries, while two entering lanes and two circulating lanes on minor entries. Thus, determination of gap-acceptance parameters could be made by entry lane, as well as estimation of traffic performance. Despite the advantage of this capacity formula, calibration of parameters to be included into the model was affected by local conditions and German driver behavior. Differently from turbo roundabouts for which a generalized capacity formula has not yet been proposed, methodological issues in the operational analysis and calculation of entry capacity at standard roundabouts were addressed by numerous studies on the topic; see e.g., Mauro (2010) for capacity calculation and issues of stochastic nature of the traffic phenomenon at roundabouts, Giuffrè et al. (2016b) for a systematic review on derivation of the analytical-based models under steady-state entry conditions and gap-acceptance models, Šaric and



Lovric (2017) for capacity evaluation at multi-lane roundabouts, and Deluka Tibljaš et al. (2018) for roundabouts performance evaluation in presence of automated vehicles in traffic.

Starting from the above considerations, further problems arise when one wants to compare two-lane roundabouts and turbo roundabouts from the performance point of view and PCEs should be evaluated considering their role in traffic analysis. In this view, the results of this research can contribute to identify more appropriate performance measures to use when the effects on traffic due to conversion of an existing roundabout into a new turbo roundabout with comparable size, or more in general the life-cycle costs of intersection design alternatives should be evaluated before the implementation in the real world. Note that this kind of evaluation is usually integrated in a life-cycle cost analysis of design alternatives, but only recently has been extended to the intersection design; see the life-cycle cost estimation tool proposed by National Academies of Sciences Engineering Medicine (2016). Thus, the paper is aimed at addressing a gap in the current literature on assessing PCEs specifically for two-lane roundabouts and turbo roundabouts.

## RESEARCH OBJECTIVES AND ASSUMPTIONS

This paper aims to present the methodological approach which used traffic microsimulation to estimate Passenger Car Equivalents (PCEs) for heavy vehicles at roundabouts. A two-lane roundabout located in Palermo City, Italy, was selected as starting point for the analysis; see **Figure 1**. A turbo roundabout with comparable size was designed as an alternative solution for traffic calming purposes; see **Figure 2** for its geometric design. In order to achieve the goal introduced before, the Haging model (Haging, 1998) was applied to estimate entry capacity by lane

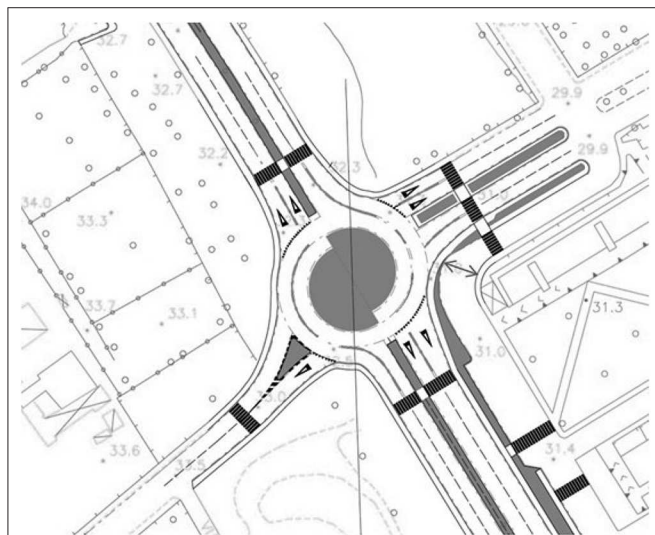
at both roundabouts. It should be noted that pre-selection of entry lane with a view to the desired destination is not bound by raised curbs at standard roundabouts. In turn, the spiral shape of the turbo block and its physically separated lanes produce the following configurations at entries: two entry lanes and one circulating lane on major-road entries; two entry lanes and two circulating lanes on minor-road entries (see Fortuijn, 2009b). Thus, turbo roundabouts show patterns of entry maneuvers with one conflicting traffic stream (right lane at minor-road entries and both lanes at major-road entries) and with two conflicting traffic streams (left lane at minor-road entries); see Mauro and Branco (2010) and Giuffrè et al. (2012). In order to adapt the Haging model (Haging, 1998) to both roundabouts, a correspondence was established between the operations at entries characterized by a similar mechanism of entry maneuver. In view of the conversion of the existing layout of two-lane roundabout into the configuration of a basic turbo roundabout with comparable size, empirical capacity functions were derived as target values and then compared to the simulated capacities by lane. Behavioral headways from literature (Vasconcelos et al., 2013; Giuffrè et al., 2016c) were used to develop the target capacity functions, while the values of entry capacity by lane were simulated in AIMSUN (2011) when traffic composition varied. A criterion of equivalence is presented to estimate the PCEs for heavy vehicles. Traffic conditions where percentages of a single class of heavy vehicles varied were reproduced by AIMSUN. In this view AIMSUN allowed to isolate the effect of a single class of trucks on traffic. Capacity functions for each percentage of the class of heavy vehicles here considered (i.e., 10% and 20% of single-unit trucks) were developed to determine how PCEs varied with the percentage of heavy vehicles. A comparison was made between PCEs estimated for each entry lane characterized by similar operations approaching the roundabout.

## MATERIALS AND METHODS FOR ESTIMATING PCEs

### Data Collection

As introduced in section Research Objectives and Assumptions, a two-lane roundabout was the starting point for the analysis. **Figure 1** exhibits the current configuration of the selected roundabout (hereafter called roundabout 1) and some information about its geometry consistent with Italian standards on geometric design (Italian Minister of Infrastructure and Transport, 2006). Different widths of the entry lanes were imposed by the built environment around the area where the intersection is operating. Roundabout 1 is installed along

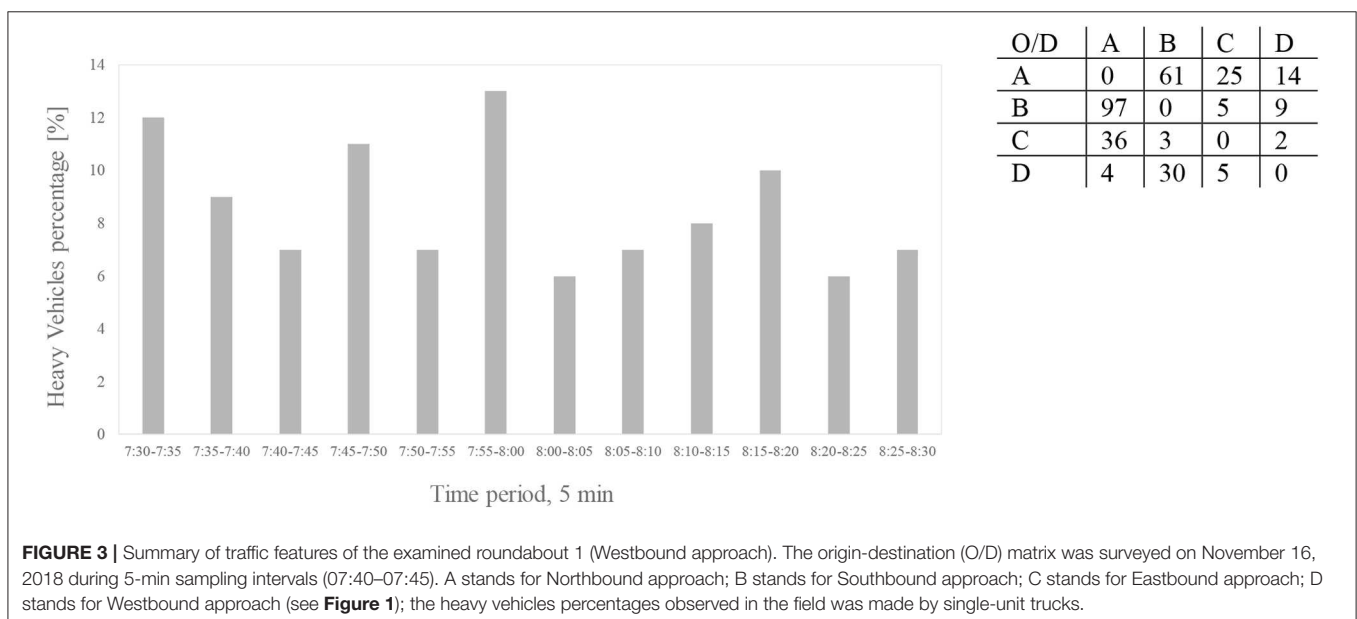
an urban road corridor where the major direction of traffic flow is North-South and vice-versa. Traffic data collection and subsequent analysis were carried out as part of research activities undertaken for the purpose of monitoring polluting emissions at a sample of six roundabouts located in Palermo City, Italy (Giuffrè et al., 2020). At the time of the study no roundabouts having a conventional design had been installed in Palermo City; so far, several non-typical roundabouts, unsignalized and signalized intersections have been built and they could be transformed into roundabouts with standard design. The main characteristics of the geometric design have been acquired from OpenStreetMaps; the geometric data were supplemented by further information detected in the field. Traffic data for the roundabout here considered were videotaped on weekdays (Tuesday to Thursday) from 7:00 to 8:30 am in October and November 2018, with reference to 5-min time intervals during peak periods. By way of example, the O/D matrix which was surveyed on November 16, 2018 during 5-min sampling intervals (07:40–07:45) is given in **Figure 3** together with the percentages of single-unit trucks vs. time throughout a peak period at Westbound approach as shown in **Figure 1**. The total entry traffic flow at that time was of 4,008 vph; it was calculated based on traffic data collected during 5-min intervals in the morning peak time periods (7:00–8:30 am) from Tuesday to Thursday. **Figure 4** shows an example of speed profile vs. travel time for the left turn (South to East) recorded by using the Speedometer GPS PRO app for Android smartphone during the 5-min sampling interval in **Figure 3**; see also Fernandes et al. (2016) for further examples of speed profile through roundabouts and turbo roundabouts.



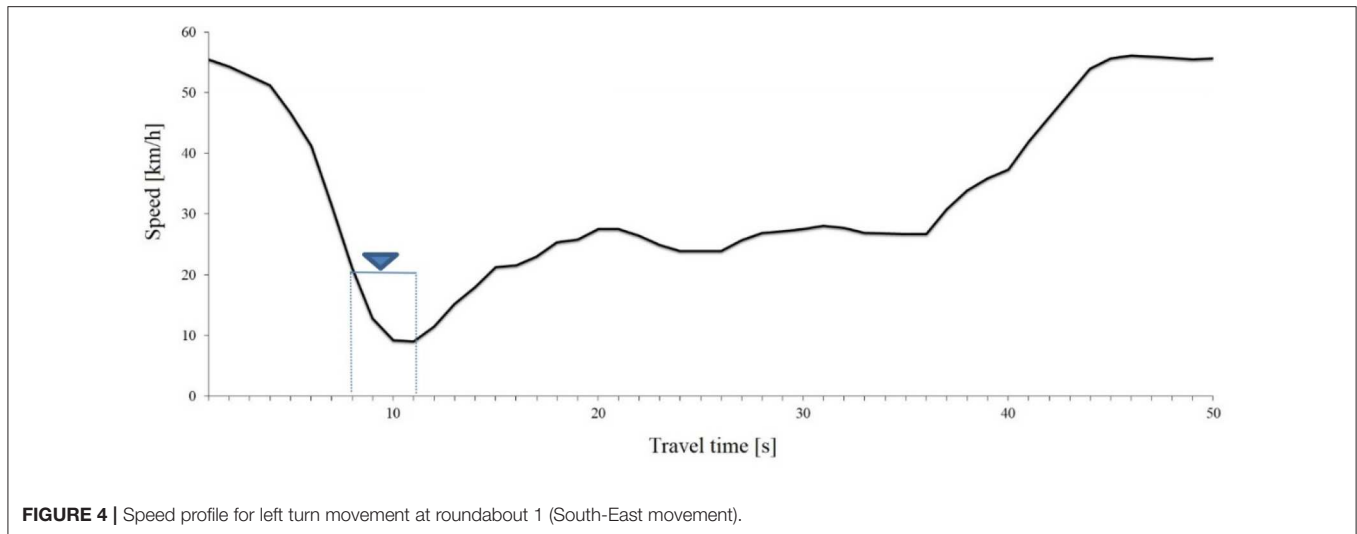
**FIGURE 2 |** Geometric design of the basic turbo roundabout (roundabout 2). The reader can find the geometry for the basic turbo roundabout in **Table 1**.

### Designing a Basic Turbo Roundabout

The turbo roundabout (hereafter called roundabout 2) with footprint size comparable to roundabout 1 has been



**FIGURE 3 |** Summary of traffic features of the examined roundabout 1 (Westbound approach). The origin-destination (O/D) matrix was surveyed on November 16, 2018 during 5-min sampling intervals (07:40–07:45). A stands for Northbound approach; B stands for Southbound approach; C stands for Eastbound approach; D stands for Westbound approach (see **Figure 1**); the heavy vehicles percentages observed in the field was made by single-unit trucks.



**FIGURE 4 |** Speed profile for left turn movement at roundabout 1 (South-East movement).

designed consistently to the basic turbo design proposed by Fortuijn (2009b); see **Figure 2** for the geometric design of roundabout 2. The geometric shape of the turbo block is characterized by two nested spirals which represent lane boundaries and consist of three semicircles with successively larger radii; the radii have to be rotated to obtain lanes and driving lines. The semicircles meet at the translation axis where the center of the turbo block must be located and connection of all entries into the roundabout must happen (Tollazzi, 2015). In accordance with the procedure laid down in the manual Roundabouts- Application Design (2009), the inner radius  $R_1$ —from the center of the intersection up to the inner edge of the inside roadway—has been set 15 m; higher values of the inner radius would have prevented the correct sizing of the side road due to the surrounding buildings. Based on a previous study (Giuffrè et al., 2012) which identified the suitability domains of double-lane and turbo roundabouts from an operational point of view, the roundabouts here examined resulted equivalent in terms of operational performances. However,  $R_1 = 15$  m may improve road safety, provide traffic calming effects by reducing vehicle speeds, and give further space to install bicycle lanes. **Table 1** shows the cross-section elements of the turbo block; inside and outside roadway widths were higher than minimum values to better accommodate heavy vehicles likely to use the intersection (Rodegerdts et al., 2010). It should be noted the consistency of geometric design of entry (exit) approaches of roundabout 2 with roundabout 1; thus, entry and exit widths are slightly greater along the major road at both roundabouts. In order to estimate and compare PCEs focus will be made on the Westbound approach of both roundabouts where entry (and exit) geometry is comparable to the entry geometry of major roads (i.e., Southbound approach and vice-versa). No possibility of shared lanes was examined at this stage. However, before calculating PCEs, AIMSUN modeling and the method of PCE estimation will be described in the next sections.

### AIMSUN Modeling

Differently from ordinary simulation used to predict the behavior of a real-world system, a microscopic traffic simulation model as AIMSUN makes able the user to look at the interaction of individual units (e.g., vehicles). Each unit is treated as an autonomous entity and the interaction among the units can vary depending on the model rules (that describe the car-following, the lane changing and the gap-acceptance behavior of the vehicles), and model parameters that should be calibrated to better represent the individual driving preferences and better match the reality; see Barceló (2010) for further details on traffic microscopic simulation with AIMSUN. In this paper AIMSUN dynamic simulator (2011) was used to build several scenarios where entering flows were characterized by different proportions of heavy vehicles. Having conducted the identification of the layouts of roundabout, AIMSUN modeling shall proceed according to the sequence of steps, together with what was done in each of them, as follows:

- 1) Estimation of empirical capacity functions by lane  
 Empirical functions of entry capacity at roundabout 1 and roundabout 2 were developed by lane. Due to absence of a gap-acceptance model for estimating entry capacity at turbo roundabouts, Fortuijn (2009a) proposed the application of the Hgrading formula (Hgrading, 1998) to turbo roundabouts. Thus, the Hgrading model (Hgrading, 1998) was applied to both roundabouts based on an analogous operating mechanism observed at each entry lane. Entry-lane capacity functions were derived from the Hgrading model (Hgrading, 1998) as follows:

$$C_e = 3600 \cdot \sum_j \frac{\varphi_j \cdot Q_{c,j}}{3600 - \Delta \cdot Q_{c,j}} \cdot \prod_k \left( \frac{3600 - \Delta_k \cdot Q_{c,k}}{3600} \right) \cdot \frac{\exp \left[ - \sum_i \frac{\varphi_i \cdot Q_{c,i}}{3600 - \Delta_i \cdot Q_{c,i}} \cdot (T_{c,i} - \Delta_i) \right]}{1 - \exp \left( - \sum_m \frac{\varphi_m \cdot Q_{c,m}}{3600 - \Delta_m \cdot Q_{c,m}} \cdot T_{f,m} \right)} \quad (1)$$

**TABLE 1** | The geometry for the basic turbo roundabout.

Cross section elements [m]					
Inner radius $R_1$ (inside roadway, inner edge)	15	Inside roadway width	5.50	Bias difference	0.10
Inner (outer) edge line offset	0.45	Outside roadway width	5.25	Inside roadway, outer edge ( $R_2$ )	20.4
Inside lane	4.35	Shift1 (inside to middle)	5.15	Outside roadway, inner edge ( $R_3$ )	20.7
Divider inner (outer) line offset	0.20	Shift2 (middle to outside)	4.95	Outside roadway, outer edge ( $R_4$ )	25.95
Divider	0.30	Bias 1 = shift1/2 (applies to $R_1$ )	2.575	Arc center bias (applies to $R_1$ )	2.60
Outside lane	4.25	Bias 2 = shift2/2 (for other radii)	2.475	Arc center bias (for other radii)	2.45

$R_2 = R_1 + \text{inside roadway width} - \text{bias difference}$  (differences match roadway widths);  $R_3 = R_2 + \text{divider width}$ ;  $R_4 = R_3 + \text{outside roadway width}$ .

where  $C_e$  is the entry-lane capacity, in veh/h,  $Q_c$  is the circulating traffic flow in veh/h,  $\phi_j$  is Cowan’s M3 parameter (that is the proportion of free traffic within the major stream),  $T_c$  and  $T_f$  are the critical headway, s, and follow-up headway, s, respectively;  $\Delta$  is minimum headway of circulating flow; j, k, l, m are indices for the conflicting lanes.

Capacity calculation was done in the same way for the entry lanes characterized by a similar entry mechanism. With reference to the selected subject approach (i.e., the Westbound approach of both roundabouts with two entry lanes and two circulation lanes), entry capacities of the left lanes at roundabout 1 and roundabout 2 were determined using the Hagring model (Hagring, 1998) as a function of the circulating flows in the inside lane and the outside lane of the circulatory roadway. In turn, entry capacities of right lanes at roundabout 1 and roundabout 2 were calculated using the Hagring model (Hagring, 1998) only as a function of the circulating flow in the outside lane of the circulatory roadway.

Reference was made to behavioral parameters, related to the capacity, observed in the field during roundabout operations. For the roundabout 1 summary random-effects estimates of the critical and follow-up headways were used as literature refers (Giuffrè et al., 2016c). For the roundabout 2 a weighted mean of critical headways by lane on-field surveyed on Dutch roundabouts was considered (Fortuijn, 2009a; Giuffrè et al., 2012). The following behavioral headways have been assumed: roundabout 1) *left lane*: critical headways of 4.16 s (inside lane of the ring) and 3.82 s (outside lane of the ring), and follow up headway of 2.85 s; *right lane*: critical headway of 3.82 s and follow up headway of 2.72 s; roundabout 2) *left lane*: critical headway of 3.20 s (inside lane of the turbo block) and of 3.03 s (outside lane of the turbo block), and follow up headway of 2.26 s; *right lane*: a critical headway of 3.74 s and follow up headway of 2.13 s. The values of behavioral headways were consistent with the values for Polish turbo roundabouts surveyed in the field by Macioszek (2019).

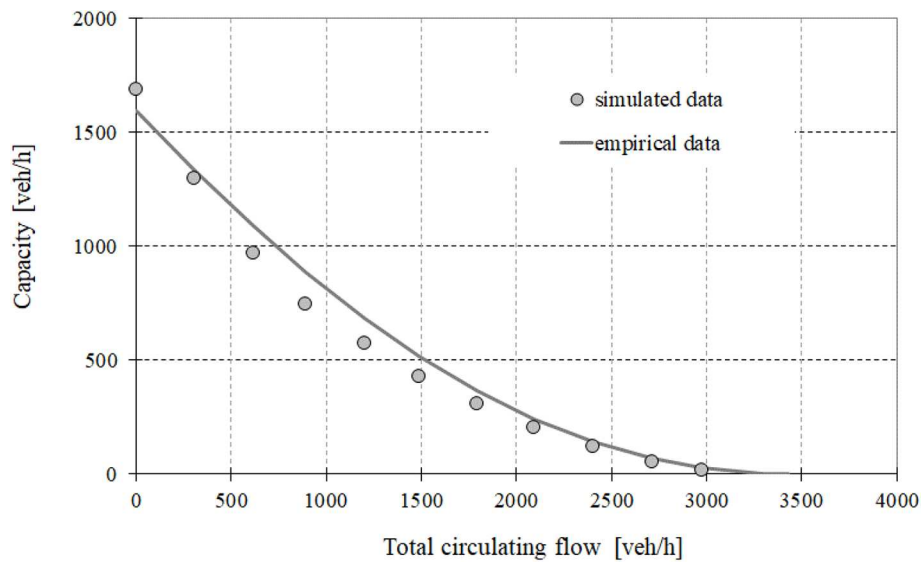
2) Network models of roundabout and turbo roundabout in AIMSUN

For this step the Westbound approach at both roundabouts was used as the subject entry to observe reaching entry capacity by lane. The network models of the roundabout and the turbo roundabout were then built in AIMSUN; as standard practice, their geometric design

layouts (i.e., the DWG files) were imported in AIMSUN and used as the background on which the network models of the roundabouts were built. Centroids of each leg identified the origins and destinations of the directions of turn. Since a saturated condition should be reached at each entry lane, traffic was assigned and a circulating flow every 200 veh/h from zero onwards was produced; thus, the maximum number of vehicles entering each roundabout corresponded to the entry capacity by lane.

3) Model calibration in AIMSUN

Each roundabout modeled in AIMSUN should be calibrated with regard to the parameters able to ensure that PCEs are accurately predicted from simulated capacities. As it is well-known, each of the parameters controls a unique aspect of the car following model, the lane-changing model or gap-acceptance. Fine-tuning adjustments to model parameters were made manually based on a sensitivity analysis. In order to enable the calibration process to better match the empirical data and simulation output, a genetic algorithm-based method has been used to optimize the parameters. This approach was also applied by Giuffrè et al. (2018) to calculate PCEs at double-lane roundabouts to which the reader is referred. The objective function to be minimized expressed the mean square of the differences between the simulated value of entry-lane capacity and the empirical value of entry-lane capacity. The problem of searching the vector of parameters to be optimized was solved through the implementation of the genetic algorithm tool in MATLAB®; the interaction with AIMSUN was implemented through a script in Python. To minimize the fitness function the maximum number of iterations was set equal to 50 generations, while the initial population to seed the genetic algorithm was set equal to 20 individuals; other options included as follows: a mutation function: *constraint dependent*; a crossover function: *scattered*; a selection function: *stochastic uniform*; an elite count of 2 and the crossover fraction of 0.8. The GA found the minimum of the fitness function for both entry lanes; it was half of the values obtained when the default parameters of AIMSUN were used as the initial condition. Note that each value of capacity was an average of 10 simulated values from each AIMSUN run. With specific reference to left lanes, 10 capacity values were simulated to varying of seven ratios of circulating flows (i.e., the circulating flow in the outside lane



capacity equation:

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

**FIGURE 5 |** Comparison of empirical and simulated data for left lane capacity at roundabout 2 ( $Q_{ci}/Q_{ce} = 1$ ).  $C_e$  = capacity at entries [veh/h]; total circulating flow = ( $Q_{ce} + Q_{ci}$ );  $Q_{ce}$ , circulating flow (outside lane) [veh/h];  $Q_{ci}$ , circulating flow (inside lane) [veh/h];  $\Delta = 2.10$  s;  $T_{ci}$ , critical headway (inside lane), s;  $T_{ce}$ , critical headway (outside lane) [s];  $T_f$ , follow up headway [s].

of the ring  $Q_{ce}$  and the circulating flow in the inside lane of the ring  $Q_{ci}$ ):  $Q_{ce} = 0, Q_{ci} = \text{var}; Q_{ci} = 0, Q_{ce} = \text{var}; Q_{ci}/Q_{ce} = 0.33; Q_{ci}/Q_{ce} = 0.5; Q_{ci}/Q_{ce} = 1; Q_{ci}/Q_{ce} = 2; Q_{ci}/Q_{ce} = 3$ . The relation  $Q_{ci}/Q_{ce} = x > Q_{ci}/Q_{ce} = 1/x$  (with  $x > 1$ ) was verified since greater capacity values could be produced with  $Q_{ci}$  higher than  $Q_{ce}$  for the left lane at roundabout 2. Analogous simulation runs were also made with reference to each mixed fleet subsequently examined when the circulating flow changed (see next section).

The optimal setting of AIMSUN parameters that was obtained by calibration is as follows: roundabout 1) *reaction time*: the default value is equal to 0.80 s; the calibrated values are =0.95 s and 0.94 for the left lane and the right lane at entries, respectively; *minimum gap*: the default value is =0.00 s; the calibrated values are =1.34 s and 1.01 for the left lane and the right lane at entries, respectively; *speed acceptance*: the default value is equal to 1.10; the calibrated values are =0.98 and 0.95 for the left lane and the right lane at entries, respectively.

roundabout 2) *reaction time*: the default value is equal to 0.80 s; the calibrated values are =1.00 s for both entry lanes; *minimum gap*: the default value is equal to 0.00 s; the calibrated values are =1.69 s for both entry lanes. For roundabout 2 the speed acceptance, which is the degree to which drivers comply with the speed limit, resulted no significant; the possible reason is that vehicles use a lower speed limit due to more pronounced curvatures where curbs as lane dividers are installed. For both roundabouts the GEH index was used as criterion for acceptance

(or not) of the model (see Barceló, 2010, p. 46). The GEH index resulted <5 in over 90 percent of the cases; so, the model was accepted (Barceló, 2010). By way of an example, **Figure 5** shows the match between empirical and simulated data for left lane having one entering flow faced by two antagonist traffic flows at roundabout 2. The same figure shows the Equation (1) adapted to the entry mechanism as before specified. With reference to **Figure 5**, the model was accepted since the root mean squared normalized error resulted 0.05. In order to verify the adaptation of the Haging formula for estimating entry capacity at both roundabouts, the Student's *t*-test was performed with reference to pairs of simulated capacities for the lanes with similar entry mechanism (i.e., one entering flow faced by one antagonist traffic flow or two antagonist traffic flows). As introduced in section Introduction, estimation of capacity at turbo roundabouts should distinguish between two kinds of lane configurations at major and minor entries (i.e., two entry lanes and one circulation lane at major-road entries; two entry lanes and two circulation lanes at minor-road entries). Thus, depending on entry lane from which drivers are coming from, entering flows face one or two antagonist traffic streams. An analogous operational scheme was also assumed for the roundabout 1 since, in absence of raised curbs at entries, the lane preselection in relation to desired destination is not mandatory but recommendable. Note that the influence of possible shared lanes at entries has been excluded.

Seven different mechanisms of entry were recognized as follows:

**TABLE 2** | Results of two-tailed *t*-test for the entry maneuvers with similar entry mechanism.

Entry mechanism	$\mu_1$ (st. dev)	$\mu_2$ (st. dev)	t-value statistical	t-critical value $t_{0.05,14}$	t-critical $t_{0.01,14}$	( $p < 0.05$ )
1	801.500 (330.649)	776.625 (514.036)	0.1151	2.145	2.977	0.910
2	1022.250 (239.660)	999.625 (445.325)	0.1265	2.145	2.977	0.901
3	1022.250 (239.660)	1005.00 (436.052)	0.0980	2.145	2.977	0.923
4	1022.250 (239.660)	999.625 (445.323)	0.1265	2.145	2.977	0.9011
5	999.625 (445.325)	989.750 (534.501)	0.040	2.145	2.977	0.9685
6	1005.00 (436.052)	989.75 (534.501)	0.0625	2.145	2.977	0.9510
7	1005.00 (436.052)	999.625 (445.324)	0.0244	2.145	2.977	0.980

$\mu_1$  and  $\mu_2$  stand for the mean values of the samples of simulated capacities for the entry lanes having the same entry mechanism; *t*-value is the result of the two tailed *t*-test which was done to compare statistically the equality of the means  $\mu_1$  and  $\mu_2$  of samples of two populations where the two sample sizes are equal; 0.05 is the significance level, while *n* stands for the degree of freedom.

- 1) left lane entry at roundabout 1 and left lane entry at roundabout 2 (minor entries);
- 2) right lane entry at roundabout 1 and right lane entry at roundabout 2 (minor entries);
- 3) right lane entry at roundabout 1; left lane entry at roundabout 2 (major entries);
- 4) right lane entry at roundabout 1; right lane entry at roundabout 2 (major entries);
- 5) right lane entry at roundabout 2 (major entries); right lane entry at roundabout 2 (minor entries);
- 6) left lane entry at roundabout 2 (major entries); right lane entry at roundabout 2 (minor entries);
- 7) left lane entry at roundabout 2 (major entries); right lane entry at roundabout 2 (major entries).

For the purpose of testing whether there is homogeneity of the pairs of entry maneuvers included in each entry mechanism, it was proceeded as follows:

- for each entry maneuver, the capacity has been obtained in AIMSUN when the circulating flow on the outside lane of the circulatory roadway changed (kept constant  $Q_{ci}/Q_{ce} = 1$ ), by limiting the variation of the circulating flow in the outside lane  $Q_{ce}$  at the value of 1,400 veh/h;
- the mean values of the capacities obtained in this way were associated with each maneuver;
- a two-tailed *t*-test was conducted for the pairs of maneuvers included in the same entry mechanism.

**Table 2** shows the results of the *t*-test. They indicate that no significant difference was highlighted between the means of the two samples, but these deviations are due to the chance. The same table also shows the *p*-values under the significance level of 0.05. As a consequence, the results are consistent with a null hypothesis that is true (see e.g., Dahiru, 2008). The scattergram analysis has been also made to compare empirical vs. simulated capacities where a similar entry mechanism has been observed at roundabout approaches, i.e., one entering flow faced by one antagonist traffic flow or two antagonist traffic flows. This kind of comparison needs scattergram analysis to display the link between empirical capacity and simulated capacity plotted along with the 95% prediction interval (Barceló, 2010).

**Figure 6** shows the scatter plots to compare empirical versus simulated capacity for all the maneuvers characterized by a similar mechanism of entry:

- a) one entering flow from the left entry lane and two circulating flows in the outside and inside lanes of the circulatory roadway;
- b) one entering flow from the right entry lane and one circulating flow in the outside lane of the circulatory roadway.

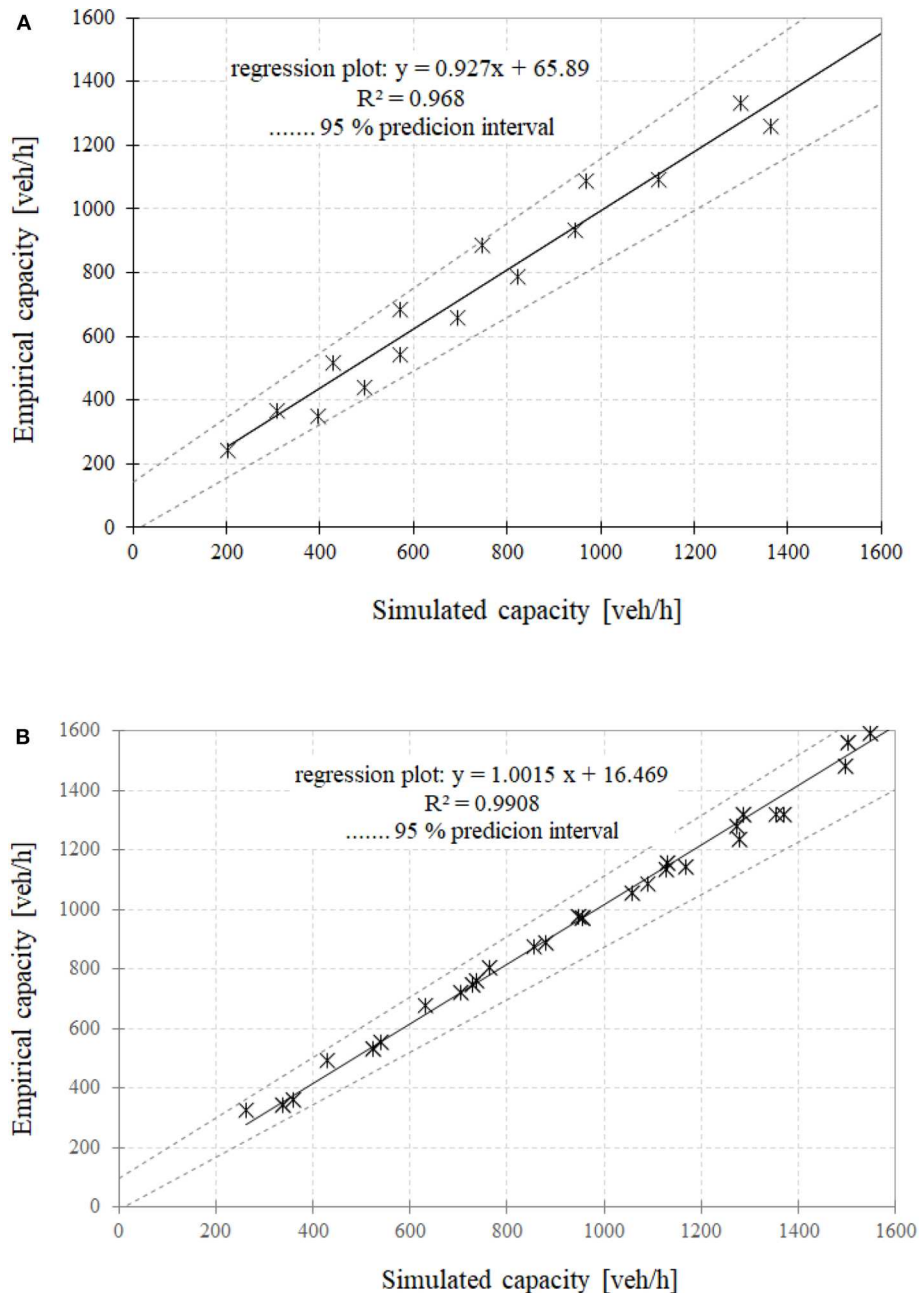
Each regression line of empirical vs. simulated capacities for maneuvers with analogous mechanism of entry is plotted along with 95% confidence band; the  $R^2$  values lead to the conclusion that the hypothesis above introduced could be accepted as close to reality.

### Estimation of Passenger Car Equivalent

In order to estimate PCEs, passenger cars and a single class of trucks were arranged in traffic mixes and then simulated. AIMSUN allowed to isolate this class of trucks in traffic. The following vehicular fleets were examined: 100% cars, 90% cars, and 10% single-unit trucks, 80% cars and 20% single-unit trucks. They shall be considered as representative of the conditions of traffic that were surveyed at the roundabout 1 under examination during the time periods of data collection. Simulation vehicle attributes of AIMSUN include single-unit trucks having a length ranging from a minimum value of 6.00 m to a maximum value of 10.00 m; a maximum desired speed of 85 km/h ranging from a minimum value of 70 km/h to a maximum value of 100 km/h; a maximum acceleration of 1 m/s<sup>2</sup> ranging from a minimum value of 0.6 m/s<sup>2</sup> to a maximum value of 1.8 m/s<sup>2</sup>; a maximum deceleration of 5 m/s<sup>2</sup> ranging from a minimum value of 4 m/s<sup>2</sup> to a maximum value of 6 m/s<sup>2</sup>.

PCEs were calculated using the equation:  $C_{car} = (1-p) \cdot C_p + p \cdot C_p \cdot E_t$ , where  $C_{car}$  is the capacity at entry lanes when the traffic demand is made of passenger cars, while  $C_p$  is the capacity at entry lanes when the traffic demand includes a percentage *p* of single-unit trucks;  $C_{car}$  is equivalent to  $(1-p) \cdot C_p$  passenger cars and  $p \cdot C_p$  multiplied by  $E_t$ , i.e., the PCE. Traffic matrices were assigned in AIMSUN from all entries considering all the turns, in order to simulate a circulating flow from zero

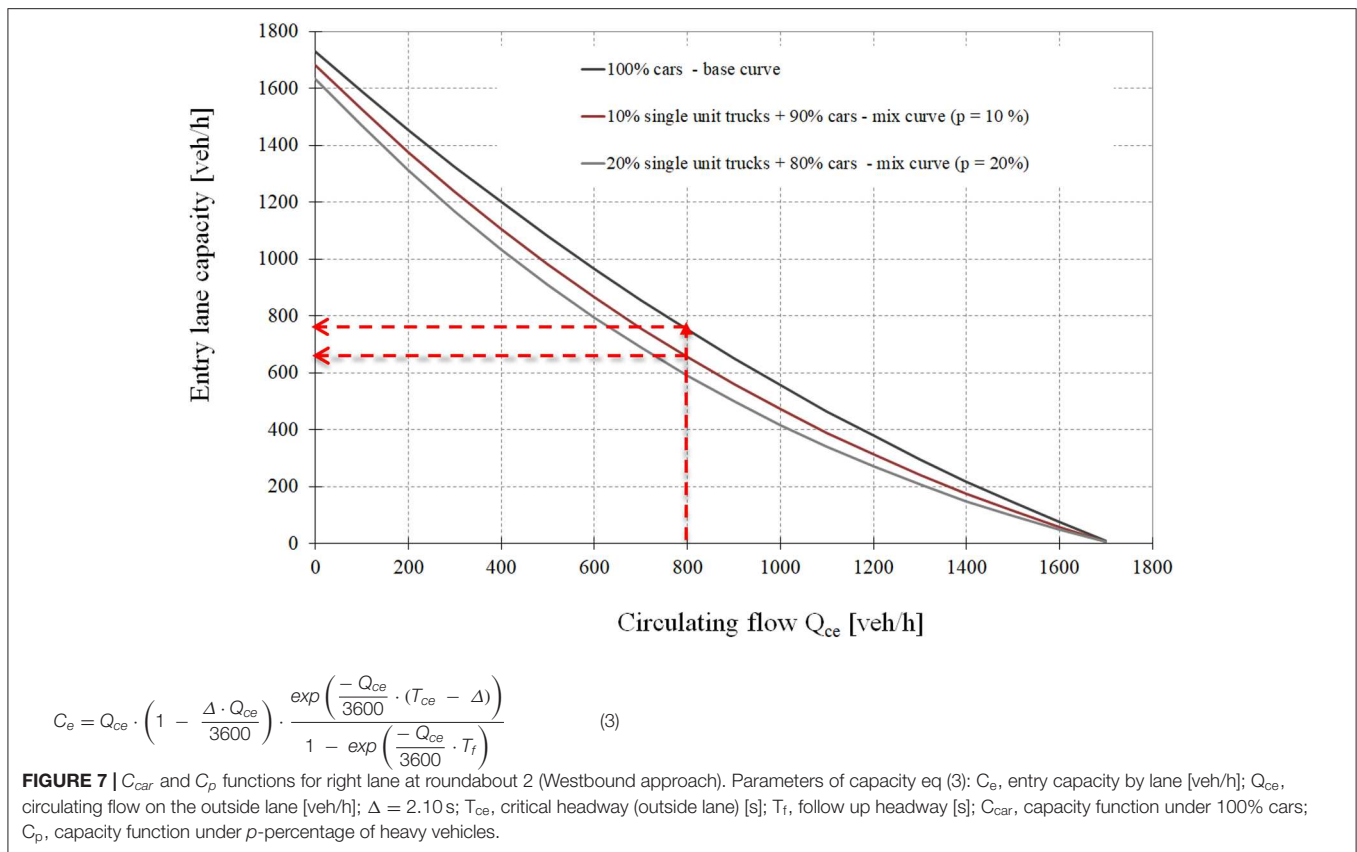




**FIGURE 6** | Empirical vs. simulated capacity for maneuvers with similar entry mechanism: **(A)** two entry lane and two circulating lanes; **(B)** one entry lane and one circulating lane.

onwards with 200 veh/h as working step. Saturation conditions were produced so that entry capacity by lane could be estimated from vehicles entering the subject approach; the maximum number of vehicles entering the roundabout gave the entry lane capacity. The percentage error resulted under 8% when collected and simulated traffic data were compared. In this study, only cars were simulated to compose the circulating flow during AIMSUN runs. In order to calculate the left lane entry capacity Eq (1) was used as a function of the circulating

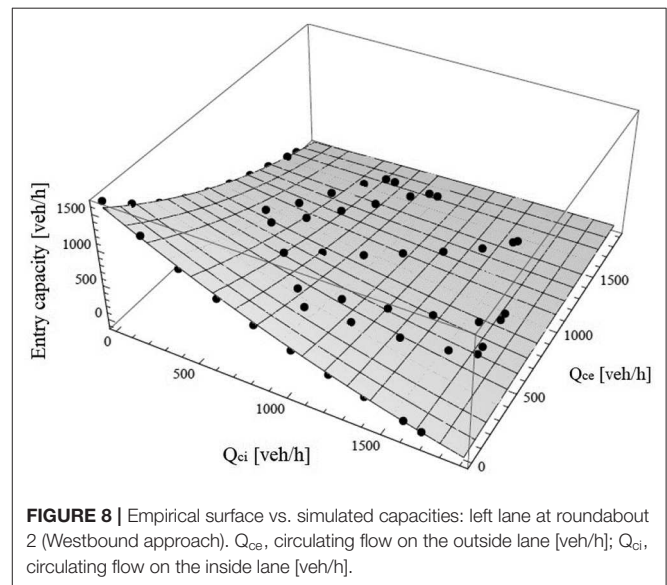
flow in the inside lane ( $Q_{ci}$ ) on the ring for roundabout 1 (or the turbo block for roundabout 2) and the circulating flow in the outside lane ( $Q_{ce}$ ) on the ring for roundabout 1 (or the turbo block for roundabout 2); the right entry lane capacity was calculated using Eq (1) as a function of the circulating traffic flow ( $Q_{ce}$ ) in the outside lane on the ring for roundabout 1 (or the turbo block for roundabout 2). The Hagring (1998) model in Eq (1) was then adopted as the functional form to perform regressions on simulation data, where the critical headways and



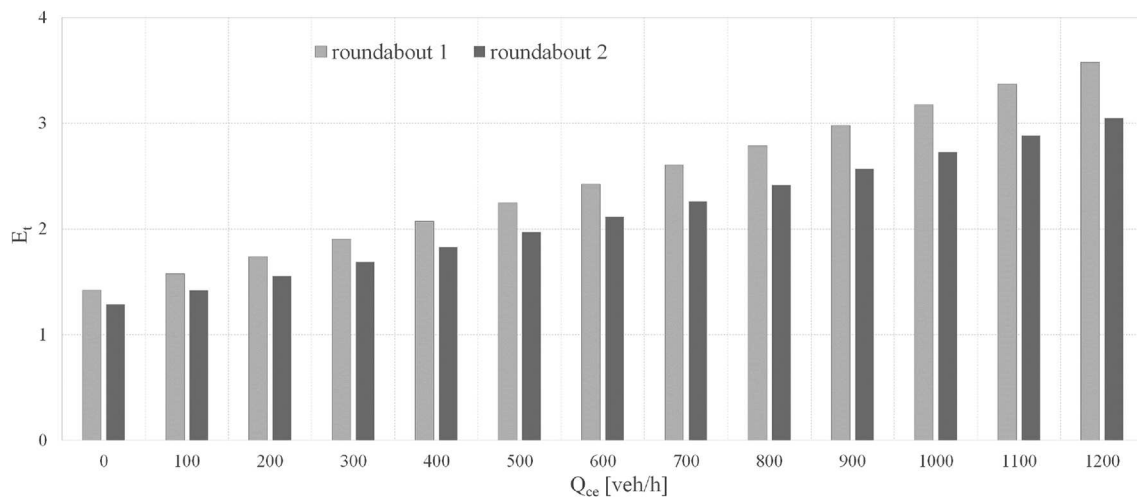
the follow-up headways were the parameters to be estimated by regression.

With reference to right lane at roundabout 2 (Westbound entry) **Figure 7** shows, by way of example, how to calculate PCEs beginning from the function  $C_{car}$  (100% cars) and the functions  $C_p$ , with a  $p$  of 10% (or 20%) for single-unit trucks, and 90% (or 80%) for cars. The same figure shows the equation (1) adapted to the entry mechanism having one entering flow faced by one antagonist traffic flow; regression parameters (and standard errors) of the capacity functions, i.e., the critical headway (outside lane)  $T_{ce}$  and the follow up headway  $T_f$ , were: (100% car):  $T_{ce} = 4.03$  (0.101) s;  $T_f = 2.10$  (0.025) s; (90% car–10% single-unit trucks):  $T_{ce} = 4.55$  (0.065) s,  $T_f = 2.14$  (0.016) s; (80% car–20% single-unit trucks):  $T_{ce} = 4.93$  (0.034) s,  $T_f = 2.21$  (0.010) s.

In the case of an entry mechanism of one entering flow faced by two antagonist traffic flows (i.e., the left entry lanes), the corresponding capacity function is graphed by a surface. In this regard, **Figure 8** shows the capacity surface for the left entry lane at roundabout 2 and simulated points when 90% of cars and 10% of single-unit trucks were arranged in the traffic mix. The surface of capacity value depends on traffic flows within each lane of the turbo block. Regression parameters (and standard errors) of the capacity equation (2) in **Figure 5**, i.e., the critical headway (outside lane)  $T_{ce}$ , the critical headway (inside lane)  $T_{ci}$  and the follow up headway  $T_f$ , were: (100% car):  $T_{ci} = 3.70$  (0.047) s;  $T_{ce} = 3.95$



(0.048) s,  $T_f = 2.19$  (0.014) s; (90% car–10% single-unit trucks)  $T_{ci} = 3.97$  (0.065) s;  $T_{ce} = 4.23$  (0.067) s,  $T_f = 2.30$  (0.020) s. In this graph one can see only points of simulated capacities greater than the values represented by the surface of capacity.



**FIGURE 9** | Estimation of mean PCEs for right entry lane at roundabout 1 and roundabout 2 (Westbound approach) for percentage of heavy vehicles between 10 and 20%.  $Q_{ce}$ , circulating flow in the outside lane [veh/h];  $E_i$ , equivalence factor.

## RESULTS

Once the capacity functions were developed for the vehicular fleets having different percentages of cars and heavy vehicles, PCEs were calculated based on the criterion as introduced before. Reference is made to the subject approach (i.e., Westbound entry for both roundabouts) where the same entry configuration characterized both roundabouts and similar operations occurred at the entry lanes.

Bearing in mind the selected subject approach, **Figure 9** shows the results of PCEs estimation for the right lanes at roundabout 1 and roundabout 2 when the interaction occurs between one traffic flow entering from the right lane and one traffic flow circulating on the outside lane of the circulatory roadway. In this case reference is made to the percentages  $p = 10\%$  and  $p = 20\%$  of single-unit trucks (with 90 and 80% cars, respectively). With reference to roundabout 1, the regression parameters (and standard errors) of the capacity functions (see equation 3 in **Figure 7**), i.e., the critical headway (outside lane)  $T_{ce}$  and the follow up headway  $T_f$ , were: (100% car):  $T_{ce} = 4.54$  (0.037) s;  $T_f = 2.67$  (0.010) s; (90% car–10% single-unit trucks)  $T_{ce} = 5.19$  (0.038) s,  $T_f = 2.77$  (0.010) s; (80% car–20% single-unit trucks):  $T_{ce} = 5.57$  (0.052) s,  $T_f = 2.90$  (0.016) s.

In turn, with reference to roundabout 2 the regression parameters (and standard errors) of the capacity functions (see equation 3 in **Figure 7**), i.e., the critical headway (outside lane)  $T_{ce}$  and follow up headway  $T_f$ , were: (100% car):  $T_{ce} = 4.02$  (0.101) s;  $T_f = 2.08$  (0.025) s; (90% car–10% single-unit trucks)  $T_{ce} = 4.54$  (0.065) s,  $T_f = 2.14$  (0.016) s; (80% car–20% single-unit trucks):  $T_{ce} = 4.92$  (0.034) s,  $T_f = 2.20$  (0.010) s.

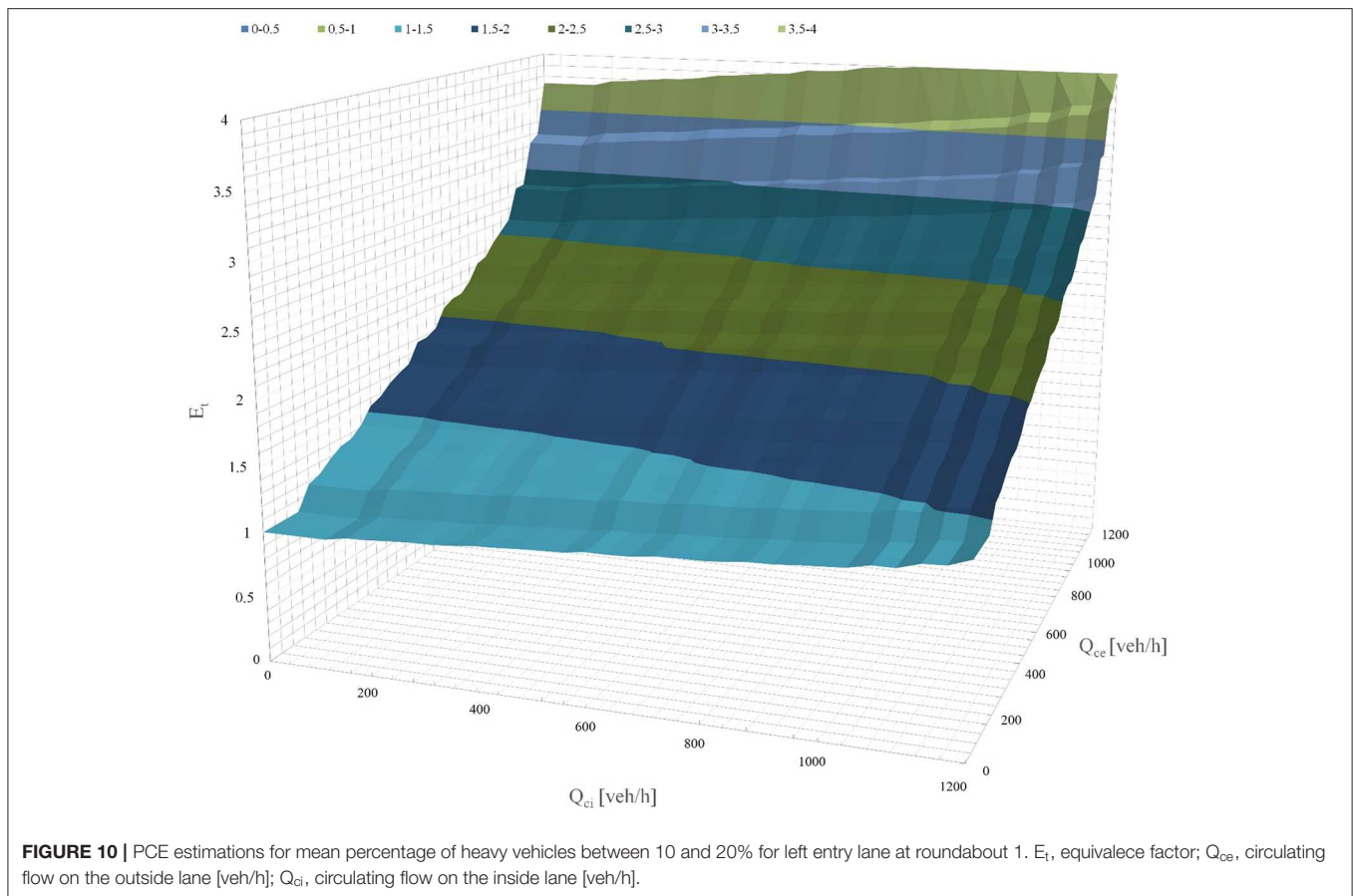
It is assumed from traffic surveys that these percentages are most common and likely to happen in real life. Beyond the percentages above specified, however, PCEs continue to rise considerably. Thus, simulations under  $p = 40\%$ –100% of single-unit trucks were neglected because not usual especially in urban

environment. In the case under examination (i.e., one entry traffic flow and one circulating traffic flow on the outside lane of the ring), there were minor differences in PCEs when  $p$  of 10% and 20% of single-unit trucks were simulated by AIMSUN; thus, the mean values of PCEs were plotted. **Figure 9** shows that the equivalence factors increase when the circulating flow on the outside lane ( $Q_{ce}$ ) of the ring increases from  $Q_{ce} = 0$  veh/h onwards.

PCEs for the right lane on entry at roundabout 1 and the right lane on entry at roundabout 2 above the value of circulating flow (outside lane) of  $Q_{ce} = 500$  veh/h overcome the value of 2 and reach higher values as the circulating flow increases. Thus, the use of a single constant value of PCE as proposed by literature (e.g., Highway Capacity Manual, 2010, 2016; Lee, 2015) could underestimate the impact of heavy vehicles as the circulating flow increases (from  $Q_{ce} = 500$  veh/h onwards), while below  $Q_{ce} = 500$  veh/h overestimation may occur (from  $Q_{ce} = 0$  veh/h up to about  $Q_{ce} = 500$  veh/h).

In turn, **Figures 10, 11** show the impact of single-unit trucks on traffic for the left lane on the subject approach at roundabout 1 and roundabout 2 (i.e., Westbound entry in **Figures 1, 2**). Regression parameters (and standard errors) of the capacity functions for roundabout 1, i.e., the critical headway (outside lane)  $T_{ce}$ , the critical headway (inside lane)  $T_{ci}$ ; the follow up headway  $T_f$ , were: (100% car):  $T_{ci} = 3.70$  (0.127) s;  $T_{ce} = 4.01$  (0.093) s,  $T_f = 2.85$  (0.10) s; (80% car–20% single-unit trucks)  $T_{ci} = 3.98$  (0.170) s;  $T_{ce} = 5.49$  (0.130) s,  $T_f = 2.85$  (0.10) s; (90% car–10% single-unit trucks)  $T_{ci} = 3.80$  (0.118) s;  $T_{ce} = 4.74$  (0.10) s,  $T_f = 2.85$  (0.10) s.

Then, regression parameters (and standard errors) of the capacity functions for roundabout 2, i.e., the critical headway (outside lane)  $T_{ce}$ , the critical headway (inside lane)  $T_{ci}$ , the follow up headway  $T_f$ , were: (100% car):  $T_{ci} = 3.70$  (0.046) s;  $T_{ce} = 3.94$  (0.048) s,  $T_f = 2.19$  (0.014) s; (80% car–20% single-unit trucks)  $T_{ci} = 4.20$  (0.097) s;  $T_{ce} = 4.49$  (0.101)



s,  $T_f = 2.40$  (0.031) s; (90% car–10% single-unit trucks)  $T_{ci} = 3.97$  (0.065) s;  $T_{ce} = 4.23$  (0.066) s,  $T_f = 2.30$  (0.02) s. Unlike the previous case of **Figure 9**, the equivalence factors are depending on both circulating flows, i.e., the circulating flow ( $Q_{ce}$ ) in the outside lane of the circulatory roadway and the circulating flow ( $Q_{ci}$ ) in the inside lane of the circulatory roadway. As a consequence, the results for the specified percentages of single-unit trucks are introduced through the corresponding surface plots, where, for a given constant value of the circulating flow  $Q_{ce}$  in the outside lane of the circulatory roadway, PCEs rise with the increases in the circulating flow  $Q_{ci}$  in the inside lane of the circulatory roadway; in turn, for a given constant value of  $Q_{ci}$ , PCEs rise with the increases in  $Q_{ce}$ . **Figure 10** shows the PCE estimation for the mean percentage of single-unit trucks between 10 and 20% for the left lane on entry at roundabout 1, while **Figure 11** shows the PCE estimation for the mean percentage of single-unit trucks above specified for the left lane on entry at roundabout 2. Specifically, with mean percentage of the specified heavy vehicles between 10 and 20% a maximum equivalent factor about four can be obtained for roundabout 1 (see **Figure 10**), while a maximum equivalent factor about three can be reached for roundabout 2 (see **Figure 11**). By way of example, the **Figure 12** shows PCE estimations for the left entry lane at roundabout 1 when the percentage  $p = 20\%$  of single-unit trucks is considered, while **Figure 13** shows the analogous case for roundabout 2.

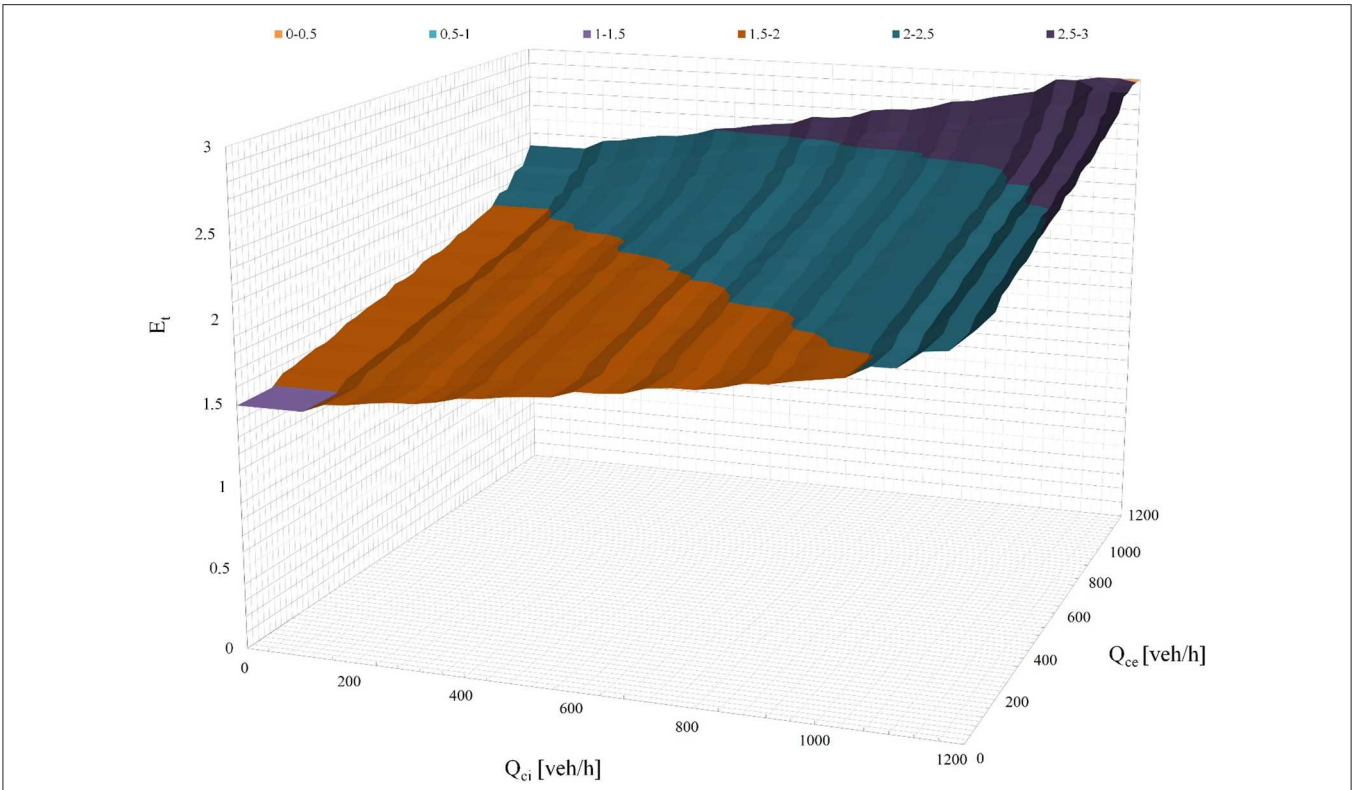
Thus, setting the equivalent factor equal to two when usual operational conditions occur (10 and 20% of trucks in traffic demand), the impact of heavy vehicles on traffic operation may be underestimated.

## DISCUSSION

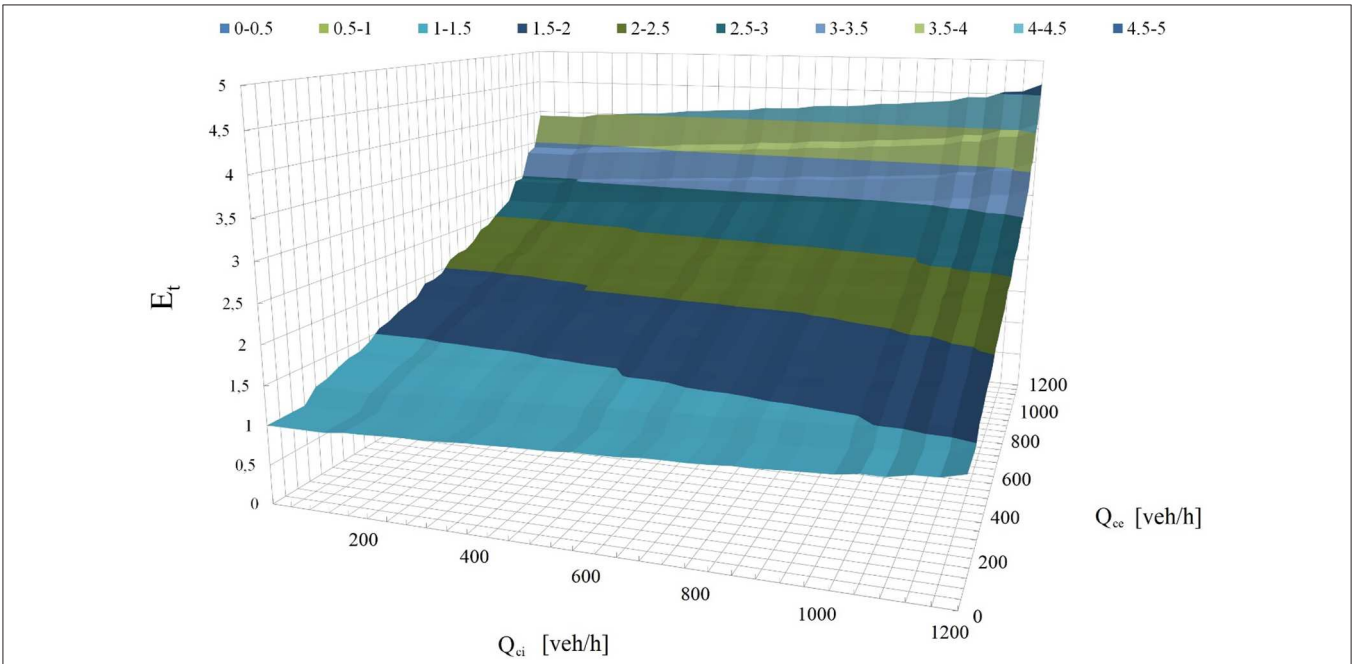
Results from **Figures 9–13** show that the equivalent factors vary depending on traffic conditions and continue to rise when the circulating flow increases. Similar results were also found when PCEs were estimated by Lee (2015) which based his study on field data collected from saturated conditions in the entering flows at Canadian roundabouts.

It should be noted that heavy vehicles here considered (i.e., single-unit trucks) are only one class of heavy vehicles used to estimate the PCE values as the HCM propose; while it might appear to be a limit, this choice means that only their impact on traffic was highlighted by using microsimulation. This class of heavy vehicles also had the highest percentage during the observation time periods.

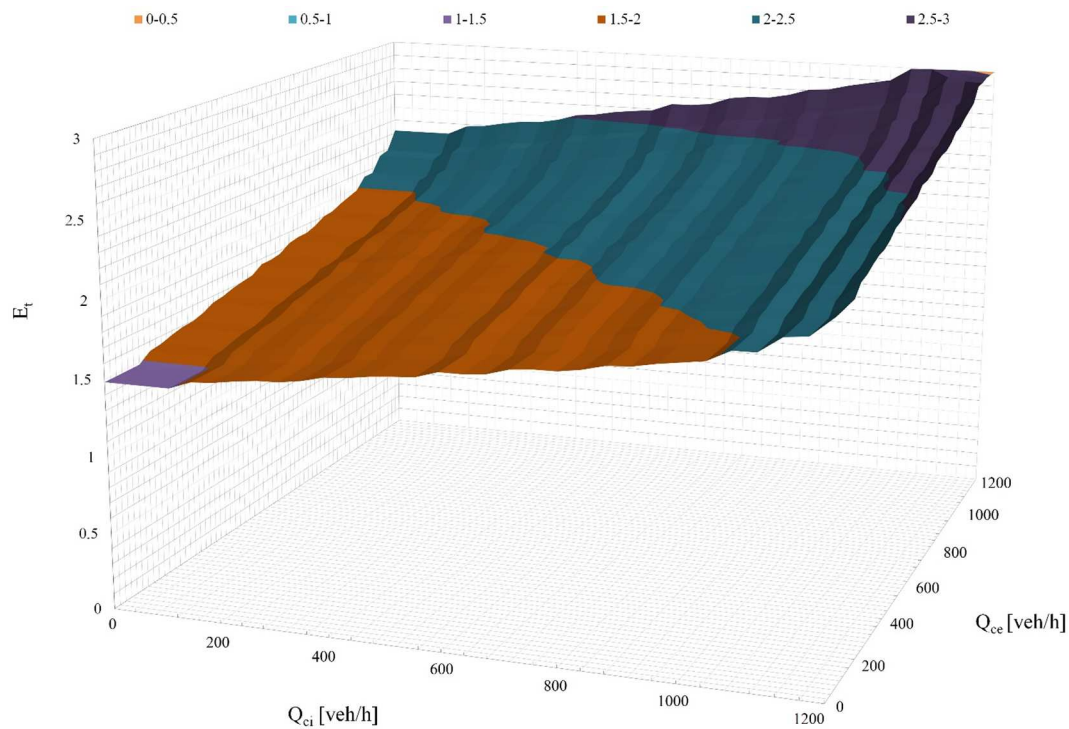
However, literature on this topic provides values of equivalent factors estimated for trucks lower than the default value of PCE as proposed by the Highway Capacity Manual (2010) and Highway Capacity Manual (2016); see e.g., Lee (2015) and Macioszek (2019). In this regard, Lee (2015) recommended that light trucks



**FIGURE 11 |** PCE estimations for mean percentage of heavy vehicles between 10 and 20% for left entry lane at roundabout 2 (minor entries).  $E_t$ , equivalent factor;  $Q_{ce}$ , circulating flow on the outside lane [veh/h];  $Q_{ci}$ , circulating flow on the inside lane [veh/h].



**FIGURE 12 |** PCE estimations for percentage of heavy vehicles of 20% for left lane at roundabout 1.  $E_t$ , equivalent factor;  $Q_{ce}$ , circulating flow on the outside lane [veh/h];  $Q_{ci}$ , circulating flow on the inside lane [veh/h].



**FIGURE 13** | PCE estimations for percentage of heavy vehicles of 20% for left lane at roundabout 2 (minor entries).  $E_t$ , equivalent factor;  $Q_{ce}$ , circulating flow on the outside lane [veh/h];  $Q_{ci}$ , circulating flow on the inside lane [veh/h].

were weighted in a different way by heavy trucks in the entering flows at roundabouts and concluded that the difference identified in delay and yielding were considered in capacity prediction.

It should be also noted that to compare equivalent factors between roundabout 1 and roundabout 2, reference was made to a subject approach where the same kind of lane configuration at the entry could be noted (i.e., Westbound approaches with two entering lanes and two circulating lane at both roundabouts) and similar operations occurred.

For the purpose of testing whether there is no significant difference between the PCEs in **Figure 9**, the mean values of PCEs were calculated for each maneuver and then associated with each of them; a two-tailed  $t$ -test was then conducted for the pair of right turning maneuvers related to the same subject approach of both roundabouts where an analogous geometric configuration is observed. Since  $t$ -value of 1.265 resulted less than  $t$ -critical ( $t_{\alpha,n}$ ) of 2.064 (at significant level  $\alpha$  of 0.05 and degree of freedom  $n$  of 24), and  $p$ -value of 0.217, the null hypothesis was accepted under the significance level of 0.05 (see e.g., Dahiru, 2008). Similarly, the  $F$ -test was performed to check possible difference in variance in the PCEs estimated for the right lanes at roundabout 1 and roundabout 2 (see **Figure 9**). The test gave a  $F$ -value of 1.601 that is less than the critical value ( $F_{0.05,1,24}^1$ ) of 4.26. Thus, the result did not authorize to deny the null hypothesis at a significance level of 0.05 ( $p$ -value of 0.495).

With reference to the left entry lanes at roundabout 1 and roundabout 2 (see **Figures 1, 2**) where an analogous geometric entry configuration at both roundabouts can be observed, the

results about PCE estimations show the increasing trend of the equivalence factors as the circulating flows on the inside and outside lanes increase (see **Figures 10–13**). With reference to the PCE surfaces, for both roundabouts the GEH index was calculated for the PCE values obtained keeping one value of circulating flow constant with increasing the other circulating flow. Given that the deviation between the pairs of PCE values resulted smaller than 5 in more than 85% of cases, the results for left entry lanes could be considered consistent (Barceló, 2010). Thus, a constant value of the equivalence factors, if used in traffic analysis, could give misleading results, especially when the calculation of PCEs should be differentiated by lane.

It should be noted that the mixed fleets here studied were consistent with data observed in the field during traffic surveys. However, microsimulation allowed to generate traffic scenarios less easily observable especially in urban areas. It has proved to be a useful tool for the development of the considerations related to the case study presented in this paper.

## CONCLUSIONS

The paper addresses issues related to Passenger Car Equivalents (PCEs) for heavy vehicles at roundabouts. Heavy vehicles have a significant impact on operational performances of traffic, particularly where the curvilinear elements of geometric design of a road unit may influence the vehicular trajectories and the swept envelope of heavy vehicles. The aim of the study is to present the methodological approach, which is based on

<sup>1</sup>0.05 is the significance level, and  $n = 1$  and  $m = 24$  are degrees of freedom.

traffic microsimulation, for estimating Passenger Car Equivalents (PCEs) for heavy vehicles at two-lane and turbo roundabouts.

Although the evaluation of the convenience of one roundabout scheme on the other scheme is outside the objectives of the paper, this article aims to contribute to the determination of PCEs at roundabouts taking into account the role of PCEs in traffic analysis. More specifically the case study shows how to determine the PCEs starting from a real case, when changes must be made to a scheme in operation in the road network. Microsimulation confirms to be a useful tool, although it requires a special effort for calibration.

Considering the conversion of the existing two-lane roundabout into the configuration of a basic turbo roundabout with comparable size, empirical capacity functions by lane were derived as target values to which compare the simulated capacities. Behavioral headways from surveys of existing roundabouts and summarized by meta-analysis as literature refers, were used as input to obtain target values of capacity at each entry lane, while lane-based capacity values were simulated in AIMSUN varying the traffic composition.

Based on previous studies, a criterion of equivalence is presented and used to estimate the PCEs for heavy vehicles. AIMSUN allowed to simulate traffic conditions where the percentage of a single class of heavy vehicles varied; thus, the capacity functions by lane were developed to determine how PCEs changed with the percentage of heavy vehicles and the circulating flows (see **Figures 9–13**). Comparison was made between PCEs estimated for each entry lane characterized by a similar mechanism of entry.

The results show the feasibility and soundness of the methodological approach which used traffic microsimulation to estimate PCEs for heavy vehicles at roundabouts. The results also highlight that the use of appropriate PCEs should be considered in view of the conversion of the existing layout of two-lane roundabouts into the configuration of basic turbo roundabouts with comparable size given their role in operational performance assessment. It should be noted that traffic composition was selected based on what was observed in the field. Note that the choice made in this study has allowed us to deduce the impact of single-unit trucks on operating conditions, but this does not exclude that further mixed fleets should be arranged with heavy vehicles having sizes different from those examined here in future studies. The readers are advised that heavy vehicles used here are a part of trucks simulated to estimate the PCE values as proposed in subsequent editions of the Highway Capacity Manual. However, these results are consistent with the study made by Lee (2015), namely that values of PCEs depend on traffic conditions; thus, PCE values different from the value proposed by the Highway Capacity Manual (2010) and Highway Capacity Manual (2016) for roundabouts should be recommended to treat in an appropriate way each road unit that, from time to time, should be assessed. Despite assumptions may have affected the results, they show the dependence of PCEs for heavy vehicles on the amount of circulating traffic: when circulating flows increase, a higher PCE value is expected than the value of 2 that the Highway Capacity Manual proposes for roundabouts. Given that each specific case study should be studied with reference to its own traffic distribution, the methodological considerations

and comparisons performed in this paper can contribute: to choose a two-lane roundabout or a turbo roundabout; to assess the effects on traffic due to the conversion of an existing two-lane roundabout to a new turbo roundabout with similar space footprint; to estimate the life-cycle costs of intersection design alternatives before the implementation and installation in the real world. Intersections are key components of the road network and their design can impact the maintenance and other costs that accrue after their construction. Among the other things, a life-cycle cost analysis allows to include factors that can be monetized, but there are often non-monetary community goals that should be considered in the design of an intersection or roundabout. If it is true that this kind of evaluation is usually integrated in a life-cycle cost analysis of design alternatives, it is also true that only recently has been extended to the intersection design; see the life-cycle cost estimation tool proposed by National Academies of Sciences Engineering Medicine (2016). In this view, the methodological approach presented in this paper through a case study and its application to more complex scheme of intersections and roundabouts can contribute to address further problems that transportation engineers - which usually apply microsimulation for real world case studies in the professional context - have to solve. Future developments also include that the criterion should be specified to consider more classes of heavy vehicles and explore further mixed traffic conditions. At the last, the analysis should also be extended to other geometrical configurations in order to evaluate the impact of geometric variables (such as the width of the circulating lanes, entry and exit lanes, etc.) on the determination of PCEs and the consequent operational level-of-service.

## DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

## AUTHOR CONTRIBUTIONS

AG, TG, and EM designed the organization of the paper and criteria of bibliographic research. AF made the bibliographic research and prepared figures. AG and EM provided oversight for the capacity analysis methodology. AG and TG wrote the draft of the paper. All of the authors read the paper, all authors approved the final paper.

## ACKNOWLEDGMENTS

Special thanks go to Engineers F. Galatioto (Transport Systems Catapult, UK), Sergio Marino, Maria Luisa Tumminello and Antonino Sferlazza (University of Palermo, Italy) for their contributions and efforts as co-authors in past research activities consistent with this specific topic as documented by the bibliographic references. Special thanks go to Dodi (2019) for contribution to geometric design of turbo roundabouts given during the writing of her Bachelor's Thesis in Urbanistic and City Science, University of Palermo, Italy.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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