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The Passenger Car Equivalent Factors for Heavy Vehicles on Turbo Roundabouts

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The presence of heavy and slower vehicles within the traffic stream significantly reduces traffic capacity. This reduction increases with the higher participation of heavy vehicles in the stream, which, compared to passenger cars, move at a lower speed. Furthermore, they occupy more space on the road, are characterized by a longer reaction time to the road traffic situations, and put greater pressure on the surface structure, etc. In order to conduct analyses related to determination of the conditions in the traffic stream, the traffic stream mixed in terms of composition is converted from real vehicles into passenger car equivalents. For this purpose, the passenger car equivalent factors *(Ei)* appropriate for a given group of vehicles are used. The paper presents the results of a study aimed to determine the numerical values of passenger car equivalent factors for heavy vehicles (trucks, buses, trucks with trailers, articulated buses) on turbo roundabouts. The research was carried out on turbo roundabouts located in Poland.

Keywords: turbo roundabouts, passenger car equivalent factor, heavy vehicles, homogeneous traffic stream, road traffic engineering

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INTRODUCTION

The capacity of various elements of the transport system (e.g., intersections without traffic lights, roundabouts) is most often expressed as passenger car equivalents per hour [Pce/h]. In general, capacity is defined as the maximum number of vehicles which can cross a given (conventional) road section or an intersection entry per unit of time. The presence of heavy and slower vehicles within the traffic stream significantly reduces traffic capacity. This reduction increases with the higher participation of heavy vehicles in the stream, which, compared to passenger cars, move at a lower speed. Furthermore, they occupy more space on the road, are characterized by a longer reaction time to the road traffic situations, and put greater pressure on the surface structure, etc. In order to conduct analyses related to determination of the conditions in the traffic stream, the traffic stream mixed in terms of composition is converted from real vehicles into passenger car equivalents. For this purpose, the passenger car equivalent factors *(Ei)* related to a given group of vehicles are used.

Passenger car equivalent factor (E_i) for a given group of vehicles denotes the number of passenger cars (so-called passenger car equivalents) which would have the same effect on the traffic stream conditions as the vehicles from the analyzed group.

In detailed analyses of intersection capacity and road traffic conditions, failure to take into account the presence of vehicles with large diversity in terms of design and operation modes in the traffic stream can lead to misrepresentation of real traffic conditions. One of the most popular methods used in practice to solve this problem is to use passenger car equivalent factors to convert vehicles from different groups of vehicles into passenger car equivalents. The values of passenger car equivalent factors are estimated using dedicated theoretical calculation models. Based on the available scientific literature, it can be concluded that these models constitute a quite large group and are based on different assumptions and different calculation algorithms.

Many scientific studies both in Poland and abroad have been devoted to the problems related to the conversion of real vehicles into passenger car equivalents and taking into account the impact of heavy vehicles on the traffic stream conditions and pavement design. These studies aimed to determine numerical values of passenger car equivalent factors for intersections without traffic lights (e.g., Mohan and Chandra, 2018a,b), intersections with traffic lights (e.g., Asaithambi et al., 2017; Mohan and Chandra, 2017; Biswas et al., 2018), roundabouts (e.g., Giuffre et al., 2017, 2018; Kang and Nakamura, 2017; Sugiarto et al., 2018), and highways (e.g., Srikanth and Mehar, 2017, 2018; Zhou et al., 2018).

The paper presents the results of a study aimed to determine the numerical values of passenger car equivalent factors for heavy vehicles (trucks, buses, trucks with trailers, articulated buses) on turbo roundabouts. The research was carried out on turbo roundabouts located in Poland. The paper is a continuation of the author's research on the effect of different types of vehicles in the traffic stream on road traffic conditions (e.g., traffic capacity, level of service, visibility in the area of intersections, vehicle delays, traffic smoothness) (Macioszek, 2009, 2010a,b,c, 2012, 2018, 2019; Szczuraszek and Macioszek, 2010).

OVERVIEW OF PREVIOUS STUDIES RELATED TO PASSENGER CAR EQUIVALENT FACTORS ON ROUNDABOUTS

Due to the fact that turbo roundabouts are a relatively new type of roundabouts, few studies in the scientific literature have focused so far on determination of passenger car equivalents factors for turbo roundabouts. These were mainly studies written by researchers from Italy (Giuffre et al., 2016a,b). The comparison of the results of their studies is presented in **Table 1**.

However, some studies have also determined passenger car equivalent factors dedicated to other types of roundabouts. Many of these studies have shown that passenger car equivalents for roundabouts depend on: type of road (rural, urban), vehicle power, dimensions, vehicle speed, road geometry (including curves, gradients, access controls), roundabout location (urban areas, suburban areas, rural areas), acceleration and braking characteristics of the vehicles, traffic volume values, and many others factors. Therefore, passenger car equivalents are considered essential in carrying out most of road traffic analyses since they incorporate the impact of heavy vehicles on road traffic operations, thus making the performance analysis more accurate.

Based on the results of previous studies in this field, the HCM 2010 manual (Transportation Research Board, 2010) proposes the value of PCEs for heavy vehicles to equal two for all types of roundabouts for every road traffic conditions. HCM does not stipulate values of PCEs for heavy-duty vehicles moving on turbo roundabouts.

Furthermore, Lee (2015) presented results of a study of PCEs for heavy vehicles at roundabouts in Vermont, Ontario, Canada and Wisconsin. The results showed that the PCEs for heavy and light trucks are 1.5–2.5 and 1.0–1.5, respectively. In particular, the PCE for light trucks was lower than a default value of 2.0. The results also showed that in general, the model predicted the capacity more accurately when the critical gap and follow-up time were adjusted by different weights instead of the same weight (i.e., the default value of the PCEs). A significant effect of passenger car equivalents values adopted in the analyses on traffic capacity has been also indicated by Yong-Jae et al. (2010) and List et al. (2015). Lee, in another study (Lee, 2014), determined passenger car equivalents for heavy vehicles based on the research conducted at roundabouts located in Brattleboro, Vermont. The PCE was estimated such that the variation in the capacity is minimized for a given circulating flow rate to determine the observed capacity. The study also proposed two PCEs which specifically concern the difference in the critical gap and follow-up gap between passenger cars and heavy trucks. The results demonstrated that the PCEs for heavy trucks are 3.5–6.0 in 540–840 pcu/h of the circulating flow rate, which is significantly different from a default value of 2.0 specified in HCM 2010.

Kang and Nakamura (2016) conducted research on the impact of heavy vehicles on traffic capacity and the analysis of changes in PCEs values depending on the congestion at the entries and the circular roadways in roundabouts in Japan. They estimated entry capacity considering characteristics of heavy vehicle behavior in Japan by microscopic simulation. Using the simulation, the researchers found that roundabout entry capacity is reduced when heavy vehicle percentage increases. Furthermore, estimated PCEs results showed that the PCE value of entry flow increase when circulating flow increases and decreases when circulating flow is at a high level. They also concluded that PCEs of entry flow is lower than that of circulating flow which has priority at roundabouts. In another paper by Kang and Nakamura (2017) used field data from a single-lane roundabout in Japan to conduct an empirical analysis on headway parameters for examining the characteristics of heavy vehicles. It was confirmed that the headways which are formed by heavy vehicles are usually greater than those formed by passenger cars only.

Sonu et al. (2016) and Sugiarto et al. (2018) carried out an estimate of passenger car equivalents at roundabouts for different vehicle categories based on the concept of time occupancy. Giuffre et al. (2017) presented the results of estimation of passenger car equivalents for single-lane roundabouts using a microsimulation-based procedure (AIMSUN). Kollar (2014) also presented the results of estimation of passenger car equivalents using a microsimulation based procedure (VISSIM).

TABLE 1 | Passenger car equivalent factors for turbo roundabouts—research results.

Author (-s)	Research subject	Conclusions
Giuffre et al., 2016a	Estimation of passenger car equivalents (E_i) for heavy vehicles driving turbo-roundabouts using microsimulation	Based on the output of multiple runs of the different mixed fleet scenarios simulated in Aimsun, capacity functions for each lane from the turbo-roundabout entries were developed and the E_i for heavy vehicles driving turbo-roundabouts were calculated by comparing a fleet of passenger cars only with a mixed fleet characterized each time by different percentages of heavy vehicles
Giuffre et al., 2016b	Measuring the effect of heavy vehicles on operational conditions of a turbo-roundabout using microsimulation (AIMSUN)	In usual operational conditions (i.e., an entry demand with 20 and 10% of heavy vehicles), the values of E_i for heavy vehicles were below 2.0 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_i 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_i 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_i 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_i of 2, as HCM 2010 suggests for roundabouts.

Among the studies that have examined values of PCEs indicating the presence of relationships between the psychotechnical parameters of drivers of various types of vehicles (i.e., critical gap and follow-up time) and the geometry of roundabouts are the papers published by Dahl (2011) and Dahl and Lee (2012), which examined the effect of heavy vehicles (trucks) on the entry capacity of roundabouts. Gap-acceptance parameters were estimated for passenger cars and trucks separately. It was found that the critical gap and follow-up time were longer for trucks than for passenger cars and that the follow-up times for truck-involved vehicle-following cases were associated with the central island diameter and the entry angle. This study underscored the importance of considering the effect of trucks on traffic capacity for the roundabouts with a high truck volume. In this group of studies, noteworthy is the study by Lee and Khan (2013), who determined the PCEs for trucks based on measurements gap acceptance parameters for trucks. Then, the researchers estimated roundabout capacity using new values of gap acceptance parameters for trucks. The results obtained allowed for finding a better reflection of the capacity at the entries in the calculation of new values of gap acceptance parameters for trucks.

Furthermore, Tanyel et al. (2013) stated that heavy vehicles have a strong effect on roundabout operations. Their research results demonstrated that different passenger car equivalent values should be used in the analysis separately for minor and major flows. They concluded that using the same PCE value for both kinds of flows may lead engineers to overdesign or make inadequate designs. Furthermore, it was demonstrated that the effect of heavy vehicles on the major flow was greater when the mean speed of the major flow was low.

THEORETICAL MODELS USED TO CALCULATE PASSENGER CAR EQUIVALENTS FACTORS

There is a considerable number of studies both in Poland and abroad devoted to the problems of passenger car equivalent factors and the effect of heavy vehicles on the traffic streams. The theoretical models for the passenger car equivalent factors calculation most commonly used in practice are presented in **Table 2**. The models presented in **Table 2** can be divided into four groups, based on the following criteria:

- comparison of two traffic streams (passenger and mixed traffic streams) under similar road traffic conditions (models 1–6),
- comparison of densities of two traffic streams (passenger and mixed traffic streams) under similar road traffic conditions (model 7),
- comparison of average time differences or distances between the vehicles in two homogeneous streams (passenger car stream and analyzed vehicle type stream) under similar traffic conditions (models 8 and 9),
- comparison of some characteristics related to overtaking in the traffic stream for two vehicles: passenger car and vehicle from the analyzed group (models 10 and 11).

In practice, models 2 and 10 are most frequently used to calculate the passenger car equivalent factors (E_i) for the road segments, whereas models 8 and 9 (developed by F.V. Webster and B.D. Greenshields) are often used to calculate the intersections capacity. It can be noticed that the model 8 is a specific case of the models 1 and 2, where the vehicles from the analyzed category account for 100% of the traffic stream composition.

According to the Guidelines for intersections without traffic lights, intersections with traffic lights and roundabouts capacity calculation used in Poland (Tracz et al., 2004b), the passenger car equivalent factors values depend on intersection types and types of vehicles converted to passenger cars equivalents (**Table 3**).

The coefficient of vehicle conversion into passenger cars has the following form:

$$f_c = \frac{1}{1 + u_{SC}\left(E_{SC} - 1\right) + u_{SCP}\left(E_{SCP} - 1\right) + u_{M/R}\left(E_{M/R} - 1\right)} \quad [-] \tag{1}$$

where:

TABLE 2 | Theoretical models used for passenger car equivalent factors calculation.

Model No	Theoretical model basis	Assumed measures for traffic conditions
I	The comparison of traffic volumes in traffic stream consist only from passenger cars and in traffic stream consist only with the same group of vehicles (other than passenger cars) at the same level of traffic conditions	Average travel time for the vehicles in the traffic stream
II		Average vehicles travel speed or momentary speed
III		85% quintile of the vehicles speed in the traffic stream
IV		Maximum traffic volume (capacity)
V		Total travel time of all vehicles in the traffic stream
VI		Average speed of passenger cars
VII	The comparison of density of traffic stream consist only from passenger cars and the density of traffic stream consist only with the same group of vehicles (other than passenger cars) at the same level of traffic conditions	Maximum traffic volume or maximum density
VIII	The comparison of average time gap or distances between the vehicles in two homogeneous traffic streams (passenger cars stream and a stream of vehicles from the analyzed group of vehicles) at the same level of traffic conditions	Average travel time or average vehicles travel speed in traffic flow
IX		Maximum traffic volume—capacity (Webster & Greenshields model)
X	The comparison of measures of traffic conditions for the two traffic streams: passenger cars stream and a stream of vehicles from the analyzed group of vehicles	Average number of vehicles overtakings
XI		The average delay caused vehicles overtaking in the traffic stream

Own based on Branston and Zuylen (1978); Cunagin and Messer (1982), Matthew (1982); Elefteriadou et al. (1997); Szczuraszek (1999); Webster and Elefteriadou (1999); Benekhoal and Zhao (2000); Szczuraszek et al. (2007), and Macioszek (2009, 2010a,b,c).

TABLE 3 | Passenger car equivalent factors values according to Polish Quidelines.

Vehicle type	Denotation	Intersection type		
		Intersections without traffic lights	Roundabouts	Intersections with traffic lights
Passenger cars and passenger vans	E_{SOD}	1.0	1.0	1.0
Trucks and buses	E_{SC}	1.7	1.7	2.0
Trucks with trailers, articulated buses	E_{SCP}	2.5	2.5	2.0
Motor bikes and bicycles	$E_{M/R}$	0.5	0.5	0.3

Own research base on Chodur (2004) and Tracz et al. (2004a,b).

f_c - coefficient of conversion of real vehicles into passenger cars [–],
u_{sc}, u_{scp}, $u_{m/r}$ - shares of particular types of vehicles in the traffic stream [–],
sc - trucks and buses,
scp - trucks with trailers, articulated buses,
m/r - motor bikes and bicycles,
E_{SC}, E_{SCP}, $E_{M/R}$ – passenger car equivalent factors according to the **Table 3**.

If a simplified road traffic structure is considered, only two groups of vehicles occur in the traffic stream. These are passenger cars and heavy vehicles (trucks with and without trailers, buses and articulated buses). In this case, Polish Guidelines recommended the use of the following values of passenger car equivalent factors (Chodur, 2004; Tracz et al., 2004b): $E_o = 1.0$ [–] and $E_{SC} = 2.0$ [–]. The coefficient of vehicle conversion into passenger cars has the following form (Chodur, 2004; Tracz et al., 2004b):

$$f_c = \frac{1}{1 + u_{SC}\left(E_{SC} - 1\right)} \quad [-] \tag{2}$$

where:

f_c - coefficient of conversion of real vehicles into passenger cars [–],
u_{sc} - share of heavy vehicles (trucks with and without trailers, buses and articulated buses) in the traffic stream [–],
E_{SC} - passenger car equivalent factor ($E_c = 2.0$ [–]).

The vehicle conversion coefficient value calculated according to the formula 1 or 2 is used to convert the traffic volume consisting only of passenger cars to the traffic volume consisting of different types of vehicles. When real vehicles are converted into passenger cars (change from veh/h to pcu/h), the real vehicles should be multiplied by $1/f_c$. When traffic volume consisting of only passenger cars is converted to real vehicles (change from pcu/h to veh/h), the passenger cars should be multiplied by f_c.

FIELD RESEARCH AND METHODOLOGY OF EMPIRICAL RESEARCH

The research on turbo roundabouts have been performed in recent years on 23 turbo roundabouts located in Poland in built-up areas. All turbo roundabouts had four entries and are characterized by different geometries. On each turbo roundabout, the measurements were made for a roundabout entry with two traffic lanes and a circular roadway with two traffic lanes, with one starting at the entry level (**Figure 1**).

During the empirical research, the following road traffic stream characteristics were measured at turbo roundabouts:

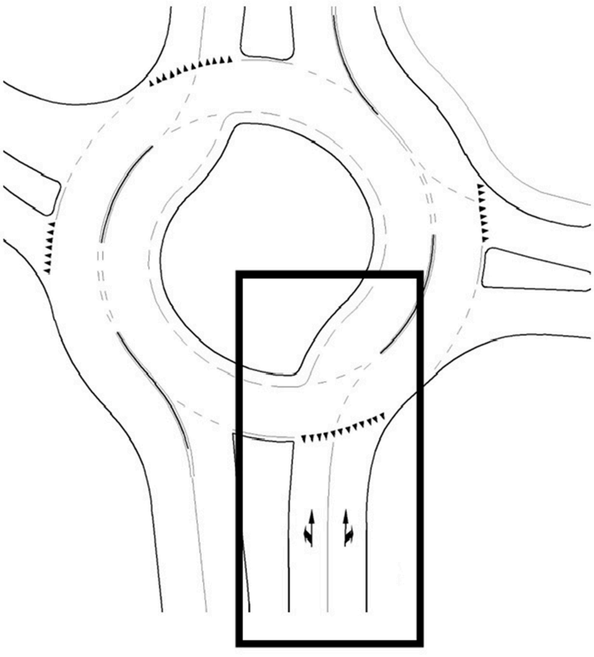

FIGURE 1 | Traffic control scheme for turbo roundabout entry at which measurements were made.

- follow-up times between the vehicles entering the circular roadway from the entry lanes,
- gaps accepted and rejected by individual vehicle drivers from entry lanes, which then formed the basis for the designation of the critical gaps values for the vehicle drivers from entry lanes,
- time gaps between the vehicles moving on the circular roadways.

Follow-up time (t_f) expresses the gap between the first vehicle from entry lane passing the edge of the roundabout and passing the next vehicle using the same gap between vehicles moving on the roundabout circular roadway, assuming that they enter the roundabout circular roadway from the queue at the entry lane. If a gap between vehicles on roundabout circular roadway allows further vehicles to enter the roadway, they pass the edge of the roundabout at t_f one after another. During the empirical research, the time of passing the roundabout edge by subsequent vehicles entering the circular roadway was recorded (separately for the left and right entry lane). Based on these temporal data, the follow-up times for successive vehicles from the queue at the entry lane were calculated from the equation:

$$t_{f\ (i)-(i+1)} = t_{w(i+1)} - t_{w(i)[s]} \tag{3}$$

where:

$t_{w(i)}$, $t_{w(i+1)}$ - times of vehicle passing the roundabout edge for i and $i+1$ vehicles [s],

$t_{f\ (i)-(i+1)}$ - follow-up time between i and $i+1$ vehicles (referred further in the paper as t_f) [s].

The example of the camera location for the measurement of the follow-up times of vehicle drivers at turbo roundabout entry lanes is presented in **Figure 2A**.

Furthermore, the critical gap (t_g) is the gap value between vehicles moving on roundabout circular roadway, at which each gap equal or greater will be used by the average (from the statistical point of view) vehicle driver to enter the roundabout circular roadway, while any smaller gap (making it impossible to perform the intended maneuver) will not be used. The procedure used during the measurements is similar to that used by Drew (1968). For each vehicle driver stopping at the roundabout edge line, two gaps were recorded: the longer rejected gap and accepted gap. Furthermore, for each vehicle driver who enter the roundabout circular roadway without stopping at the roundabout edge, only the accepted gap was further considered. The data collected in this way were the basis for estimation of critical gaps for individual vehicle drivers at turbo roundabout entry lanes. The critical gap values can be estimated using different determination methods (e.g., cumulative curves, the acceptance curves, histogram, maximum likelihood method). The methods of measurement and research techniques used for evaluation of critical gaps have been described in detailed in Brilon et al. (1999). For the collected data, the critical gap was determined graphically based on cumulative curves and acceptance curves, as well as algebraically, using the formula proposed by Drew (1968):

$$t_g = t + \frac{(c-a)\,\Delta t}{\left(b+c\right) - \left(a+d\right)} \quad [s] \tag{4}$$

where:

t - the middle of the time interval, in which critical gap is located [s],

Δt - the spread of the time interval, in which critical gap is located [s],

a, b - the numbers of accepted gaps smaller than t in individual time intervals, for which the numbers of rejected gaps bigger than t are close to each other (ideal in ideal cases),

c, d - the numbers of rejected gaps bigger than t in individual time intervals, for which the numbers of accepted gaps smaller than t are close to each other (equal in ideal cases).

The measurements of time gaps between the vehicles moving on the circulatory roadways were made in cross-sections located in the front of the roundabout entry. Measuring station (digital camera) was placed in each case on the island at the roundabout entry (**Figure 2B**). The measurement procedure consisted in recording gaps between the fronts of subsequent vehicles passing the same selected road section. The recorded gap was the sum of the time needed for the passage of the vehicle itself and the time gap to the front of the next vehicle. The measurements were made taking into account the road traffic structure.

The research was carried out in peak hours with high traffic volume both at the entry lanes and on the circular roadway lanes. The research was performed using Sony digital cameras with 60 GB HDD and a battery pack allowing for continuous recording the traffic streams up to 8 h. Using the

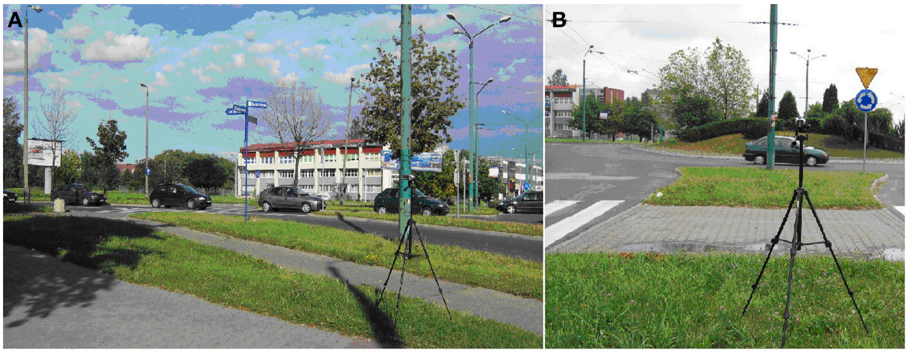

FIGURE 2 | The example of the camera location for the measurement of **(A)** follow-up time for vehicle drivers at entry, **(B)** time gaps between the vehicles moving on the turbo roundabouts circular roadway.

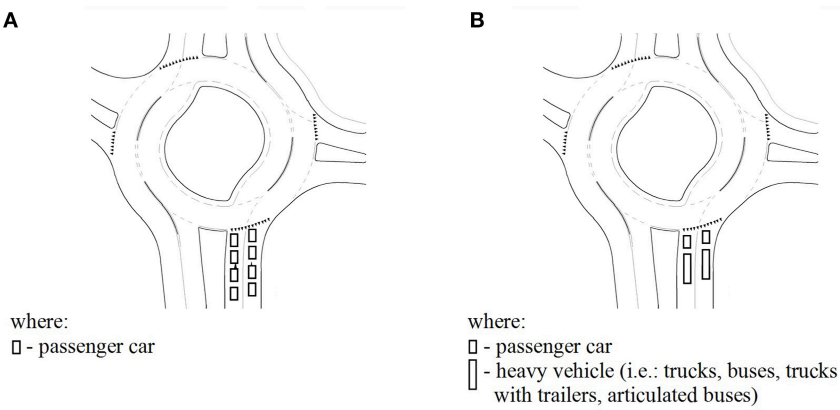

FIGURE 3 | The situations taken into account during measurements of the follow-up times between the vehicles entering the circular roadway from turbo roundabout entry lanes. **(A)** Only passenger cars. **(B)** Passenger cars and heavy vehicles (i.e., trucks, buses, truck with trailers, articulated buses).

cameras allowed for obtaining data accuracy of 0.04 s (the image was recorded at the rate of 25 frames/second). In each case, the measuring station was located in a place not very visible to the vehicles drivers (so that the measurements do not affect the drivers behaviors), but at the same time ensuring an accurate reading and analysis of the measured values. All measurements were taken in good weather conditions (no atmospheric precipitation). For further analysis, both samples consisting only of passenger cars and vans and samples consisting of different types of vehicles were taken into account. In the collected data, the percentage of heavy vehicles did not exceed 22.0%.

ESTIMATION OF PASSENGER CAR EQUIVALENT FACTORS FOR TURBO ROUNDABOUTS

The measurements were used to calculate values of passenger car equivalent factors according to model 8 (see **Table 1**) i.e., by comparing the average time gaps between the vehicles in two homogeneous traffic streams (passenger cars stream and a stream of vehicles from the analyzed group of vehicles) at the same traffic conditions.

Passenger Car Equivalent Factors for Follow-Up Times Between the Vehicles Entering the Circular Roadway From the Turbo Roundabout Entry Lanes

Two cases were analyzed during the measurements. In the first case, the behaviors of the queue of vehicles consisting only of the passenger cars were analyzed. The follow-up times between the passenger cars entering the circulatory roadway from the turbo roundabout entry lanes were measured (**Figure 3A**). The second case analyzed the traffic streams mixed in terms of composition. In the queue on roundabout entry lanes, heavy vehicles (i.e., trucks, buses, trucks with trailers, articulated buses) were behind the passenger car (**Figure 3B**).

The follow-up times between two passenger cars (t_{f-SOD}) and between passenger cars and heavy vehicles (t_{f-SC} or t_{f-SCP}, respectively) entering the circular roadway from the turbo roundabout entry lanes were calculated as an average

TABLE 4 | The passenger car equivalent factors for follow-up times between the vehicles entering on the circulatory roadway from the turbo roundabout entry lanes.

Entry lane	Sample size (n)	$\overline{t_{f-SC}}$ [s]	$\overline{t_{f-SCP}}$ [s]	$\overline{t_{f-SOD}}$ [s]	$E_{f\text{-SC}}$ [–]	$E_{f\text{-SCP}}$ [–]
Left	158	3.22	3.53	1.91	1.68	1.84
Right	411	3.62	3.96	2.12	1.71	1.86
		Average values			1.69	1.85

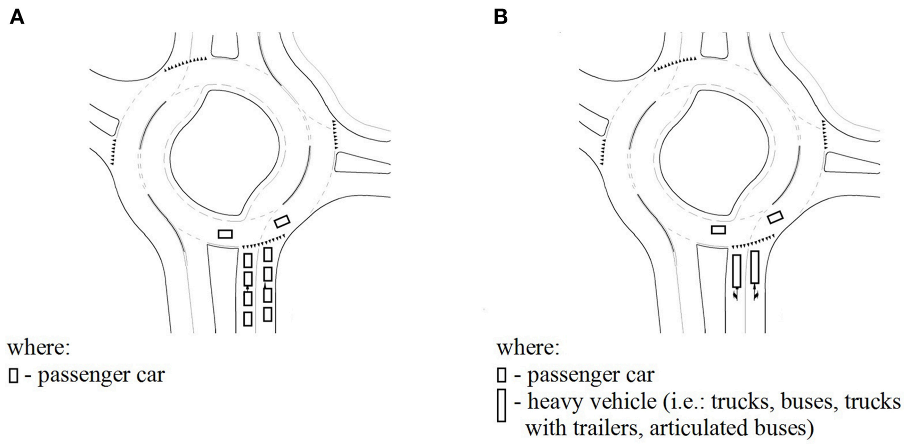

FIGURE 4 | The situations taken into account in measurements of critical gaps for vehicle drivers at turbo roundabouts. **(A)** Only passenger cars. **(B)** Passenger cars and heavy vehicles (i.e., trucks, buses, truck with trailers, articulated buses).

value for each turbo roundabout. The passenger car equivalent factor for follow-up times between the vehicles entering the circular roadway from the turbo roundabout entry lanes was calculated as:

$$E_f = \frac{t_{f\ -SC}}{t_{f\ -SOD}}\ [-]\ and\ E_f = \frac{t_{f\ -SCP}}{t_{f\ -SOD}}\ [-] \tag{5}$$

where:

E_f - passenger car equivalent factor for heavy vehicles (i.e., trucks, buses, trucks with trailers, articulated buses) [–],
t_{f-SC} - follow-up time between passenger cars and heavy vehicles (i.e., trucks, buses) [s],
t_{f-SCP} - follow-up time between passenger cars and heavy vehicles (i.e., trucks with trailers, articulated buses) [s],
t_{f-SOD} - follow-up time between two passenger cars [s].

The results of the analysis are presented in **Table 4**.

Passenger Car Equivalent Factors for Critical Gaps for Vehicles Drivers at Turbo Roundabouts

Critical gaps measurements were performed in two cases. The first case occurred when a driver of a passenger car accepted or rejected a gap between two passenger cars moving on the turbo roundabout circular roadway (**Figure 4A**). The second case was when a driver of a heavy vehicle (i.e., trucks, buses, trucks with trailers, articulated buses) accepted or rejected a gap between two passenger cars moving on the turbo roundabout circular roadway (**Figure 4B**).

Based on the collected data about the longest time gaps rejected and the time gaps accepted by individual drivers, the critical gaps were determined using cumulative curves (**Figure 5A**) and the acceptance curves (**Figure 5B**) for the two cases described above separately for vehicle drivers from the left and right entry lanes.

The passenger car equivalent factor for critical gaps for vehicle drivers entering the circular roadway from the turbo roundabout entry lanes was calculated from the formula:

$$E_g = \frac{t_{g\ -SC}}{t_{g\ -SOD}}\ [-] and E_g = \frac{t_{g\ -SCP}}{t_{g\ -SOD}}\ [-] \tag{6}$$

where:

E_g - passenger car equivalent factor for heavy vehicles (i.e., trucks, buses, trucks with trailers, articulated buses) [–],
t_{g-SC} - critical gap for heavy vehicles (i.e., trucks, buses) [s],
t_{g-SCP} - critical gap for heavy vehicles (i.e., trucks with trailers, articulated buses) [s],
t_{g-SOD} - critical gap for passenger cars [s].

The results of the analysis are presented in **Table 5**.

Passenger Car Equivalent Factors for the Time Gaps Between Vehicles Moving on the Circular Roadways of Turbo Roundabouts

Two cases of the time gaps between vehicles moving on the circular roadways of turbo roundabouts were analyzed during

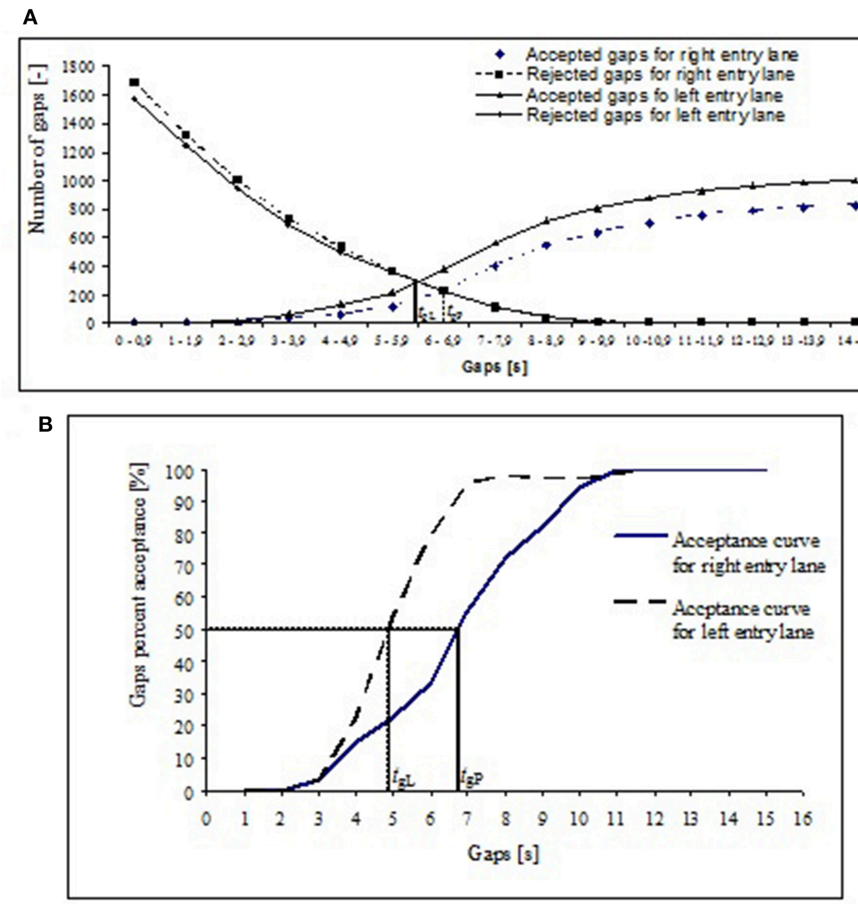

FIGURE 5 | Example of graphical determination of critical gaps using **(A)** cumulative curves an **(B)** the acceptance curves (where: t_{gP}, critical gap for vehicle drivers from the right entry lane; t_{gL}, critical gap for vehicle drivers from the left entry lane).

TABLE 5 | The passenger car equivalent factors for critical gaps for vehicle drivers on turbo roundabout entry lanes.

Entry lane	Sample size (*n*)	$\overline{t_{f-SC}}$ [s]	$\overline{t_{f-SCP}}$ [s]	$\overline{t_{f-SOD}}$ [s]	$E_{f\text{-}SC}$ [–]	$E_{f\text{-}SCP}$ [–]
Left	479	6.19	6.37	3.60	1.72	1.76
Right	511	7.83	8.46	4.48	1.74	1.88
		Average values			1.73	1.82

the measurements. In the first case, the time gaps between two passenger cars were analyzed (**Figure 6A**). The second case concerned the time gaps between passenger cars and heavy vehicles (**Figure 6B**). Finally, the passenger car equivalent factor for the time gaps between vehicles moving on the circulatory roadway of turbo roundabout was calculated from the following formula:

$$E_p = \frac{t_{SC} + u_{SOD-SC}}{t_{SOD} + u_{SOD-SOD}}\ [-]\ \ and\ \ E_p = \frac{t_{SCP} + u_{SOD-SCP}}{t_{SOD} + u_{SOD-SOD}}\ [-] \tag{7}$$

where:

E_p - passenger car equivalent factor for heavy vehicles (i.e., trucks, buses, trucks with trailers, articulated buses) [–],

t_{SC} - travel time of heavy vehicles (i.e., trucks, buses) calculated as: $t_{SC} = \frac{l_{SC}}{V_{SC}}$ [s],

t_{SCP} - travel time of heavy vehicles (i.e., trucks with trailers, articulated buses) calculated as: $t_{SCP} = \frac{l_{SCP}}{V_{SCP}}$ [s],

l_{SC} - length of heavy vehicles (i.e., trucks, buses) [m],

l_{SCP} - length of heavy vehicles (i.e., trucks with trailers, articulated buses) [m],

V_{SC}, V_{SCP} - speed of heavy vehicles. According to the data presented in Guidelines (2001), the speed was assumed as 20 [km/h] = 5.56 [m/s],

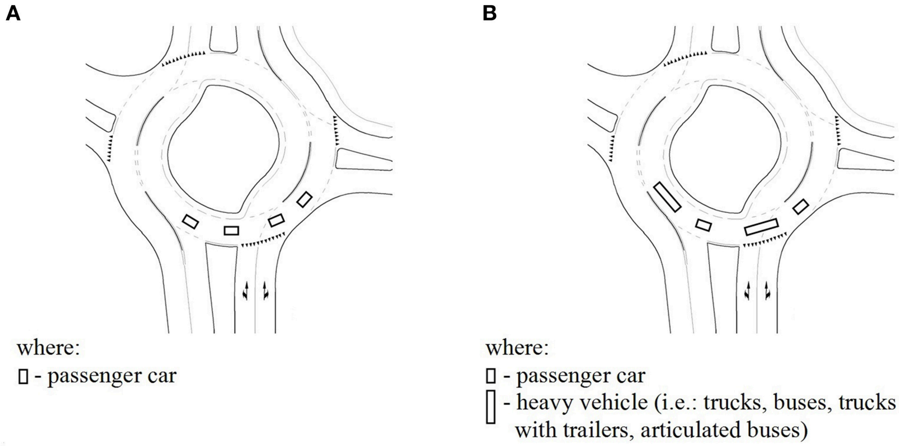

FIGURE 6 | The situations taken into account in the measurements of the time gaps between the vehicles moving on the circular roadways of turbo roundabouts. **(A)** Only passenger cars. **(B)** Passenger cars and heavy vehicles (i.e., trucks, buses, truck with trailers, articulated buses).

TABLE 6 | The lengths of the selected types of vehicles.

Vehicle type	Mean length of the vehicle [*m*]
Passenger car	4.00
Truck and bus	8.20
Truck with trailer, articulated bus	16.50

Own research based on PMS[1] *(Szczuraszek et al., 2007).*

t_{SOD} - travel time of passenger car calculated as: $t_{SOD} = \frac{l_{SOD}}{V_{SOD}}$ [s],
l_{SOD} - length of passenger car [m],
V_{SOD} - speed of passenger cars [m/s]. According to the data presented in Guidelines (2001), the speed was assumed as 30 [km/h] = 8.33 [m/s],
u_{SOD-SC} - time gap between the rear of the first vehicle—i.e., a passenger car and the front of the next vehicle—i.e., heavy vehicle (i.e., trucks, buses) [s],
$u_{SOD-SCP}$ - time gap between the rear of the first v$u_{SOD-SOD}$ehicle—i.e., a passenger car and the front of the next vehicle—i.e., heavy vehicle (i.e., trucks with trailers, articulated buses) [s],
$u_{SOD-SOD}$ - time gap between the rear of the first vehicle—i.e., a passenger car and the front of the next passenger car [s].

The length of each type of vehicle has been adopted in accordance with the classification of types of vehicles into groups according to their length (PMS)[1] (Szczuraszek et al., 2007). The lengths of the selected types of vehicles adopted for the analysis are presented in **Table 6**. The results of equivalent factors calculations are shown in **Table 7**.

Finally, the values of the equivalent factors for heavy vehicles on turbo roundabouts have been calculated as arithmetic means. The results of calculations are presented in **Table 8**.

The passenger car equivalent factor for trucks and buses (E_{sc}) is 1.74 for entry, with 1.71 for the left entry lane and 1.77 for the right entry lane. Furthermore, the passenger car equivalent factor for trucks with trailers and articulated buses (E_{scp}) is 1.86 for entry, with 1.82 for the left entry lane and 1.90 for the right entry lane.

The constraints to the vehicle trajectories at roundabouts imposed with the curvilinear geometric design and the driver gap acceptance behavior led to the impact of the heavy vehicles on the quality of traffic flow different from that found for freeways and two-lane highways or other at-grade intersections. This is also because the entering flow is opposed by the circulating flow which has the priority and travels in an anticlockwise direction around the central island. Because of this impact, the method according to model 8 (**Table 1**) adopted in the study, i.e., by comparing the average time gaps between the vehicles in two homogeneous traffic streams (passenger cars stream and a stream of vehicles from the analyzed group of vehicles) at the same level of traffic conditions seems to be appropriate because it allows for adequate modeling of real traffic situations occurring at roundabouts.

THE EFFECT OF HEAVY VEHICLES ON THE PARAMETERS OF CAPACITY CALCULATION MODEL

Heavy vehicles such as trucks, buses, trucks with trailers, and articulated buses are different from passenger cars due to e.g., their size or acceleration and deceleration performance. As shown in the paper, these futures have a significant effect on the capacity calculation model parameters such as follow-up time (t_f), critical gap (t_g), and time gap between the vehicle on the circular roadway (t_p). Therefore, in order to calculate the turbo roundabout entry capacity

[1]PMS. Pierwszy Serwis Miedzynarodowy Transportu i Spedycji: Tabela dopuszczalnych wymiarów pojazdów w krajach europejskich, http://psm.pl/informacje/wymiary.html (data dostepu: 23 XII 2018 r.) [In Polish: PMS. The First International Transport and Forwarding Service: Table of Permissible Vehicle Dimensions in European Countries (accessed December 23, 2018)].

TABLE 7 | The passenger car equivalent factors for the time gaps between vehicles moving on the circulatory roadways of turbo roundabouts.

Entry lane	Sample size (n)	$\overline{t_{SC} + u_{SOD-SC}}$ [s]	$\overline{t_{SCP} + u_{SOD-SCP}}$ [s]	$\overline{t_{SOD} + u_{SOD-SOD}}$ [s]	$E_{p\text{-}SC}$ [–]	$E_{p\text{-}SCP}$ [–]
Left	382	3.69	3.96	2.11	1.74	1.87
Right	614	4.33	4.56	2.32	1.86	1.96
		Average values			1.80	1.91

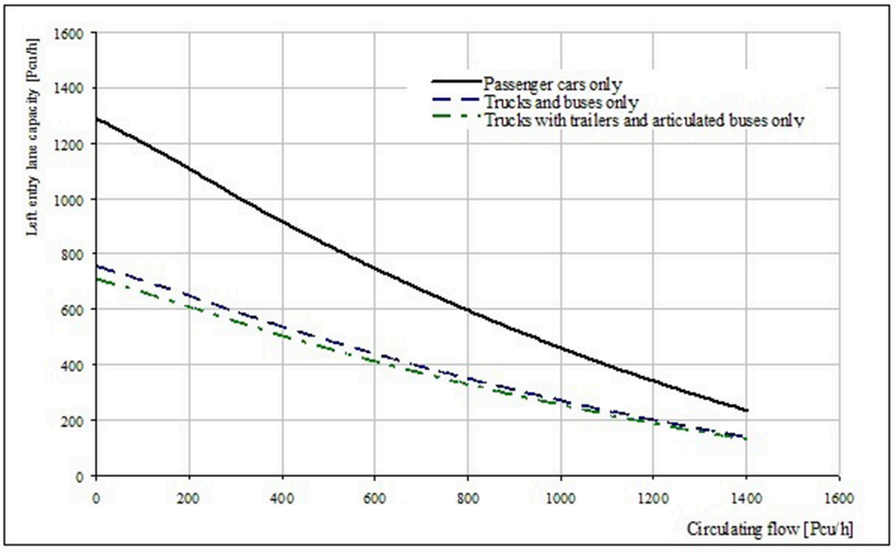

FIGURE 7 | Capacity of the left entry lane of the turbo roundabout for passenger cars only and heavy vehicles only.

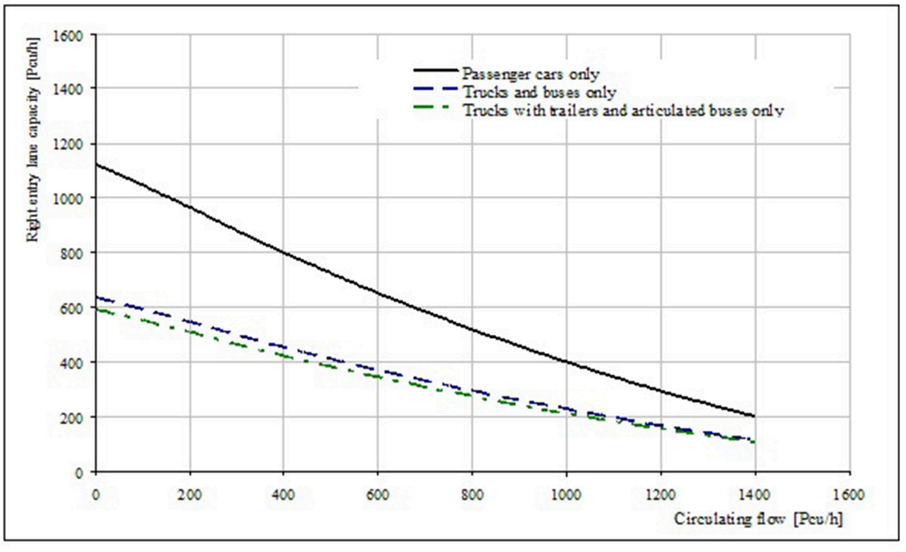

FIGURE 8 | Capacity of the right entry lane of the turbo roundabout for passenger cars only and heavy vehicles only.

taking into account heavy vehicles, the effect of heavy vehicles on the headway parameters should also be analyzed. Usually, the headway parameters are influenced by national or local driver behaviors. In this case, the driver behaviors were represented by Polish drivers. **Figures 7**, **8** present the theoretical values of the turbo roundabout entry lanes

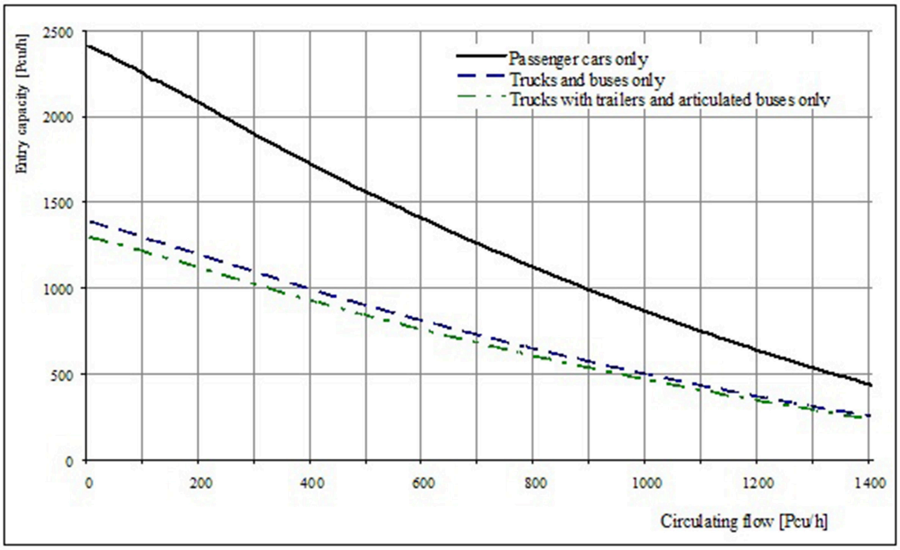

FIGURE 9 | Turbo roundabout entry capacity for passenger cars only and heavy vehicles only.

TABLE 8 | Passenger car equivalent factors values for turbo roundabouts.

Vehicle type	Denotation	Left entry lane	Right entry lane	Entry
Passenger cars	E_{SOD}	1.00	1.00	1.00
Trucks and buses	E_{SC}	1.71	1.77	1.74
Trucks with trailers, articulated buses	E_{SCP}	1.82	1.90	1.86

capacity for passenger cars only and heavy vehicles only. Furthermore, **Figure 9** illustrates the turbo roundabout entry capacity for passenger cars only and heavy vehicles only. The capacity values were determined based on the models presented in the study (Macioszek, 2013). Passenger car equivalent factors presented in this paper were used for capacity calculations (**Table 8**). It is obvious that the calculated capacity of passenger cars only is higher than that of heavy vehicles only at the same level of circulating flow. Furthermore, the capacity values with a certain percentage of heavy vehicles in the traffic stream will be between curves presented in **Figures 7–9**, respectively.

CONCLUSIONS

This paper presents an empirical analysis for determination of the passenger car equivalent factors for heavy vehicles (trucks, buses, trucks with trailers, articulated buses) on turbo roundabouts in Poland. For the purpose of the evaluation of the passenger car equivalent factors, the effect of heavy vehicles on the three headway parameters i.e., follow-up time (t_f), critical gaps (t_g), and time gaps between the vehicles moving on turbo roundabouts circular roadways (t_p) was examined. It was found based on the results that all headway parameters which include heavy vehicles are longer than those under the conditions of passenger cars only. The increasing tendency for the presence of heavy vehicles in traffic streams implies that headway parameters become longer with the increase of heavy vehicle percentage.

The analysis presented in this paper allows for the conclusion that the passenger car equivalent factor on turbo roundabouts in Poland for trucks and buses (E_{sc}) is 1.74 for the entry, with 1.71 for the left entry lane and 1.77 for the right entry lane. Furthermore, the passenger car equivalent factor for trucks with trailers and articulated buses (E_{scp}) is 1.86 for entry, with 1.82 for the left entry lane and 1.90 for the right entry lane.

However, these research results should be treated as preliminary and pilot results. It is necessary to extend the number of analyzed turbo roundabouts in future research and to examine the effect of the variable percentage of heavy vehicles in traffic streams on the values of passenger car equivalent factors. Further analyses should also take into account the varied geometry of turbo roundabouts and various cases of road traffic control in the area of turbo roundabout circular roadway and entries.

DATA AVAILABILITY

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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