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Micro driving behaviour in different roundabout layouts: Pollutant emissions, vehicular jerk, and traffic conflicts analysis

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Abstract

Driving behaviour affects both road safety and the environment, either positively or negatively. An unsafe driving behaviour characterized by hard acceleration/braking (also called driving volatility) can lead to an increase in emissions. Driving volatility can occur due to driving style, traffic, or road conditions. Although roundabouts present better safety performance than other traffic-control treatments, different layouts may lead to different levels of traffic-related impacts. This paper aims to evaluate vehicle movements through three types of roundabouts (Single-lane (SL), Compact two-lane (CTL), and Multi-lane (ML)) focusing on assessing the impact of driving volatility on traffic conflicts and pollutant emissions. A micro driving behaviour analysis of emissions, driving volatility, and conflicts were conducted for the links of the entry, circulating, and exit areas of the studied roundabouts. Speed was used as a variable parameter directly related to the driver while vehicular jerk and traffic conflicts, as well as global (carbon dioxide – CO_2) and local (nitrogen oxides – NOx) pollutants were used to evaluate the traffic safety and emissions performance, respectively. Field measurements obtained from a light-duty probe vehicle equipped with an on-board diagnostic reader on three different layout roundabouts located in suburban environments were used to develop a microscopic traffic simulation for the baseline. Simulations were conducted using VISSIM, emissions were estimated using the Vehicle Specific Power (VSP) methodology, and the Surrogate Safety Assessment Model (SSAM) was applied for estimating the traffic conflicts between motor vehicles. Four speed-distribution scenarios were considered, and associated impacts were evaluated for each roundabout. In general, speed variation and subsequently vehicular jerk had more impact on traffic conflicts than pollutant emissions. The number of conflicts in the exit area was less than entry and circulating in all roundabout designs but ML presented more traffic conflicts.

Keywords: Roundabout; Vehicular jerk; Safety; Emissions; Conflicts; Micro driving behaviour

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1. Introduction and Research Objectives

Road transport has been responsible for various negative impacts. In particular, not only global pollutant emissions from road traffic, such as carbon dioxide (CO_2), increased successively in the last years [(0.9% in 2019 compared to 2018) (EEA, 2020)], but local pollutants, such as nitrogen oxides (NOx), have a major contribution on millions of deaths around the world Pinto et al. (2020). To improve traffic performance, transport authorities have been considering different types of intersection layouts, from stop-controlled intersections to signalized ones or roundabouts. In fact, roundabouts have shown to be efficient alternatives to improve both traffic performance and safety as mentioned by Brilon (2016). Besides traffic capacity, safety, and delay improvements, studies show that different configurations may yield different magnitudes of benefits in terms of capacity [Vasconcelos et al., (2014)], safety [Vasconcelos et al. (2014), Fernandes et al. (2017), Bahmankhah et al. (2019)] and pollutant emissions [Vasconcelos et al. (2014), Fernandes et al. (2017 and 2020)].

Fernandes et al. (2015 and 2020) explored traffic-related pollutant emissions of different roundabout types considering different traffic demand scenarios. Findings suggest that compact two-lane (CTL) generated the highest amount of pollutant emissions per vehicle and the speed profile distributions had a significant influence on the pollutant emissions. Such results highlight that the adopted speed can be a relevant factor that affects emissions. In fact, it is the driver that decides to maintain speed or input acceleration/deceleration (variables that can be used to characterise driving volatility) and affect the traffic stream and subsequently the emissions. Driving volatility can be considered as a indicator for driving performance Liu et al. (2017) and Fernandes et al. (2021). A commonly used driving volatility measure is the vehicular jerk, which is the second derivative of speed Liu et al. (2017). Although there are works investigating driver behaviour in urban areas, they are mainly focused on safety, mostly related to driving volatility, and fuel consumption such as Liu et al. (2017), Bahmankhah et al. (2019) and Fernandes et al. (2021). It was verified that the design of roundabout has a significant effect on speed and speed variation at different segments of each roundabout has a significant impact on emissions, according to the research by Davidović et al. (2021). Liu et al. (2017) suggest the importance associated to evaluate driving decisions in specific contexts, but regarding an evaluation of driving behaviour impacts, there is a clear research gap in what concerns a joint analysis for pattern identification of emissions, vehicular jerk, and traffic conflicts. Thus, following the research previously developed by Fernandes et al. (2020), it is possible, in the light of the foregoing, to further explore microscopically the driver behaviour at different roundabouts [layouts single-lane (SL), multi-lane (ML) and compact-two lane (CTL)] and carry out an integrated pattern evaluation regarding global and local pollutant emissions, jerking movements (which affects driver/passenger comfort) and traffic conflicts, as part of a thorough analysis, which is the main objective of the present study. Different speed distribution scenarios will be explored to assess the impacts of driving behaviour for each roundabout layout. The impacts of safety and emissions were analysed considering 5 speed distributions (baseline speed, and its variation from -15% to +15% its value) for each roundabout layout. The major contributions of this study are as follows:

- To explore microscopically the driver behaviour at roundabouts with different geometric features;
- To evaluate the variations of different entry speed distributions and its impact of driving volatility, pollutant emissions, vehicular jerk, and traffic conflicts on an integrated way.

2. Methodology and Methods

Figure 1 illustrates the methodology followed in this research. Three suburban roundabouts in the Aveiro region (Portugal), namely, a Single-lane (SL), Compact two-lane (CTL), and Multi-lane (ML) were empirically explored Fernandes et al. (2020). About traffic volume, SL, CTL and ML represented 180, 127 and 387 vehicle per hour (vph) for approaching, 177, 173 and 271 (vph) for exit, and 35, 76 and 69 (vph) for conflicts traffic, respectively. Experimental monitoring was performed with a probe vehicle equipped with global positioning system (GPS) and on-board diagnostic reader (OBD) to collect second-by-second vehicle dynamic data. Traffic volumes and traffic queues were collected through cameras. Data collected during the afternoon peak hours, during 140 km of road coverage which contains 200 travel runs through movement were analysed in this research. Statistically, for a 95% confidence interval, this number of runs was sufficient to ensure the accuracy of the results according to Fries et al. (2017). The present research is based on the microscopic simulation of traffic conditions. To better reflect the potential differences in driving behaviour, speed-distribution analysis was performed at each entry, circulating and exit areas of each roundabout. VISSIM traffic model (PTV, 2016) was chosen to simulate traffic operations due to its capabilities to reproduce accurately traffic operations and driving behaviour for motor vehicles in urban road networks [even for roundabouts Li et al. (2013)]. To assess safety performance, the Surrogate Safety Assessment Model (SSAM) (Gettman et al., 2008) was applied since it allows to estimate the traffic conflicts through evaluation of motor vehicle trajectories obtained from microscopic traffic models such as VISSIM. Then, it records surrogate measures of road safety to determine if the conditions of interaction between motor vehicles can be defined as a conflict. The surrogate safety measures Minimum time-to-collision (TTC) and Minimum post-encroachment time (PET) were applied to evaluate the severity of conflict event, while the Maximum speed (MaxS) and Maximum relative speed difference (DeltaS) were considered since they are indicators of the potential crash severity according to Gettman et al. (2008). TTC = 1.5 was adopted for the roundabouts to define a conflict between motor vehicles, as suggested by (Huang et al., 2013) and was applied for the roundabouts in the same region Bahmankhah et al. (2020). SSAM classifies conflicts into three types based on a conflict angle (x): rear end (0º<x<30°), crossing (85º<x<180°), and lane change (all remaining conflict angles) according to Gettman et al. (2008). About emissions, the Vehicle Specific Power (VSP) methodology developed by Frey et al. (2002) was used to estimate CO_2 and NOx generated by vehicles. A specific MATLAB routine was developed to integrate the vehicle dynamics and trajectory data from VISSIM with both VSP and SSAM to estimate pollutant emissions and traffic conflicts, respectively, and to compute the driving volatility (vehicular jerk). Four alternative speed distribution scenarios were considered and simulated to assess the impact of speed variation on traffic performance, safety, and emissions (-5%, -15%, +5%, and +15% less and more than actual speed) beside the baseline scenario at entry, circulating and exit areas of each roundabout. Driving behaviour was also analysed at each segment of roundabouts under these scenarios based on vehicular jerk classification that was defined by Liu et al. (2017). Minimum 5 runs were used to evaluate each alternative scenario. More details about VISSIM model can be found here Fernandes et al. (2020).

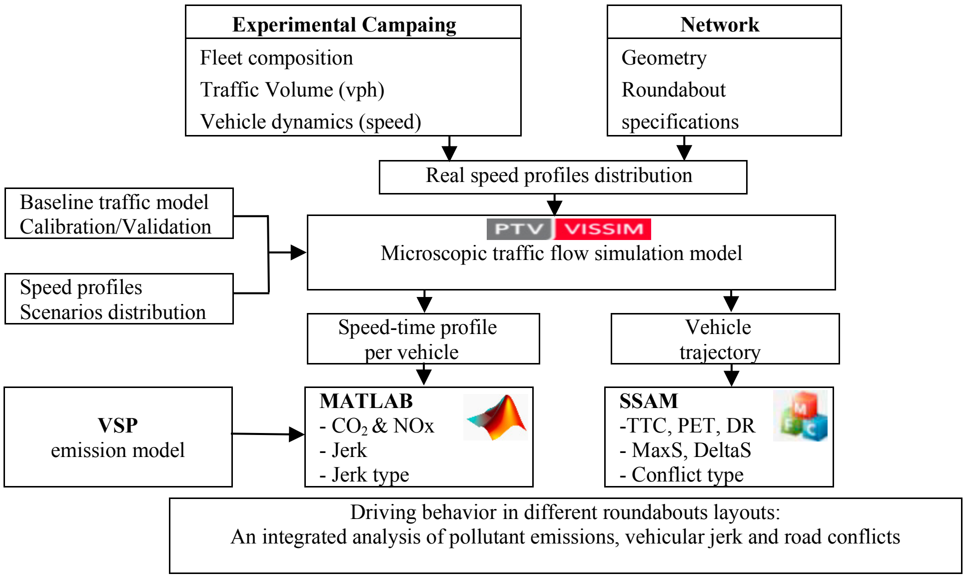

Fig. 1. Methodology overview.

3. Results

3.1. Vehicle Speed analysis

To assess traffic performance, first, an empirical speed analysis at the entrance of each roundabout was conducted. Regarding speed distribution, it was found that more than 70% of the cases represented speeds higher than 24 km/h, 33 km/h, and 26 km/h for CTL, ML, and SL, respectively, as shown in Fig. 2. Speed distribution was examined and classified to justify its impact on the number and severity of the conflicts besides the effect of layout and traffic volumes. The main idea is to include these data in the simulation environment of the current traffic speed for each roundabout area as much realistic as possible. Fig. 2 shows that speed performance at SL was higher than in the others since most of the distribution was higher than 34 km/h.

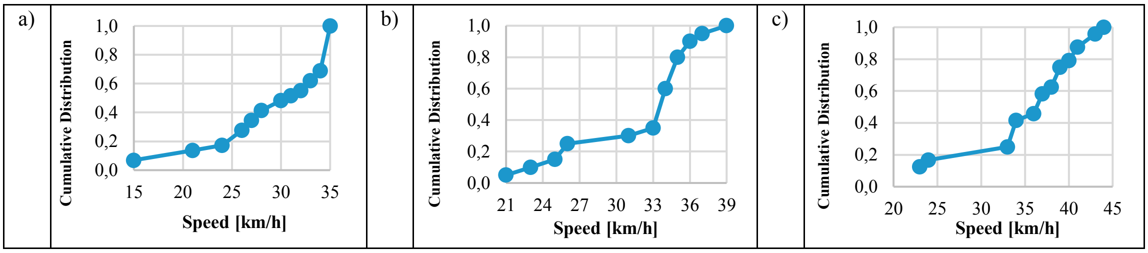

Fig. 2. Speed profile distributions by roundabout layout: a) CTL; b) ML; c) SL

All simulation experiments were made for the analysis with a 10-minutes "warm up" period prior to load the study domain adequately with corresponding traffic flow. For the calibration phase, the observed and estimated traffic volumes of the approach and exit were evaluated for each roundabout. The GEH (Geoffrey E. Havers) statistic was considered, accounting for at least 85% of simulation points matching the observed with GEH values lower than 4. A linear regression analysis was applied for each roundabout and the value of R-squared (R^2) was higher than 93% for all the roundabouts. The statistical data analysis confirmed that differences between observed and estimated traffic volumes and travel time at a 95% confidence interval were not significant. Model validation was based on VSP modes distribution. To examine the discrepancy between the estimated and observed VSP modes distribution, the two-sample Kolmogorov – Smirnov test (K–S test) for a 99% confidence level was employed. The assessment of VSP modes in terms of cumulative distributions revealed that two results from the observed and estimated data of the monitoring routes followed an identical trend.

3.2. Emissions analysis

Fig. 3 a-f presents the results on CO_2 and NOx (per kilometre) at three different areas of the roundabouts: Entry, Circulating, and Exit. In general, the trends of CO_2 and NOx emissions changes are identical for all scenarios in all segments of each roundabout. For example, in CTL more pollutants are emitted in the circulating area and less in exit area (circulating area emitted 54% and 13% more than entry and 88% and 45% more than exit for CO_2 and NOx respectively). ML is not showing a significant emission variation under different scenarios at each segments (less than 4% and 10% for CO_2 and NOx respectively) but SL showing more emissions at entry area than circulating area (80% and 46% for CO_2 and NOx respectively) and also more emissions at circulation than exit area (4% and 40% for CO_2 and NOx respectively). The major amount of emissions belong to -15% speed distribution scenario at all the segments of each roundabout while +15% scenario did not make significant difference compared to baseline scenario. About CTL, it represents more emissions compared to SL and ML (except for the entry links when compared to SL) in all speed distribution scenarios which is due to the low number of lanes at the approach, lower entry speed and moderate conflicting traffic. The emissions at ML roundabout were not changed significantly under different speed distribution scenarios, although there is a slight variation for -15% speed distribution scenario (in average -5% for CO_2 and +5% for NOx considering all scenarios). A similar pattern can be observed for SL: CO_2 and NOx emissions tend to be higher in the entry than circulating areas but a more evident reduction in exit areas. The entry traffic volume for SL is higher than others while represented lower traffic conflicts. Although the variation of reduction from entry to circulating areas and then exit areas is more for NOx but it is approximately the same for both emissions at SL segments. SL has a lower traffic volume with higher entry speed than other roundabouts and due to this fact, it represents more emissions in almost all segments compared to ML and CTL (except circulating area compared to CTL), which is in line with Fernandes et al. (2020). Although there is no significant variation of CO_2 and NOx for the CTL, unlike the SL and ML the emissions in the circulation area are higher than in the entry and exit areas. Two main reasons explain this outcome, first, the number of stop and go situations that is more than other roundabouts because of the lane numbers and second because of the traffic volume that also increases the number of stop and go in this roundabout. The vehicles also spending more time in circulating areas in a queue that are waiting to exit. Although the trend is the same for both presented emissions, the variation of CO_2 from entry to circulating area is more significant than NOx (45%). In general, it is visible that the results of -%5 and + 5% speed distributions scenarios are more and less similar in CTL, ML and SL.

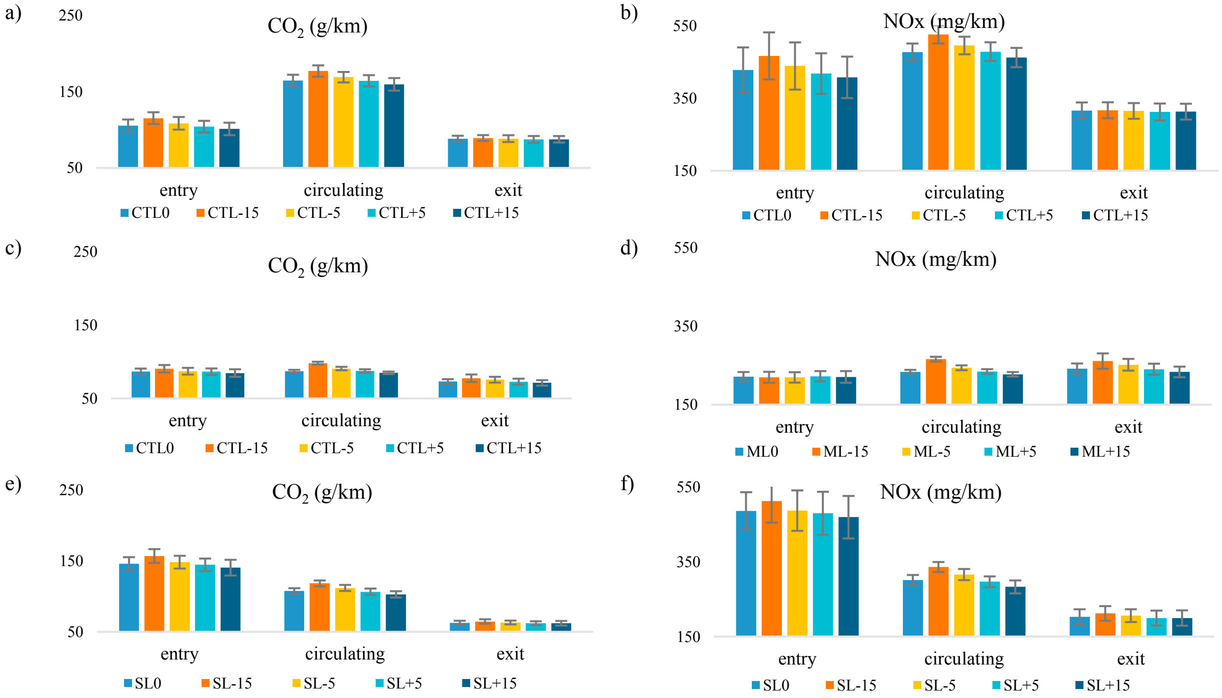

Fig. 3. CO_2 and NOx emissions per unit distance based on 5 speed distribution scenarios: a, b) CTL; c, d) ML; e, f) SL

Fig. 4 a-h depicts 9 examples of the CO_2/km, for baseline, 15% less speed, 15% more speed at SL, CTL and ML.

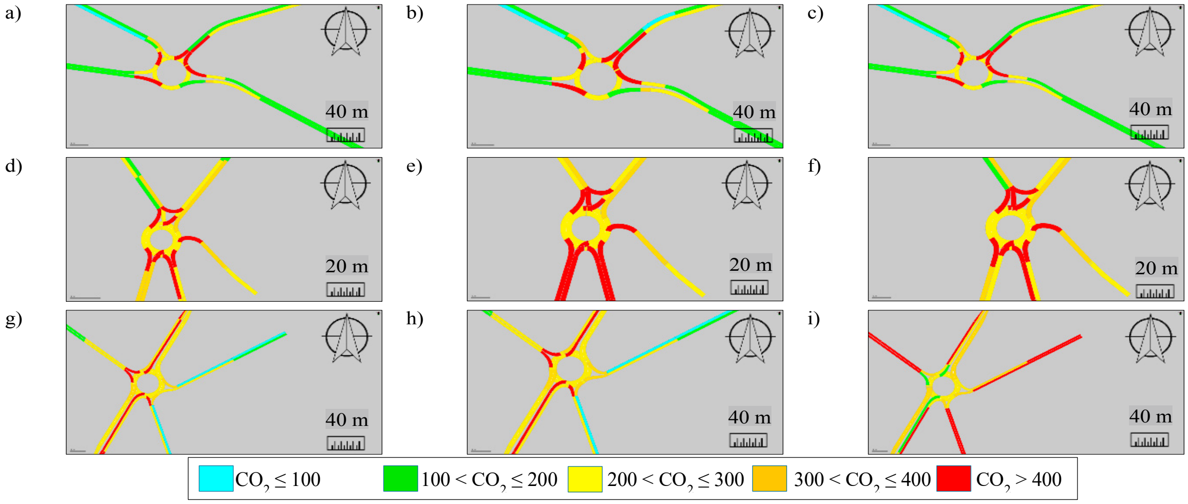

Fig. 4. Hotspot CO_2 emissions location (g.km^{-1}) by roundabout and scenario: (a) SL-baseline; (b) SL15%lessSpeed; (c) SL15%moreSpeed; (d) CTL-baseline; (e) CTL15%lessSpeed; (f) CTL15%moreSpeed; (g) ML-baseline; (h) ML15%lessSpeed; and (i) ML15%moreSpeed.

The speed distribution scenarios of -15% and +15% were selected because of their impact on CO_2 that was more significant than other scenarios. The results of Fig. 4 confirm the above discussion considering -15% and +15% of speed distribution scenarios and showed that SL represents more significant differences regarding CO_2 with more green coloured links, mainly at entry and exit areas, while in CTL there is mainly before the circulation areas.

3.3. Driving volatility analysis

Table 2 lists vehicular jerks' type from A to F during driving when the vehicle was in lower acceleration, higher acceleration, deceleration, lower deceleration, higher deceleration, and acceleration, respectively Liu et al. (2017).

Table 2: Relative frequency of different vehicular jerk for baseline, 5% and 15% variation on baseline speed at CTL, ML and SL roundabouts.

Safety Measurements	**CTL**														
	Entry					**Circulating**					**Exit**				
	0%	-15%	-5%	+5%	+15%	0%	-15%	-5%	+5%	+15%	0%	-15%	-5%	+5%	+15%
A	1004	1220	1034	952	901	1693	1961	1789	1670	1567	1216	1257	1230	1196	1177
B	914	1057	952	897	858	942	179	1013	908	827	857	872	852	857	857
C	321	406	338	311	288	648	625	644	637	639	101	69	86	107	118
D	1760	1882	1797	1722	1651	501	339	457	519	587	86	95	85	83	89
E	786	908	825	778	768	385	251	343	416	477	19	21	17	19	33
F	1073	1174	1096	1066	1038	612	534	581	615	637	547	522	552	549	547
Safety Measurements	**ML**														
	Entry					**Circulating**					**Exit**				
	0%	-15%	-5%	+5%	+15%	0%	-15%	-5%	+5%	+15%	0%	-15%	-5%	+5%	+15%
A	5964	5919	5809	6033	5955	5260	5912	5589	5273	5152	2682	2957	2823	2686	2623
B	1168	1254	1197	1143	1104	584	974	713	572	518	1767	1989	1876	1771	1737
C	1662	1777	1680	1681	1637	1121	934	1119	1136	1115	352	366	351	365	400
D	5004	5475	5214	4917	4795	1311	775	1058	1411	1575	597	328	453	616	701
E	1480	1640	1557	1511	1518	1052	587	862	1129	1250	485	294	429	493	526
F	2435	2630	2493	2459	2369	1168	1179	1249	1175	1163	894	642	804	919	958
Safety Measurements	**SL**														
	Entry					**Circulating**					**Exit**				
	0%	-15%	-5%	+5%	+15%	0%	-15%	-5%	+5%	+15%	0%	-15%	-5%	+5%	+15%
A	2606	3080	2741	2499	2421	2930	3111	3033	2907	2815	645	727	662	622	604
B	2326	2624	2501	2294	2188	837	1267	979	789	672	563	594	586	546	546
C	664	840	720	666	620	1021	986	1018	1016	1007	650	754	690	642	621
D	4365	4565	4347	4335	4225	937	755	833	964	1049	1862	1774	1809	1891	1938
E	1759	1972	1785	1728	1674	740	461	634	773	871	791	671	763	806	796
F	1964	2215	2053	1948	1875	324	312	328	315	316	874	865	874	881	879

The threshold of each vehicular type was defined by Liu (2017): Type A ($j<0$ & $a_i>=0$ & $0< a_{i+1}<a_i$); Type B ($j>0$ & $a_i>0$ & $a_i<a_{i+1}$); Type C ($j<0$ & $a_i>=0$ & $a_{i+1}<0$); Type D ($j>0$ & $a_i<0$ & $a_i<a_{i+1}<0$); Type E ($j<0$ & $a_i<0$ & $a_{i+1}<a_i<0$); and Type F ($j>0$ & $a_i<0$ & $a_{i+1}>0$), where j=vehicular jerk; ai=acceleration at time i; ai+1=acceleration at time i+1. It can be observed that ML presents more vehicular jerk almost at all the segments compared to SL and CTL. For example, type A vehicular jerk (lower acceleration) occurred more than 5964, 5260 and 2682 at entry, circulating and exit areas respectively at ML for baseline that is significantly more than other roundabouts. By increasing and decreasing speed, the same difference as in the baseline scenario is found, even when compared to other roundabouts as well. The main reason is due to the low traffic volume and lower speed (Fig. 2). Type B conflicts at SL also represents a significant difference in all three segments compared to CTL and ML. This type of vehicular jerk is responsible for high acceleration that occurred due to high speed and more freedom of the vehicle movement at SL roundabout. It should be mentioned that conflict type E which is responsible for lower deceleration represents more frequency at entry compared to circulating area and more frequency at circulating areas compared to the exit areas, regardless to the type of roundabout. The value in entry is more since there is a queue before entering to circulating area and more acceleration by vehicles to pass circulating area and then to exit with higher speed.

3.4. Safety analysis

There is a strong relationship between SSAM conflicts and crashes in roundabouts Giuffrè et al. (2018). Three different types of conflicts (rear-end, lane change, and crossing) were evaluated based on entry, circulating, and exit links. The trajectories of vehicles obtained from the traffic model are analysed through the SSAM and vehicle interactions and potential conflicts are reported if a specific condition is met. The software was run by considering TTC as the safety indicator to assess if inter vehicles interactions can lead or not to conflicts and it is commonly set to be 1.5s, being itself a measure of conflict severity (low values of TTC indicate high severe conflicts) (Vasconcelos et al., 2014). The new open-source SSAM software with improved safety measures was applied. TTC and PET were applied to evaluate the severity of conflict events, while MaxS and DeltaS are indicators of the potential crash severity.

Table 3: Safety results for baseline, 5% and 15% less and more than baseline speed at CTL, ML and SL roundabouts.

Safety Measurements		**CTL**														
		Entry					**Circulating**					**Exit**				
		0%	-15%	-5%	+5%	+15%	0%	-15%	-5%	+5%	+15%	0%	-15%	-5%	+5%	+15%
TTC (s)		0.99	1.03	1.05	0.99	0.95	0.55	0.60	0.54	0.46	0.51	0.05	0.19	0.09	0.25	0.07
PET (s)		1.7	1.07	1.75	1.64	1.65	1.07	0.99	0.95	0.90	0.81	0.01	0.13	0.15	0.03	0.01
MaxS (m/s)		5.09	4.85	4.89	5.13	5.29	4.87	4.52	4.73	5.29	5.29	9.14	5.34	8.78	12.05	9.73
DeltaS (m/s)		-1.61	-1.59	-1.63	-1.57	-1.63	-1.95	-1.39	-1.21	-1.19	-1.55	0.18	0.23	0.09	0.32	0.05
Conflict	Rear end (n)	18	16	15	19	17	13	14	14	14	12	0	1	0	0	0
	Crossing (n)	23	25	23	25	24	16	17	15	15	17	0	0	0	0	0
	Lane change (n)	6	7	4	5	5	1	1	1	1	1	2	1	2	2	2
Safety Measurements		**ML**														
		Entry					**Circulating**					**Exit**				
		0%	-15%	-5%	+5%	+15%	0%	-15%	-5%	+5%	+15%	0%	-15%	-5%	+5%	+15%
TTC (s)		1.06	1.09	1.07	1.06	1.07	0.39	0.40	0.41	0.37	0.33	0.36	0.46	0.43	0.55	0.59
PET (s)		2.35	2.39	2.36	2.32	2.31	0.76	0.82	0.80	0.77	0.82	0.73	0.56	0.70	0.95	1.08
MaxS (m/s)		2.90	2.66	2.84	2.97	3.06	5.42	5.29	5.28	5.61	5.65	4.89	4.99	4.95	4.99	4.98
DeltaS (m/s)		-2.13	-2.06	-2.13	-2.23	-2.21	-1.34	-1.46	-1.48	-1.65	-1.48	-0.49	-0.24	-0.78	-1.11	-1.98
Conflict	Rear end (n)	381	415	395	372	352	45	40	54	59	55	8	5	8	12	12
	Crossing (n)	32	33	33	34	34	37	30	38	45	46	3	3	3	3	5
	Lane change (n)	2	1	2	4	4	1	1	1	2	1	0	0	0	0	0
Safety Measurements		**SL**														
		Entry					**Circulating**					**Exit**				
		0%	-15%	-5%	+5%	+15%	0%	-15%	-5%	+5%	+15%	0%	-15%	-5%	+5%	+15%
TTC (s)		1.33	1.96	1.37	1.33	1.32	0.84	0.38	0	0.69	0.23	0	0	0	0	0
PET (s)		1.89	1.78	1.25	1.91	1.99	0.55	0.24	0	0.95	0.22	0	0	0	0	0
MaxS (m/s)		4.38	3.62	2.85	4.27	4.22	8.48	8.90	0	9.78	10.57	0	0	0	0	0
DeltaS (m/s)		-2.42	-2.10	-1.01	-2.36	-2.40	-1.79	-1.12	0	-1.75	-1.08	0	0	0	0	0
Conflict	Rear end (n)	30	37	4	33	34	2	2	0	1	1	0	0	0	0	0
	Crossing (n)	4	4	0	4	4	1	1	0	1	1	0	0	0	0	0
	Lane change (n)	1	1	0	1	1	2	3	0	2	3	0	0	0	0	0

The number of conflicts was extracted from SSAM for the main approach of each roundabout using TTC value of 1.5 s which represented the lowest Absolute Percent Errors (MAPE) values between estimated and observed conflicts (12%). Crash data was in a very low frequency of annual data according to the published data by the Portuguese Safety Authority (ANSR, 2019). Lower TTC and PET values represent the severity of conflicts while MaxS and DeltaS represent the potential of crash severity. The results of Table 3 showed that in general, the severity of conflicts in low speeds (when speed distribution is -5% and -15%) is less in all the segments regardless of the roundabout design. About PET values it is difficult to conclude a certain result since there is no significant variation at each segment (the value of baseline compared to the values of the alternatives) except SL that represents lower values for low speeds distributions. SL did not show any types of conflicts and the value of any of the safety parameters was 0 since SSAM didn't record conflict interaction between vehicles in the exit. The number of conflicts at ML was higher than CTL and SL in all the segments due to the traffic queue and number of stop and go events while rear end conflicts were significantly higher than others. For example, ML represented 381 rear-end conflicts for the baseline compared to 18 and 30 for CTL and SL, respectively. There is no significant variation of conflicts in all exit areas.

4. Conclusions

The achieved results showed that the SL roundabout represents significant differences regarding emissions and safety concerns compared to other roundabouts under different speeds distribution scenarios. SL also represents more CO_2 mainly at entry and exit areas while in CTL there is more concentration of CO_2 mainly before circulation areas compared to the others. The findings confirmed that the roundabout design can impact traffic performance in terms of traffic conflicts and pollutant emissions, as different results were obtained for different roundabout layouts, in particular, in the entry, circulating, and exit areas. About vehicular jerk evaluation, findings showed that different types of vehicular jerk (jerks type A, B, C, D, E and F), caused by speed variation, were found at entry, circulating, and exit areas of different roundabouts. Regarding safety, SL represents the lowest severity of conflicts and the potential of a crash compared to other roundabouts and in general, ML represents more conflicts. The variation of speed in 5% and 15% of less and more than baseline showed that the severity and potential of a crash in low speeds distribution (-15%) is less than others almost in all the segments regardless of the type of roundabout although vehicles in exit area show fewer safety concerns than entry and circulating areas. SL represented the best safety performance in the exit area. The findings showed that although the layout and geometric information of the roundabout has an impact on speed and subsequently on emissions and safety concerns, but the results may be different in the microanalysis view based on entry, circulation and exit segments.

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