Estimation and safety validation of a roundabout gap-acceptance model in a simulated environment

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Extended abstract

1. Introduction

Roundabouts have gained great popularity as they provide the advantage of intersection control without the use of traffic signals and also improve safety as the number of conflict points is reduced [1]. The traffic throughput of a roundabout is significantly affected by drivers' decisions to merge through the circulating traffic. This process is known as gap-acceptance behaviour. Two of the most studied concepts of roundabout gap-acceptance are the critical gap and the critical headway. The former relates to the minimum gap the driver of the entering vehicle is willing to accept to merge in the roundabout while the latter refers to the following behaviour in a queue of entering vehicles. In existing modelling software, the critical gap is used as a parameter of the roundabout simulation models. Some of the most common methodologies to define critical gap are Raff's method [2], Ashworth's method [3, 4], and the maximum likelihood method [5]. Other techniques are the macroscopic probability equilibrium method [6] or the simple logit model. Most of these approaches treat critical gap as an aggregate measure with a single measure, which is extracted from observed traffic data.

The approach of applying a single critical gap value to all drivers may be considered as a limitation. With reference to [7], a single value critical gap values ignores heterogeneity in driver behaviour, randomness in capacity and other metrics. In [8] is presented a relatively different approach regarding critical gap, where the latter is updated for every gap-acceptance situation. The authors assumed that critical gaps follow log-normal distributions which are not directly observed but can be expressed as dependent on a series of explanatory variables. The authors concluded that only vehicle type and time spent in the conflict zones (which was considered as a proxy of roundabout congestion) were significant predictor variables. However, the authors did not validate the performance of their model in traffic simulation scenarios. The current paper is extending the aforementioned roundabout approach to account for interactions with circulating traffic considering additional explanatory variables, as the presence of circulating vehicles in the conflict zones and speed of circulating and entering vehicle. Moreover, the model is using different specifications and sets of parameters depending on whether the entering vehicle is interacting with only one or two circulating vehicles (moving in the inner and outer lanes of the roundabout). The component with one circulating vehicle of the proposed model was compared with a simpler reference model estimated following a similar specification but only considers single mean critical gap values. The testbed for this analysis was SmartActors, a newly developed micro-traffic simulation platform aimed to evaluate and compare the performance of new models.

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2. Methodology

The analysis presented in the paper was conducted using the rounD data [9]. The rounD data include vehicle trajectories observed by drones. Data were collected at several locations in Germany; most of these at the Neuweiler roundabout which is a four-armed infrastructure that connects a highway with Aachen. The data were further processed to extract a series of variables required for model estimation. The roundabout was segmented into zones/areas which included (a) the entrance lanes, (b) the main roundabout areas, (c) the conflict zones and (d) the exit lanes. The infrastructure is dual lane for entering the roundabout. For the remainder of the paper the left lane will be mentioned as the inner lane while the right lane will be mentioned as the outer lane. There are no lane markings in the roundabout hence, users can perceive it as either single-lane or multi-lane [9]. In the current approach, the roundabout was considered to consist of two areas namely, the inner and the outer area. Finally, the areas where the entering traffic had overlapping paths with the circulating vehicles were considered as conflict zones. The segregation of the roundabout into zones is presented in Figure 1 (original figure by [9]).

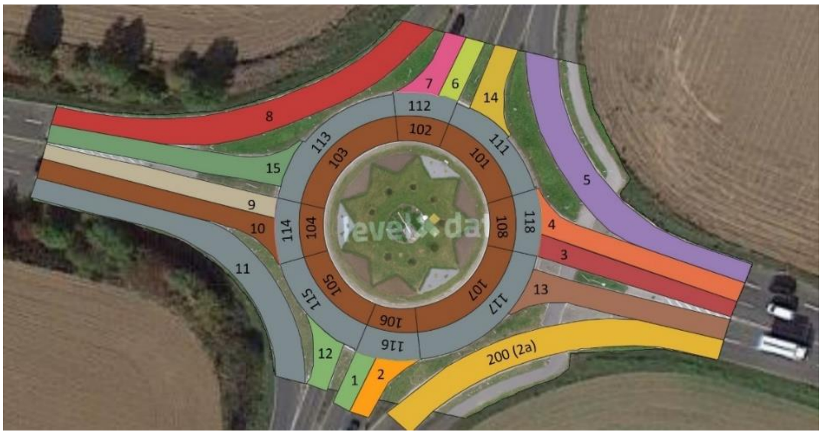

Figure 1: The roundabout areas after segmentation

The segmentation of the roundabout into smaller areas was followed by defining the gaps evaluated by the drivers. For any vehicle attempting to enter in the roundabout, only the closest "half" part of the roundabout was used for the definition of gaps. In particular, if a vehicle attempted to enter either from lane 1 or 2 (Figure 1), then lanes 102 to 105 were examined for the inner available gap and lanes 112 to 115 for the outer available gap. In this specific example, lanes 106 and 116 would be the conflict zones. Finally, lanes 9 and 1o would be the closer entry lanes for circulating traffic and lanes 6 and 7 would be the further entry lanes. The presence of a vehicle close to the merging line of this lanes (0.5 m) was considered as an explanatory variable in the model specification. If gap acceptance was observed while the conflict zone was occupied by a circulating vehicle, its effect was captured as a dummy variable indicator and the gap available for the entering vehicle was considered using as reference the circulating vehicles in the preceding roundabout area. For the definition of the gaps in each of the two roundabout zones, only the circulating vehicles closest to the subject vehicle were considered. The gaps were measured as the time taken from the current position of a circulating vehicle until the beginning of the conflict zone. At any time-step, an entering vehicle could encounter none, one or two circulating vehicles (in the outer and inner areas of the roundabout). For the latter case, the proposed model assumed that both gaps had to be accepted. A gap event was defined when a change in any of the circulating vehicles closest to the subject vehicle was observed. The decision to accept or reject a gap event was assumed to take place at the first timestep of its occurrence. Finally, for model estimation, the available gaps were considered only when the front part of the subject vehicles was 0.5 m or closer to the roundabout entrance.

The final dataset used for model estimation consisted of 4,100 vehicles that were observed to enter in the roundabout. In total, 12,390 observations were used for model estimation. It should be mentioned that vehicles that were not observed to have rejected a gap i.e. accepted the first gap event were removed from the analysis. Moreover, only cars were considered for model estimation; motorcycles and heavy vehicles were removed. However, these latter categories were considered when observed in the circulating traffic.

The model specification is based on the concept of critical gap. Critical gaps are not observed but are assumed to follow a log-normal distribution to ensure positive values. A critical gap is defined as follows in Equation (1)

$$G_{nt}^{cr,\,g} = e^{\left(X_{nt}\beta_g + \varepsilon_{nt}\right)} \qquad (1)$$

where:

$G_{nt}^{cr,\,g}$ is the critical gap of driver n, at time t
X_{nt} is a vector of explanatory variables that affect the critical gap
β_g is a vector of parameters to be estimated
ε_{nt} is an independent and identically normally distributed disturbance term: $N(0,\sigma_g^2)$
$g \in$ (near, far)

The index g refers to the lane for which the gap is being considered. The critical gap model had for two possible components, (a) one oncoming vehicle (either in the inner or outer roundabout part) and (b) two oncoming vehicles – one in each of the inner and outer areas of the roundabout. Moreover, a third model component (c) was introduced to capture decisions when no oncoming vehicles were observed. With respect to the first model component, drivers would enter the roundabout if they accepted the available gap to the oncoming vehicle, in other words if the available gap was larger than the driver's critical gap at that time and for that lane. This probability of acceptance for a gap can be specified as

$$P_n(\text{accept gap})=P_n[G_{nt}\geq G_{nt}^{cr}] \tag{2}$$

Based on the assumption that critical gaps are lognormally distributed (ε_{nt} is normally distributed), the probability for a gap to be accepted is given by Equation 3

$$P_{nt}^{GA,\,k=a}= P_n[G_{nt}\geq G_{nt}^{cr}]=\Phi\left[\frac{\ln(G_{nt})-\left(\beta_g X_{nt}\right)}{\sigma_g}\right] \tag{3}$$

where Φ[.] is the is the cumulative distribution function of the standard normal distribution and the superscript k is used to represent one of the three gap event cases described earlier. (For each gap event, only one of a, b, and c can be true). Focusing on the second model component, a driver needs to simultaneously accept both available gaps with the vehicles moving in the inner and outer areas of the roundabout in order to enter. This probability can be formulated as (Equation 4)

$$P_n(\text{accept gap})=P_n(\text{accept near gap})P_n(\text{accept far gap})=P_n\left[G_{nt}^{near}\geq G_{nt}^{cr\ near}\right]P_n\left[G_{nt}^{far}\geq G_{nt}^{cr,\ far}\right] \tag{4}$$

while the probability for rejecting an available combination of gaps is given as $1\text{-}P_n(\text{accept gap})$.

As mentioned before, it could also be the case that no vehicles were present in the examined roundabout section. In this situation, it would be expected to observe gap-acceptance in all cases however, this expectation was not confirmed by the data. After examining the data, it was observed that events without circulating vehicles could be very short. The reason for the short durations of these events was the presence of a new vehicle in the examined (for gaps to be evaluated by the entering vehicle) area of the roundabout either from the other entrance lanes or the non-considered roundabout area. The events occurred in these observations could not be addressed by the critical gap model specification presented earlier thus, the probability to observe a merge into the roundabout was expressed via a binary logit formula as (Equation 5)

$$P_{nt}^{GA,\,k=c}=\frac{e^{(\delta X_{nt})}}{1+e^{(\delta X_{nt})}} \tag{5}$$

where δ is a vector of parameters to be estimated and X_{nt} represents the explanatory variables

3. Analysis and Results

With respect to parameter estimates, the *No vehicles* component has a positive constant parameter, which highlights that drivers are more likely to accept an event without oncoming vehicles. Also, both parameter estimates related to the presence of vehicles in the conflict zones have a significant impact on gap-acceptance behaviour. Moreover, the presence of vehicles at the entry lanes, have a significant negative effect on acceptance decisions, both for the closer and further entry lanes. This outcome may primarily indicate the impact of traffic priority on drivers' behaviour. An additional conclusion with respect to this finding may regard the gap events per se, as defined in the present work; the occurrence of a *No vehicles* event may not be sufficiently long to allow for gap acceptance, as it shifts to a *one/two vehicles* event which is then evaluated by the entering subject vehicles.

With respect to the *Critical gap* model with two circulating vehicles, different parameters were found to be significant for the vehicles moving in the inner and the outer zone of the roundabout. Regarding the interaction with the vehicle moving in the outer roundabout zone, subject's speed has a decreasing effect on the critical gap, meaning that the higher the speed a vehicle is approaching the roundabout, the smaller the gap is likely to be accepted, all others being equal. As expected, the presence of vehicles in both the conflict areas increases the critical gap value. Moreover, if the circulating vehicle is heavy (bus or truck), the critical gap increases. Finally, increase of time-to-collision with vehicle in the inner zone resulted in increases of the critical gap. Regarding the circulating vehicle moving in the inner zone of the roundabout, its speed was found to have a significant positive impact on the critical gap. On the other hand, the higher the speed of the subject vehicle the shorter the critical gap. Moreover, when a subject vehicle was attempting to enter the roundabout from the inner lane, that had a negative impact of the critical gap. Results also indicated that critical gap is decreasing the longer the distance with the circulating vehicle is. Similarly to the outer zone model, the presence of vehicles in the conflict zones result in higher critical gap values. Additionally, both heavy vehicles and motorcycles had a positive effect on the critical gap. Finally, results suggested that there is a marginally significant negative impact of the time gap with the vehicle moving in the outer roundabout zone to the critical gap estimation of the inner roundabout zone.

The parameter estimates of the model component related to a single oncoming vehicle resulted in similar insights with the two circulating vehicles model component. The same effects were found with respect to vehicles merging from the inner lanes, and the speeds of both circulating and oncoming vehicles, the presence of vehicles in the conflict zones and the type of the circulating vehicles. Moreover, the presence of a vehicle in the inner roundabout zone resulted to the increase of critical gap.

The performance of the model presented in the previous section was evaluated in terms of traffic output and safety performance using SmartActors, a new microscopic simulation software platform developed at the University of Leeds. In the current analysis, a single-lane roundabout setting was tested. Given the simpler road layout, compared to the model estimation data, only the parameter estimates of the *One circulating vehicle* were implemented in SmartActors, for conducting the simulations. The performance of the roundabout model was evaluated at three different levels of speed for the traffic before and moving in the roundabout. These levels will be referred in the remainder of the paper as "high" (30m/s road, 20m/s roundabout), "medium" (20m/s road, 15m/s roundabout) and "low" (15m/s road, 7m/s roundabout) speed. Different values of critical (minimum) probability for gap-acceptance (P_{cr}) were tested, ranging from 0.4 to 0.9. Each pair of speed level and critical gap probability was simulated 10 times for 60 minutes each. Surrogate safety measures (SSM) of time-to-collision (TTC) and Post Encroachment Time (PET) were then calculated using the SSAM (Surrogate Safety Assessment Model) software.

In terms of traffic flow, both speed input and critical gap probability affected the performance of the models. The high speed models produced higher levels of traffic per simulation however, these models also resulted in the occurrence of crashes while vehicles were attempting to enter in the roundabout. It is worth mentioning that although crashes did not occur in the the *slow speed* model, results suggested a higher number of conflict events, compared to *high speed* and *medium speed* models. This finding could be related to the effect of the explanatory variables on critical gap; very low speeds allowed for accepting gaps even at short space headway.

With respect to TTC, higher speed levels resulted in shorter average TTC values. On the other hand, the differences observed by altering the P_{cr} were negligible. Given that the main difference across the three scenarios was traffic speed, the results indicate that this variable may have a considerable impact on the gap-acceptance behaviour and model performance overall. On the other hand, the significant differences observed in TTC are on average less than 0.2s. This indicates that significance may be a result of data size without strong safety implications. Regarding PET, no significant differences were found between the high and the low speed levels for the average values, in all P_{cr} conditions. On the other hand, differences were always significant when the medium speed level PET values were compared to both the high and the low speed levels. Overall, the PET values at the medium speed level indicated the occurrence of less severe conflicts (higher PET values), compared to the higher speed level. Regarding the low speed level, it is likely that lower speed values of the circulating traffic allowed for the acceptance of gaps at shorter distances which then led to smaller PET values, but this finding requires further investigation. Finally, it should be mentioned that in the vast majority of cases, the reference model resulted in significantly smaller TTC and PET values.

4. Discussion

The current work presented a roundabout critical gap-acceptance model where drivers' decisions were based on the specific traffic conditions related to each available gap, aiming to improve the realism and representation of drivers' behaviour in traffic simulation applications. The results indicated that both circulating and entering vehicles' speed had a significant impact on the definition of critical gap. Moreover, other significant variables included the type of the circulating vehicle, the presence of other vehicles in the conflict zones and the distance of the circulating vehicle(s) in meters.

The model performance was tested for the traffic throughput and safety (in the form of SSM) using different levels of speed and critical gap acceptance probability values. The results showed speed level can affect the traffic volume, with higher speeds resulting in more vehicles being generated however, this also results to crash occurrence and more severe conflict events. The proposed gap-acceptance model was compared to a reference model without however including any explanatory variables (constant only model). The results suggested that the reference model resulted in a higher number of crashes while it led to a higher number of conflicts that also were more severe. This finding implies that a generic critical gap value to represent merging behaviour at roundabouts may not always be the most efficient approach.

The findings presented come with a series of limitations that could be tackled in future work. These include unobserved heterogeneity, approaching behaviour (e.g. making a full stop before entering the roundabout or not) or the gap definition. For instance, some "no circulating vehicles" cases were not accepted in the current data because of the short duration of these events (a circulating vehicle entered the roundabout and this anticipation effect was not captured in the current specification). The model is also expected to be validated using a road layout similar to the data collection site considering similar traffic characteristics with the observed data.

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