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The Development of Pedestrian Gap Acceptance and Midblock Pedestrian Road Crossing Behavior Utilizing SUMO

Peter J. Lawrence [1*], Veronica Pellacini[1†], Darren Blackshields[1‡] and Lazaros Filippidis[1§]
[1] University Greenwich, London, UK.
P.J.Lawrence@greenwich.ac.uk, veronicapellacini@yahoo.it,
D.Blackshields@greenwich.ac.uk, L.Filippidis@greenwich.ac.uk

Abstract

While there are several published studies for modelling pedestrian behavior at signalized crossings in SUMO, the behavior of pedestrians crossing a road at a location other than a designated crossing, has not been considered to date. This work looks at how to represent pedestrian agents selecting to cross a road at arbitrary locations along the length of the road. The pedestrian agents utilize a gap acceptance model that represents how a pedestrian decides when to cross a road, based on the frequency and speed of approaching vehicles, while considering the spacing between them. Furthermore, the gap acceptance model allows the pedestrians to choose to cross all lanes in one go, when safe to do so, known as *Double Gap* or one stage crossing. Alternatively, if an agent is identified as a risk-taker, they may choose to cross lane by lane, sometimes waiting in the middle of the road, known as *Rolling Gap* or risk-taker crossing behavior. The inclusion of these two crossing behaviors allows for situations where urgency plays an important role in behavioral decision making, such as in emergencies, rush hour or in crowd management events. The outlined pedestrian crossing model is attained by integrating the pedestrian model EXODUS with SUMO, via the TraCI API.

1 Introduction

The interaction between pedestrians and vehicles in urban environments is a common occurrence, as such numerous studies exist on pedestrian safety issues in urban transportation, mainly focusing on pedestrian behavior at designated pedestrian crossings (Brosseau et al., 2017, Xin et al., 2014). However, a person may not be willing to walk longer distances to a designated crossing location if crossing the road from their current location will give them convenient and direct access to their destination (Islam et al, 2014, Zhao et al., 2017, Akyol et al., 2019).

Computer models such as LEGION (LEGION, 2017), VISSIM (Han et al., 2005) and MATSIM (Lämmel et al., 2009) can represent pedestrian interaction with vehicles. However, they consider pedestrians crossing only at designated locations, such as unsignalized or signalized pedestrian crossings. These models do not consider the possibility of people crossing at non-designated locations, as suggested by Wang (Wang, 2012). SUMO has supported an intermodal pedestrian-based simulation since 2010. This was extended by Erdmann and Krajzewicz (Erdmann and Krajzewicz, 2015) to simulate pedestrians in more detail, however, this still only allowed pedestrians to cross at designated

[*] Lead author, researcher and software developer.
[†] Research into crossing behavior, specification of pedestrian crossing model and contributing author.
[‡] Coupling of SUMO with pedestrian model EXODUS and contributing author.
[§] Research on human behavior, analysis of research and contributing author.

locations. Other researchers have looked at modelling pedestrians at traffic lights (Akyol et al., 2019) and the coupling of SUMO to external pedestrian models (Flötteröd et al., 2019) but neither these approaches allow for pedestrians to cross a road on non-designated locations.

Here a method of coupling a pedestrian simulation tool, namely EXODUS (Galea et al. 1996), with SUMO via the TraCI (Wegener et al. 2008) interface is outlined. The proposed model can represent midblock crossing behavior of pedestrians at arbitrary locations along the street. The work builds on research carried out by Wang (Wang, 2012) by implementing both one-stage and two-stage pedestrian crossing behaviors, to cater for two different pedestrian crossing traits.

One-stage crossing behavior is used when a pedestrian may choose to cross all vehicle lanes in one go, when safe to do so. This behavior is selected by non-risk-taking pedestrians. The two-stage crossing, or double gap behavior, is chosen when a pedestrian chooses to cross lane by lane, sometimes waiting in the middle of the road, if necessary. This behavior is also known as rolling gap (Brewer et al., 2006) or risk-taker crossing behavior (Song et al., 2003). These crossing behaviors allow for urgency, a psychological factor, to be represented, where a pedestrian in a hurry may be more willing to take risks while crossing a road, for example, during rush hour, or maybe in an attempt to catch a bus which is about to depart. Also, urgency is a key factor when considering emergency situations where people might be evacuating from a large building, such as a transportation hub, shopping center or tower block and inevitably interacting with the surrounding traffic.

This paper tries to address the research question –

Is it possible to represent pedestrian agents crossing vehicle lanes in SUMO at arbitrary midblock locations, taking into consideration traffic levels and different crossing behaviors?

This paper will outline the key behavioral developments required to model pedestrian crossing behavior, together with the technique utilized to interface EXODUS (Galea et al., 1996 and 2017) to SUMO (Lopez et al., 2018). It will then demonstrate the pedestrian crossing behavior and vehicle interaction, by modelling a crowd of people exiting from a large building to reach a point of assembly, positioned across a busy road. This example is chosen to examine how different types of crossing behaviors can impact the time for people to reach a destination and their impact on local traffic. The demonstration scenario could be considered as either representing a precautionary emergency evacuation or simply people exiting from the building heading towards a major event.

2 Methodology and Road Network

SUMO is a well-established open source, highly portable, microscopic and continuous road traffic simulation package designed to handle large road networks (Lopez et al., 2018). SUMO also includes its own pedestrian movement model, however this model is based around lanes and areas (Erdmann and Krajzewic, 2015) and it cannot represent people in buildings or exiting from them. Also, the lane-based nature of the model restricts pedestrians to just two directions of travel which limits its application in representing urban scale pedestrian movement. A possible solution to overcome these limitations and to include more complex and comprehensive pedestrian behaviors is to link SUMO via the TraCI (Wegener et al, 2008) interface to an external pedestrian model. One such model is EXODUS (Galea et al., 2017), which has been continuously developed by the University of Greenwich, since 1994.

EXODUS is an agent-based model capable of representing pedestrian movement for a variety of modelling domains such as building, maritime, aviation and rail (FSEG, 2021). EXODUS utilizes a hybrid spatial approach. This approach allows pedestrian movement to be represented at a macroscopic level, utilising coarse regions (i.e., a flow-based model), and at the microscopic level utilizing either a fine node grid, where pedestrian agents move on a discrete grid of nodes, or a continuous spatial representation (Chooramun et al., 2017). These different spatial representations are utilized depending on what data is available regarding pedestrian behavior, the type of expected interactions or travel speeds over a given terrain, or whether optimization is required due to the scale of the model. For example, at the urban scale, EXODUS would typically utilize coarse regions and/or a fine node grid to cater for large-scale models.

Within EXODUS the simulated pedestrians are characterized by various agent attributes grouped into four main categories (Galea et al., 2017). The first category comprises all physical attributes such as age, gender, mobility and unimpeded walking speed. Further, EXODUS simulates psychological attributes such as response time and patience. Their individual sojourn time in the environment, the total travelled distance, or the cumulative time that the agent has spent waiting in a queue or congestion are categorized as the agent's experiential parameters. Finally, pedestrian agents' hazard parameters measure the physical impact of fire hazards and the accompanying toxic gases on the condition of each individual.

To ensure that EXODUS and SUMO utilize the same road information, EXODUS has been adapted to import the SUMO road network file directly. In this way the naming and locations of all road edges, lanes and junctions are consistent. If desired by the user, EXODUS can automatically add sidewalks of a user definable width around the imported SUMO road network., see Figure 1.

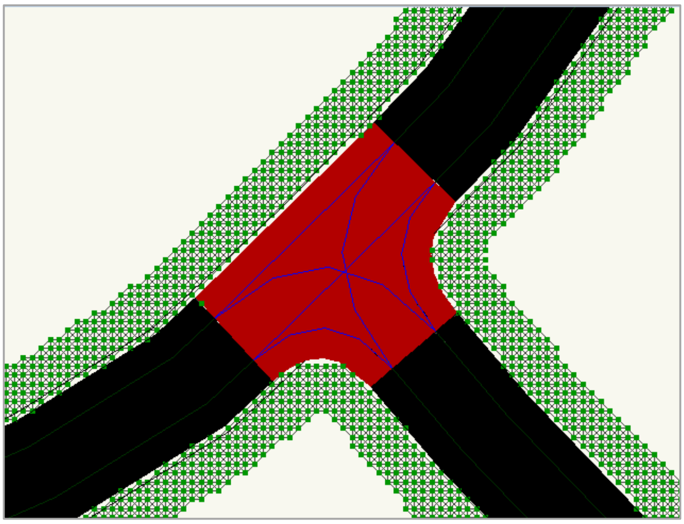


Figure 1: The EXODUS *Fine Node Mesh* representing pedestrian space around a road and junction network. Green squares represent EXODUS nodes. The black lines between nodes represent connected arcs, the large black areas represent roads, the red section is a junction and blue lines indicate traffic lanes**.**

The sidewalks are modelled in EXODUS utilizing a fine nodal mesh (Galea et al., 1996) consisting of an interconnected grid of nodes, with a typical spacing of 0.5 meters. Adjacent nodes, which can be travelled between, are connected by arcs representing the travel distance, see Figure 1. Only one pedestrian agent can occupy a given node at any given time in the simulation.

While pedestrian agents move using the EXODUS fine node model on the sidewalks, when crossing the road, they move using a continuous spatial movement algorithm (Chooranum et al., 2017). A continuous spatial pedestrian movement algorithm was selected for the road area as it consists of a well-defined region, providing greater flexibility for crossing at arbitrary locations and angles and allows for more accurate interaction with the vehicles. As the pedestrian agents need to be aware of approaching vehicles and other pedestrians on the road, a traffic lane-based collision avoidance algorithm, tied to the road network, is also utilised. In contrast, the fine node model is optimised for checking for pedestrian collisions (Galea et al., 1996) only within the locality of adjacent nodes, which is around 0.5 to 0.7 metres and thus its use on sidewalks. Furthermore, a typical vehicle can travel the distance of several fine nodes during a single EXODUS time step when travelling at a speed higher than 6m/s (21.6km/h), which prevents the utilisation of the node mesh for the road network without an increase to the EXODUS clock rate. This would in turn require recalibration to the fine node conflict resolution algorithm (Galea et al., 1996). However, the continuous spatial approach is not limited by these factors and was thus chosen.

3 Pedestrian Crossing Behavior

When a pedestrian agent encounters a road on their way to their destination and when their next move could take them onto the road surface, a probabilistic gap acceptance model is used to determine if and when the agent will attempt to cross the road. The gap acceptance model utilizes data from a number of previous studies (Wang, 2012, Schroeder, 2008, Yannis et al., 2010), see Section 3.1. The gap acceptance model allows the pedestrian agent to choose to cross all lanes, when safe to do so, in one go, known as *Double Gap* (Song et al., 2003) or one *Stage Crossing* (Paul et al., 2014). Alternatively, if the agent is identified as a risk-taker, they may choose to cross lane by lane, rather than crossing all lanes in one go, sometimes waiting in the middle of the road, known as *Rolling Gap* (Brewer et al., 2006) or risk-taker crossing behavior (Song et al., 2003). The risk-taker attribute is user defined in EXODUS, which can be either assigned at the individual pedestrian level or specified as a global percentage of the current pedestrian population.

At the start of the simulation EXODUS automatically divides the sidewalk into a number of equal sized regions as close as possible to 10 meters in width, called *Pavement Cells,* see Figure 2. These *Pavement Cells* are used to decide where a pedestrian will reattempt to cross the road, after a previous failed attempt. If the agent decides not to cross the road, they will continue along the sidewalk in a direction which takes them nearer to their target destination, i.e., *D* in Figure 2. They will then reattempt to cross if they enter the next *Pavement Cell* or if they cannot continue further along the sidewalk, for example, by being blocked by other pedestrians or have reached the end of the sidewalk. The gap acceptance model will then “fire” again to evaluate if it is now possible for them to cross the road.

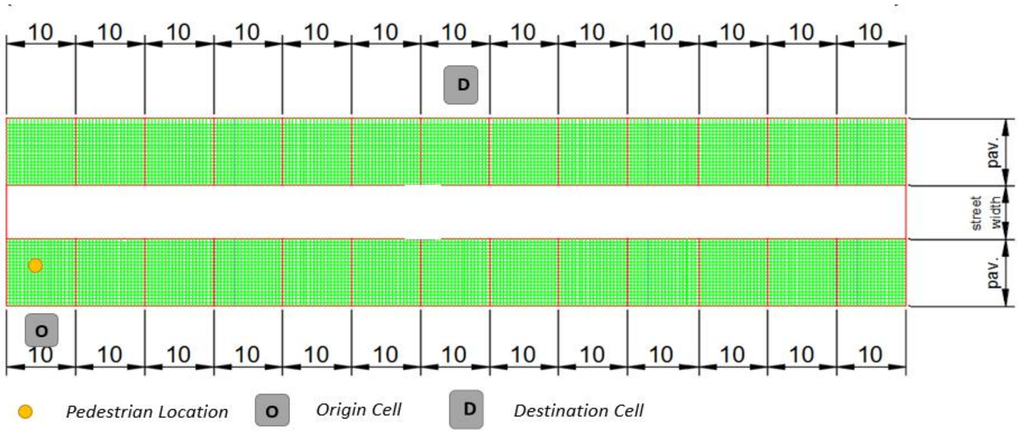


Figure 2: The Sidewalk is divided up into approximately 10-meter-wide *Pavement Cells*.

The approximate width of 10m for the *Pavement Cells*, was chosen based on research by Wang (Wang, 2012), who modelled where pedestrians chose to cross a 100m section of road with a zebra crossing. It was also identified by Song (Song et al. 1993) as representing a distance of not too far from a pedestrian crossing where a person may decide to either cross at a designated crossing or not.

3.1 Gap Acceptance (When to Cross)

The gap acceptance model deals with the behavior of how a pedestrian selects a gap in the traffic when crossing a road. Since the pedestrians have a choice to accept or reject a gap in the traffic the implementation is based on a *Cumulative Logistic Distribution Function* (Balakrishnan, 1992).

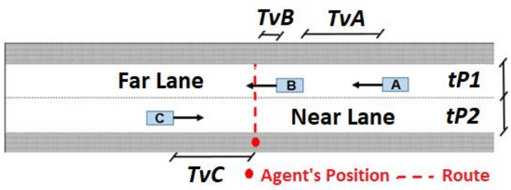


Figure 3: Gap acceptance parameters (two-way)

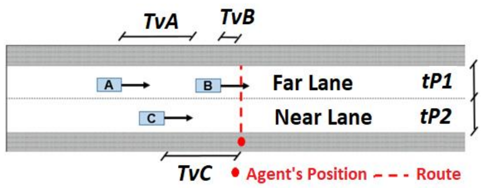


Figure 4: Gap acceptance parameters (one-way)

When an agent decides to cross the road, they consider vehicles in the near and far lane. In this model, only the nearest vehicle in the near lane and the first two vehicles in the far lane are considered. The key parameters for perpendicular road crossing are shown in Figure 3, for two-way traffic, and in Figure 4, for one-way traffic. The *TvA* parameter is the time gap, measured in seconds, between vehicles *A* and *B* in the far lane, called the *second far gap*. The parameters *TvC* and *TvB* are the times in seconds for vehicles *C* and *B* to reach the agent's crossing location, called the *first near* and *first far* gaps, respectively.

The pedestrians will use the *Double Gap Model* if they are identified as risk-averse; hence, will try to cross only when safe to cross both lanes in one go. This is when both the times to cross the first lane (*tP2*) and the second lane (*tP1*) are less than the vehicle gap in the near lane (*TvC*) and in the far lane (*TvB*). If this condition is met plus a safety margin *(S)* of *1*.5 seconds per a lane (Serag, 2014), a probability to cross is calculated, discussed later, as to whether the pedestrian accepts it and attempts to cross.

The *Rolling Gap Model* is used when the agent is considered a risk-taker. The agent will access the time to cross the first and second lanes considering *TvC* and *TvB*. Therefore, they will accept the gap on the first lane if $tP2 < TvC + S$ and the time to cross the second lane if $tP1 < TvB - tP2 + S$. However, if this gap is not accepted, the agent will consider the *second gap far* (*TvA*). They will then accept the gap if $tP1 < TvA - tP2 + S$ *and* $tP2 < TvC + S$. If either of these gaps are accepted, the agent will cross the first lane, then when they reach the middle of the lanes, the gap in the far lane is reassessed. Hence the behavior being modelled, is where the agent will cross the first lane, and then optionally, wait in the middle before continuing if in the second instance the far gap is not accepted.

If a pedestrian agent, waiting on the sidewalk to cross the road, fails to cross within the time specified by their patience attribute (uniformly randomly assigned between 1-30 seconds) (York et al., 2011) they will reassess where to cross and may choose to move further along the sidewalk and attempt to cross at a different location (i.e., choosing a different *Pavement Cell*).

Both models, *Rolling* and *Double Gap*, utilize a probabilistic model to assess if the pedestrian agent will accept a given viable gap in the traffic, which is a *Cumulative Logistic Distribution Function (CDF)* (Balakrishnan, 1992), as shown in Equation 1.

$$CDF = \frac{1}{1 + e^{-\frac{x-\mu}{s}}}$$

Equation 1

In Equation 1 x is a time gap parameter. For the *Double Gap* model x is equal to $TvC + TvB$, with *TvC* the near gap and *TvB* the far gap at time $t+\Delta t$, where $\Delta t = tP2$. The parameter *tP2* is the time to cross the first lane, see Figure 3. For the *Rolling Gap*, x is simply equal to *TvC,* the near gap. The s, parameter in Equation 1, is the scale parameter and is a function of the standard deviation in x. During the simulation, each time the CDF function is evaluated, s is assigned a random value between 0.992 and 1.221. This range is based on data collated by a number of researchers (Brewer et al., 2006, Schroeder, 2008, Yannis et al., 2010, Wang, 2012, Kadali, 2013, Serag, 2014, Pawar, 2014). The critical time factor μ, for the *Double Gap* model is calculated as $tP1 + tP2$, where for the *Rolling Gap model* it is simply *tP1,* the time to cross the near lane. A safety margin of 3 s, and 1.5 s is included in the *Double,* and *Rolling Gap* calculation, respectively, which are added to the μ value. These safety factor values represent the Safety Margin as defined by (Song et al. 1993).

Currently, the crossing behavior has only been developed for up to two lanes. For single lane roads the risk-takers and risk-averse pedestrian agents use the same one-stage crossing behavior, based on the *Double Gap Model*, without the consideration of a second lane *TvB* value. Crossing behavior for three or more lanes is left for further research.

4 Vehicles Yielding to Crossing Pedestrians

The topics related to pedestrian gap acceptance, vehicle yielding, and car-following, have been studied and analyzed separately (Zheng et al., 2015). Although, work has been conducted to investigate the decision-making process of pedestrians and vehicles, it is still not possible to describe a precise picture of the vehicle-pedestrian interaction phenomenon at locations outside marked crosswalks.

In the previous section the gap acceptance model for pedestrians' crossing behavior was described. However, a limitation of the gap acceptance model is that it only considers the current speed of any approaching vehicles and does not factor possible vehicle acceleration or deacceleration. Therefore, once a pedestrian has started to cross, any approaching and accelerating vehicle travelling in the same road lane, may need to adjust their speed to avoid a collision. Furthermore, if a crossing pedestrian is delayed, by having to avoid other pedestrians crossing the road or due to congestion on the opposite sidewalk, it may be necessary for an approaching vehicle to stop and wait, to allow the pedestrians to pass.

To accommodate the modeling of vehicles yielding to crossing pedestrians, EXODUS places a SUMO pedestrian (Erdmann and Krajzewic, 2015) agent into the SUMO simulation and on a given road lane if the presence of the agent crossing the road will impact the movement of the vehicles. The condition for this to be performed is if the distance between the crossing pedestrian and the near vehicle approaching the pedestrian is within twice the stopping distance of the vehicle's current speed. The stopping distance is calculated as s = $vt + \frac{v^2}{2d}$ where v is the vehicle's speed, t the driver's reaction time, and d the maximum deceleration rate. It should be noted that the driver's reaction time t will be dependent on several factors, such as age and gender. However, for simplicity, a mean reaction time of 0.89 seconds is utilized here, which is based on a study of vehicle reaction times in 13 provinces in China (Lui et al., 2002).

The SUMO representation of the crossing person remains stationary, located in the middle of the lane in question. This is until EXODUS deems that the crossing pedestrian has cleared the vehicle lane. At that point, the crossing pedestrian is removed from the SUMO simulation. This functionality allows the SUMO car following model to determine whether the vehicle should slow down or where and when it may need to stop.

It should be noted that if there is a group of pedestrians crossing a given lane, then only the pedestrian nearest to the approaching vehicle or vehicles is represented in SUMO. However, if the person which is nearest to the approaching vehicles, reaches the opposite sidewalk while other pedestrians are still crossing the road then the next person closest to the approaching traffic is added to SUMO as blocking the lane.

The vehicle yielding model described here is a first implementation developed for demonstration purposes that ensures that the vehicles slowdown or come to a standstill, without colliding with the pedestrians. However, this model can be replaced by a more sophisticated model at a later date, such as the models described by Zhao et al, 2020.

5 SUMO and EXODUS Integration

As mentioned previously, EXODUS links to SUMO via the TraCI API (Wegener et al, 2008). EXODUS operates as the main controlling application having knowledge of all people, vehicles, and model geometry, such as buildings and road network. The SUMO model data is initially limited to vehicle and road network information. When necessary, EXODUS will inform SUMO about certain crossing pedestrians, which may impact the movement of vehicles, and generate a pedestrian in SUMO, if necessary, as outlined in Section 4. A summary of how EXODUS and SUMO are synchronized is provided below and is shown in Figure 5:

1) The EXODUS simulation starts SUMO and defines the time step interval. This is typically a 6^{th} of a second, which is the pedestrian movement time step utilized by EXODUS (Galea et al., 1996).
2) At each clock tick EXODUS updates the movement of the agents and advances the SUMO simulation by the same amount of time thus achieving synchronization.
3) EXODUS retrieves the updated position of the vehicles from SUMO via the TraCI API and represents them in EXODUS.
4) Pedestrian agents use the vehicles' current positions and speed for assessing their crossing decisions.
5) If a pedestrian agent is crossing a given lane and is identified by EXOUDS as possibly impacting any approaching vehicle's travel speed, a SUMO pedestrian agent is added to the lane that the pedestrian is currently crossing, see Section 3. If there is a group of pedestrians crossing a lane, only the pedestrian nearest to the approaching vehicle or vehicles is represented in SUMO (i.e., not all agents are explicitly modelled within SUMO).
6) As a result, vehicles in SUMO become aware of people in lanes when necessary, and can adjust their speeds accordingly (i.e., slow down/stop).
7) Changes in vehicles' speed and location are then sent back to EXODUS, where they are again used by agents in their decisions to cross the roads etc.

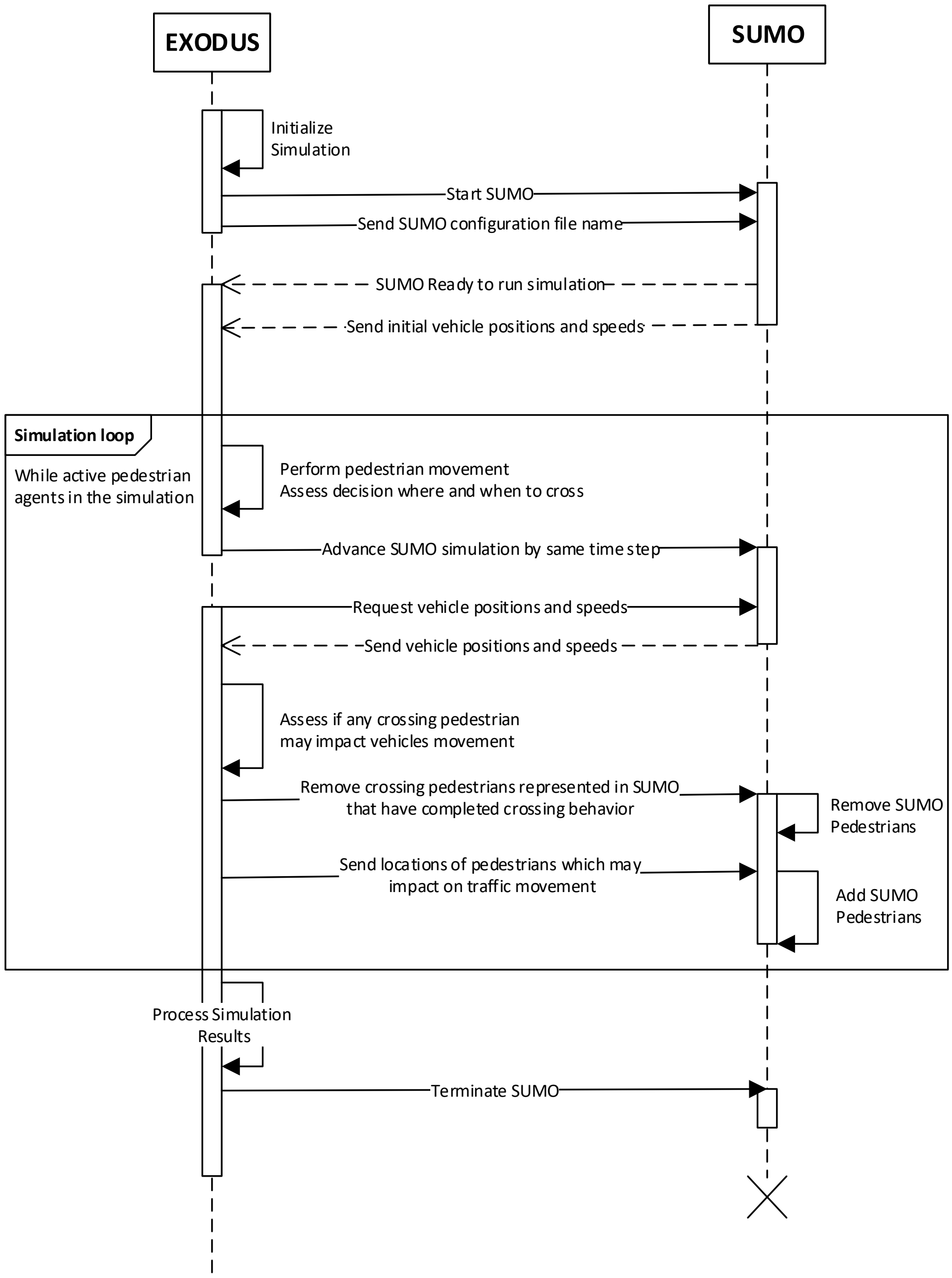


Figure 5: Sequence Diagram showing messages passed between the two applications.

6 Demonstration Case

To demonstrate the proposed crossing model, a scenario where a crowd of people are leaving en masse from a station is outlined. The scenario involves a full-scale evacuation where people must reach a place of refuge located across a main road, see Figure 6. To highlight the crossing behavior no designated pedestrian crossing is provided. This is so the simulated pedestrians are forced to select a location along a section of the road and attempt to cross it, utilizing the gap acceptance model. To highlight the proposed behaviors on traffic flow and pedestrian movement, there are four different scenarios considered. The objective of these scenarios is to establish the time for the people to assemble and therefore, determine how the assembly process is affected by the presence of traffic and pedestrian vehicle interaction.

- ***Scenario 1*** No interaction between the vehicles and pedestrians. In this case the pedestrians cross the road with no regard to vehicles on the road. Vehicles and pedestrians pass through each other, so collisions do not take place in the simulation. While unrealistic, this scenario is used as a base case for comparisons and to highlight the impact of representing pedestrian and vehicle interactions, enabled, in the next scenarios.
- ***Scenario 2*** Interaction between vehicles and pedestrians is enabled. All pedestrian agents are risk-averse, so will cross both lanes of the road in one go, when deemed safe to do so.
- ***Scenario 3*** Interaction between vehicles and pedestrians is enabled. All pedestrians are assigned as risk-takers, so will cross lane by lane, when safe to do so, sometimes waiting in the middle of the road, if deemed necessary.
- ***Scenario 4*** Interaction between vehicles and pedestrians is enabled. Here the split between risk-averse and risk-takers is evenly split at 50%. Therefore, depending on the pedestrian type they will use one of the crossing behaviors described in Scenarios 2 and 3.

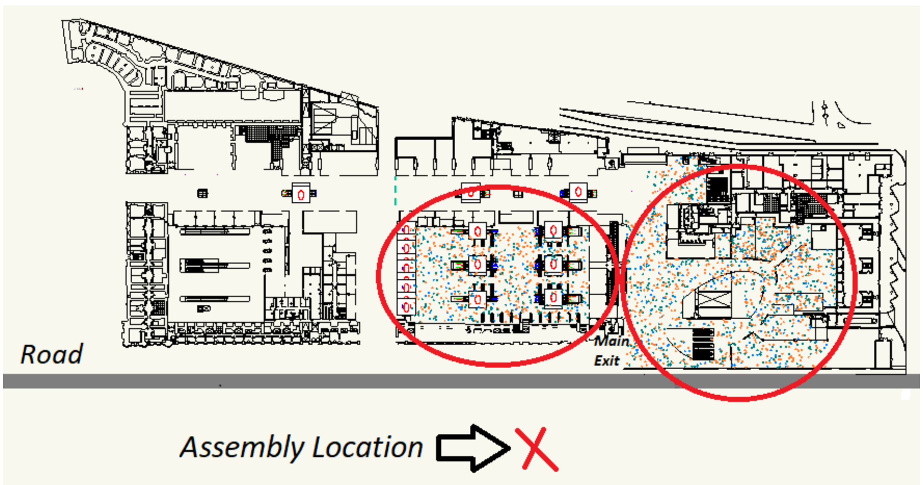


Figure 6: Station area being evacuated. The red circles indicate where people are initially located, who head through the main exit to the assembly point, marked with a red cross. Road shown in gray**.**

In all four scenarios, there are 2098 people placed within the circled areas shown in Figure 6. This population size is hypothetically based on assuming a maximum density within the circled areas of 1 person per 4m^2. In addition, the population is assigned a response time of between 60 and 90 seconds. The response time defines the time at which a pedestrian starts to evacuate the station and heads towards the assembly area. Furthermore, to eliminate the impact of different response times on the variability between simulations, each pedestrian responds exactly at the same time in all four scenarios and repeated simulation runs.

The vehicle generation rate in all simulations is also identical to minimize impact of traffic variability on results. The vehicles are generated at a rate of between 12 to 24 vehicles a minute, which represents a vehicle every 2.5 to 5 seconds, which represents a medium traffic level as defined by Hine (Hine, 1996). A bi-directional two-way road with vehicles driving on the left, as in the UK, is used for demonstration purposes. Furthermore, the SUMO's default car following model Krauss (Sumo, 2021) is utilized in all scenarios with a sigma value of zero, i.e., no randomness, to minimize variability.

The setting up of the scenarios is such that variability between the scenarios and simulation runs is artificially limited to emphasize the effect that the proposed crossing behavior has on the assembly process and how it is affected by the presence of traffic and pedestrian vehicle interactions.

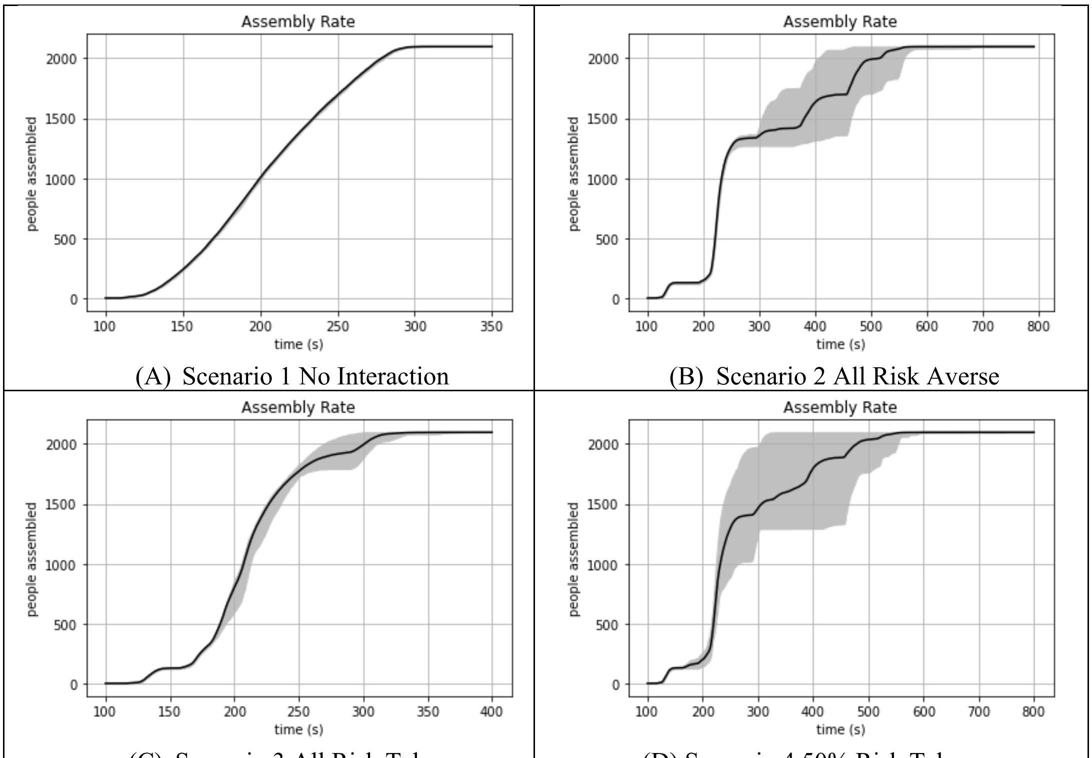
7 Results and Discussion

In Table 1 the overall simulation results from the four scenarios are presented, which include the time for the pedestrian agents to assemble at the assembly location shown in Figure 6. Each Scenario was run multiple times until an estimated accuracy of within 5% was achieved on the mean assembly time (Grandison, 2020) and shown in the column labeled "*Number of Repeated Simulations*" in Table 1. As expected, the time to assemble for the pedestrians is considerably quicker, in Scenario 1, since the pedestrians do not have to judge where or when to cross the road. Scenario 3 which included only risk-takers, pedestrians crossing lane by lane, was the next quickest (11% slower than Scenario 1), followed by Scenario 4, which had 50% risk-takers and 50% risk-averse people (55% slower than Scenario 1). As expected, Scenario 2, which only included risk-averse people took the longest time to assemble (85% slower than Scenario 1).

Scenario	Average Assembly Time (s)	Standard Deviation (s)	Number of Repeated Simulations
1 - *No Interaction*	302.9	2.18	10
2 - *All Risk Averse*	560.6	64.57	121
3 - *All Risk Takers*	337.3	20.40	21
4 – *50% Risk Takers*	469.7	109.43	168

Table 1: Pedestrian Results

To highlight the differences in behaviors and the variability of the results, the assembly time graphs for the four scenarios are presented in Figure 7. The graphs in Figure 7 shows the average assembly time graph for each scenario together with minimal and maximal ranges.



(A) Scenario 1 No Interaction

(B) Scenario 2 All Risk Averse

(C) Scenario 3 All Risk Takers

(D) Scenario 4 50% Risk Takers

Figure 7: Assemble time graphs for the four Scenarios, the shaded area represents the minimum and maximum average assembly ranges.

The graph in Figure 7A , highlights the lack of variabilty between the repeat simulations in Scenario 1. This is because the only variability in the results comes from the pedestrian-pedestrian interaction (Galea et al. 1996) in the EXODUS model, which in this scenario is very limited. Therefore, not modelling the pedestrian-vehicle interactions considerably removes significant human behavioral factors, such as when and where to cross and interaction with approaching vehicles.

The variability in assembly times for the risk-averse, Scenario 2, is shown in Figure 7B. As the pedestrian agents are risk-averse they are taking longer to find acceptable gaps in the traffic. If the probability model rejects an acceptable gap, the risk-averse pedestrian agents will take a longer time than the risk-taker agent to find an alternative acceptable gap. This is because a risk-taker only needs to consider vehicle gaps on one lane, whereas the risk-averse pedestrian needs to consider the gaps across both lanes of traffic, simultaneously. In fact, in Scenario 3, Figure 7C, the varibility is significantly less when compared to scenarios 2 and 4, i.e., Figures 7B and 7D, respectively, but larger than the non-realistic Scenario 1. Before going into detail as to the reasons behind this difference in variability between the four scenarios, it is necessary to look at vehicle behavior, which is discussed next.

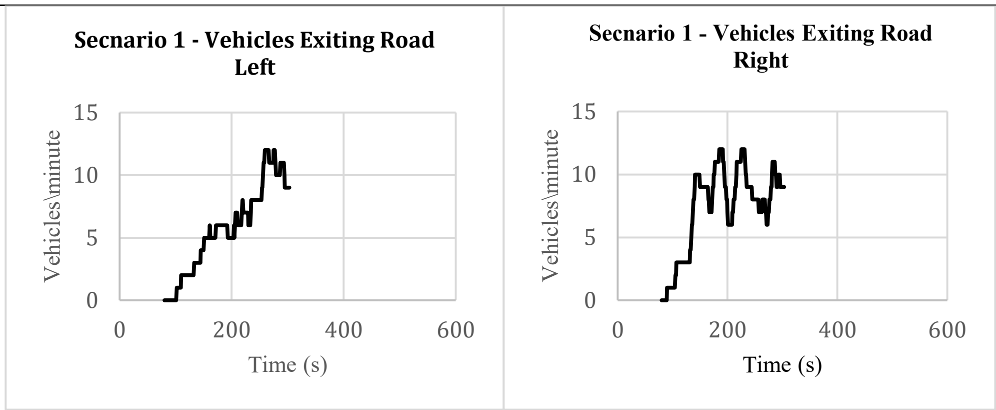
It should be noted that the same SUMO vehicle trip file, which specifies the vehicles' generation time, route, and characteristics, is used in all scenarios and across all simulations. The trip file was generated using a custom python script that generated vehicles travelling on both lanes, with a time gap between vehicles being randomly assigned a value of between 12 to 24 seconds, representing 2.5 to 5 vehicles a minute. Since the same trip file is used for all simulations and the default SUMO car following model with a sigma value of 0 is utilized, this effectively eliminates randomness from the vehicle model. Therefore, the only stochastic variability between simulations comes from the EXODUS conflict resolution algorithm (Galea et al., 1996) and the gap acceptance model described in this paper.

To highlight the impact of pedestrian crossing behaviors on traffic flows, Table 2 lists the total number of vehicles exiting from either end of the road during the simulations with the standard deviation shown in brackets. The standard deviation values are of interest here, since without pedestrian vehicle interaction the variation in assembly times between the simulations is limited. The inclusion of pedestrian crossing behavior impacts not only how long the assembly process will take, but also the variability of the data in relation to the total time for the pedestrians to assembly and the flow of traffic out of the system.

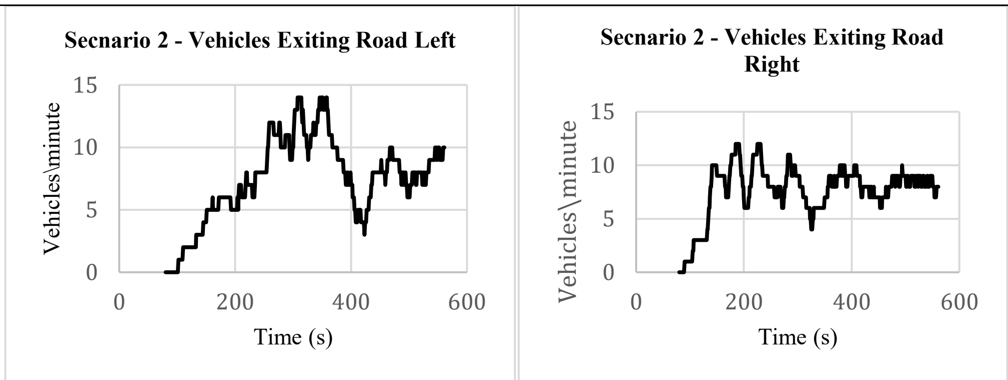
Scenario	Total Average Number of Vehicles	Average Number of Vehicles Travelling to the Right Upper Lane	Average Number of Vehicles Travelling to the Left Lower Lane
1 - *No Interaction*	53.55 (2.06)	28.44 (1.33)	25.11 (0.94)
2 - *All Risk Averse*	126.79 (19.10)	64.97 (9.03)	61.81 (10.07)
3 - *All Risk Takers*	58.95 (11.79)	29.82 (10.23)	29.14 (2.17)
4 - *50% Risk Takers*	112.11 (25.57)	58.12 (11.733)	54 (13.83)

Table 2: Vehicle Exiting Results. Note the standard deviation is shown in brackets.

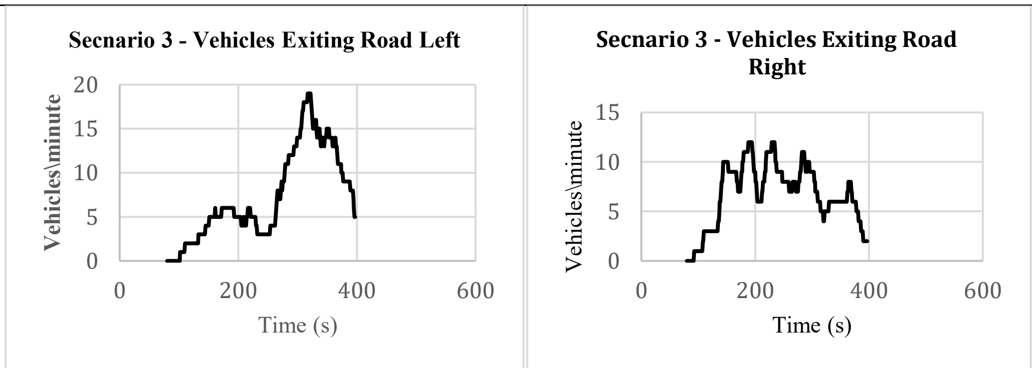
As expected, the scenarios that took the longest for the pedestrians to assemble had the greatest number of vehicles modelled. Therefore, to get some insight into the impact of pedestrians crossing behavior on traffic flow, the average exit flow rate of vehicles from either lane is shown in Figures 8 and 9, for all four scenarios. Looking at the *risk-taker,* Scenario 3, and more specifically at Figure 8C, the flow rate of the vehicles exiting the left side of the road starts to drop at around 200 seconds. This drop takes place sooner compared the other scenarios and is caused by the crossing pedestrians on the road, slowing down as the opposite sidewalk becomes congested. Consequently, the pedestrians on the road start to block the oncoming vehicles. As the vehicles start to slowdown or even stop to avoid colliding with these pedestrians, more people have the opportunity to start crossing the road, hindering further the vehicle flow, see Figure 10C. The flow rate then only picks up again once the congestion on the opposite sidewalk eases, therefore allowing the pedestrians to also clear the road.



(A) Scenario 1 – No interaction



(B) Sceanrio 2 – All risk-averse



(C) Scenario 3 - All risk-takers

Figure 8: Vehicle Exit Flow Rates, Scenarios 1 to 3

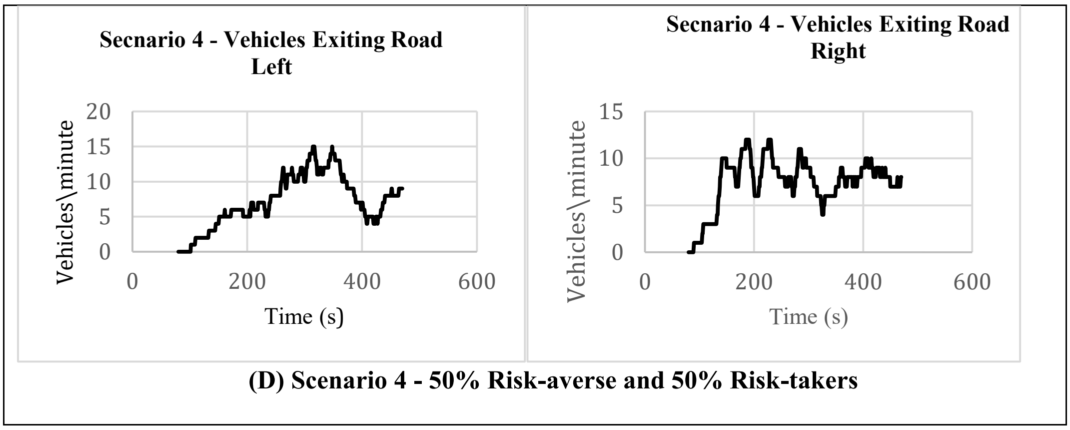


Figure 9: Vehicle Exit Flow Rates – Scenario 4

For comparison, snapshots from all four scenarios are shown in Figure 10, at around the 3-minute mark. As expected, there is a greater number of people waiting to cross in the case when all pedestrians are risk-averse, Figure 10B. In Figure 10D, it can be observed some pedestrians standing in the middle of the road, waiting for a safe gap in the lower lanes traffic before continuing to cross the final lane. Then in Figure 10C, as mentioned previously, risk-taker pedestrians are blocking the flow of traffic and crossing between the stationary vehicles.

In Scenario 1, where the interaction between the vehicles and pedestrians was not considered, very little variation between repeated simulation runs is observed and crossing pedestrians do not have an impact on the traffic flows. It should be noted, while pedestrians and vehicles do not interact in Scenario 1, some road crossing behaviors still take place, thus when the pedestrians reach the road, some delays occur as the agents negotiate the crossing of the road. In Scenario 2, the assembly of agents takes considerably longer compared to the other four scenarios. This is because the pedestrians are risk-averse and utilize only the *Double Gap* crossing behavior. Therefore, waiting longer before choosing when to cross compared to the other three scenarios. Hence, having less impact on the traffic flows than scenarios 3 and 4.

The simulation where all agents were risk-averse, Scenario 2, the pedestrian took 85% longer to assemble when compared to Scenario 1, where pedestrian vehicle interaction was not modelled. When comparing Scenario 1, with the risk-taker Scenario 3, there was only a 11% increase in assembly time. Therefore, while it is important to model pedestrian vehicle interactions as this improves realism of the scenario, a key component that must also be considered, is the crossing behavior of the pedestrians as this affects the overall movement of the pedestrians and the vehicles. Therefore, being able to quantify the impact that crossing behavior has on the pedestrian and traffic movement is an important factor when planning for mitigation strategies for crowd management.

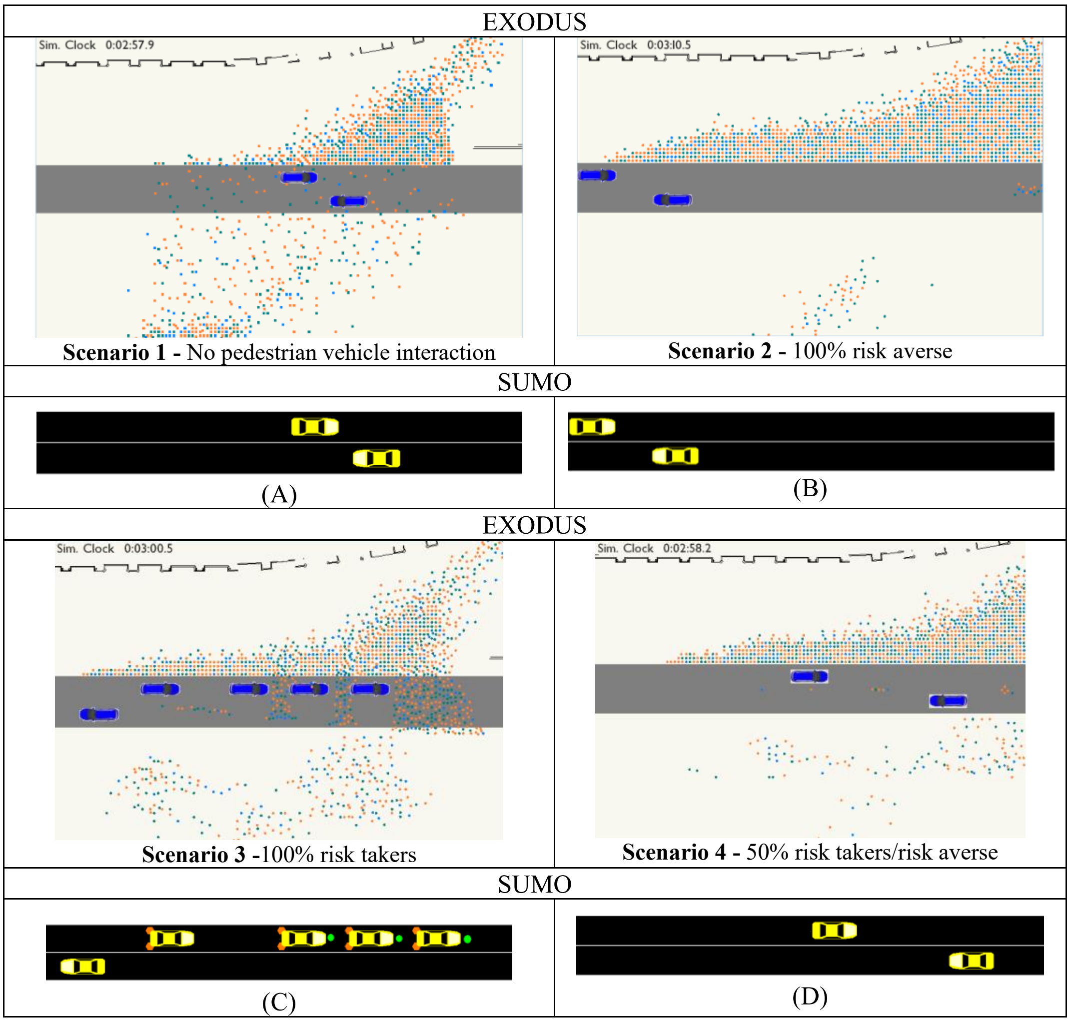


Figure 10: Snapshots of the examined scenarios at the 3-minute mark showing varying levels of pedestrians in the road. From none as in Scenario 2 (B), people waiting in the middle of the road Scenario 4 (D) and Scenario 3 pedestrians blocking vehicle and taking advantage of stationary traffic (C). The images at the top are from EXODUS while the images at the bottom from SUMO. In Scenario 3 you can see the Sumo *vType* person, the green circles, blocking the traffic in the upper lane. Red dots at the back of the vehicles indicate stopped vehicles. The colors of the individual pedestrians represent their age category, light blue ones are aged under 30, Orange 30 to 50 and Dark Green over 50.

In Scenario 3, where all the pedestrians are risk-takers and choose to utilize the *Double Gap* crossing behavior, a significant number of pedestrians choose to cross the road simultaneously. Therefore, considerable congestion can build up on the opposite sidewalk and along the center of the road, where pedestrians may choose to wait before attempting to cross the second lane of traffic. This congestion prevents other crossing pedestrians reaching the opposite sidewalk or central section of the road, resulting in pedestrians blocking the lanes of traffic. Then as the traffic slows and starts to stop, this then allows more of the pedestrians waiting to cross, the opportunity to do so. The less variability observed in the assembly time for Scenario 3, over scenarios 2 and 4, is because once the crossing pedestrians block the traffic flow, the only thing preventing them from reaching the assembly location is the congestion of pedestrians in the vicinity. The delay caused by the pedestrian congestion is considerably less than the variation in the delay caused by waiting to cross safely two traffic lanes.

In Scenario 4, where there is a 50% mixture of risk-taker and risk-averse pedestrians, the variability in assembly times is the greatest and the overall assembly time is similar to Scenario 2. This is because in parts of the simulations the risk-taker pedestrians may block traffic flows, where on other occasions this does not occur. When risk-takers slow or bring the traffic to a standstill, this provides opportunities for risk-averse pedestrians to cross. However, towards the end of the simulation, the risk-averse pedestrians will struggle to cross the road, as the traffic then starts to flow unhindered.

8 Conclusions and Final Remarks

A method of how SUMO can be connected to a third-party pedestrian model, namely EXODUS, to model pedestrian crossing and interaction at midblock locations was demonstrated. The presented model allows the user to evaluate people crossing outside designated areas using two different pedestrian crossing styles, namely *Double* or *Rolling Gap*. The ability to include a psychological *risk-taker* or *risk-averse* pedestrian attribute allows the user to consider the urgency of the pedestrians, which could be of benefit when modelling rush-hour or emergency situations, such as an evacuation from a large transportation hub.

The outlined crossing behavioral algorithm combines research from several studies to derive a unique *Gap Acceptance Model*, to accommodate the *Double* or *Rolling* Gap pedestrian crossing styles. To represent vehicles yielding to crossing pedestrians, a simplistic approach was taken, which relies on SUMO's inbuilt car following model. This simplistic approach is only a first step and research into a more suitable approach is ongoing. Therefore, it should be noted that currently this work provides a framework for experimental evaluation only, as further calibration and sensitivity of the model crossing parameters is required, before carrying out possible validation. Additional research is ongoing, looking at pedestrian choices and urgency and how this relates to the decision to use a marked pedestrian crossing (Lawrence et al. 2020). The presented demonstration case looked only at a two-way road scenario, a possible further study could be to compare these results with a two lane one-way road to identify what impact this proposed crossing behaviours may have.

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