Modeling Public Transportation Attractiveness in System Dynamics: The Significance of Safety Perception

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Abstract

The perception of safety while using public transport is a neglected influence on ridership in most system dynamics transport models. With a preliminary conceptual model, we show how safety perception could be integrated into public transport models. We modeled safety perception as a function of internal safety measures as well as the external social environment that the transport system is embedded in. Perceived safety then influences the attractiveness of public transport, on top of the typical convenience factors found in existing models. The model is sensitive to changes in both indicators of safety perception, confirming the importance of these factors. Therefore, we contend that including these factors improves the conceptualization of public transport attractiveness, which leads to a better understanding of possible policies to increase ridership. Nevertheless, the conceptual model presented here is highly simplified and preliminary. We further discuss opportunities for future directions in public transport modeling for including safety perception.

Keywords: transportation, public transport, safety perception, public transport policies, urban mobility
Word count: 4015

1. Introduction

Public transportation is a recurring subject in system dynamics models. Urban transport systems, and therefore public transportation as an important part of it, are complex dynamic systems that include interactions within its parts as well as feedback relationships – a system dynamics approach is, thus, a feasible and obvious choice (Yang et al. 2014, 522). The topic of public transportation also gains attention as the importance of low-emission urban mobility continues to rise. Researchers often either analyze its impact on the environment, which includes CO2-emissions, pollution, congestion, road safety, and land value, or its interaction with other modes of transport (e.g., Yang et al. 2014; Armah et al. 2010). Additionally, system dynamics is used to explore different policies, that aim to increase public transport usage in order to reach sustainability goals (e.g., Sayyadi and Awasthi 2017; Ercan et al. 2016).

While there are many factors that influence the use of public transportation (e.g., economic growth and the affordability of cars and urban sprawl), some of them are outside of the influence of transport operators. This analysis focuses mostly on factors within the public transport system and therefore factors that can be changed. In other words, it concerns the internal factors determining the attractiveness of public transport for potential passengers. In system dynamics models covering this topic, the attractiveness of public transport is mostly based on convenience of use, influenced by one or more of the following indicators: average distance to the next bus stop, waiting time, reliability, travel time, or area covered by public transport (Fontoura et al. 2019; Ercan et al. 2016). However, such indicators only partially capture the decision-making process of (potential) public transport users.

We contend that users' perception of public transport safety is a significant factor that partly accounts for ridership, a component that is lacking or underrepresented in existing models, to our knowledge. For instance, when analyzing the decline in public transport ridership in Southern California, a low perception of safety proved to be one of the main drivers that led people to quit using public transport, after increased access to cars. Whereas, an expansion of bus services, contrary to popular belief, had no positive effect on usage (Manville et al. 2018 40-43). Lynch and Atkins (1988), as well as Yavuz and Welch (2010) also suggest that perceived safety influences the usage of public transport, especially for vulnerable groups like women and elderly. Consequently, disregarding perceptions of safety when modeling public transportation attractiveness could prove to be insufficient.

This paper seeks to fill this gap in the literature by explicitly representing safety perception in a public transport model. We present and describe a preliminary conceptual system dynamics model that incorporates safety perception as a factor that determines public transport attractiveness. The conceptual model is a simplified representation of the public transport operator's and users' decision-making. It intentionally ignores many aspects such as maintenance costs or subsidies because it only works as a conceptual frame for introducing safety as an important factor in system dynamics transportation modeling.

In the following section, we first describe the feedback structure of the model (Fig. 1), which explains how safety perception could affect public transport usage. Then we detail our model, which is stylized in a stock and flow diagram (Fig. 2). Based on the simulation results generated by the model, we further discuss the significance of safety-related system components and how it could potentially influence policy design for increasing public transport ridership. Lastly, we consider the limitations of our conceptual model and reflect on future directions for modeling public transport attractiveness in system dynamics models.

2. Conceptualizing Safety Perception

2.1. Feedback Loop Structure

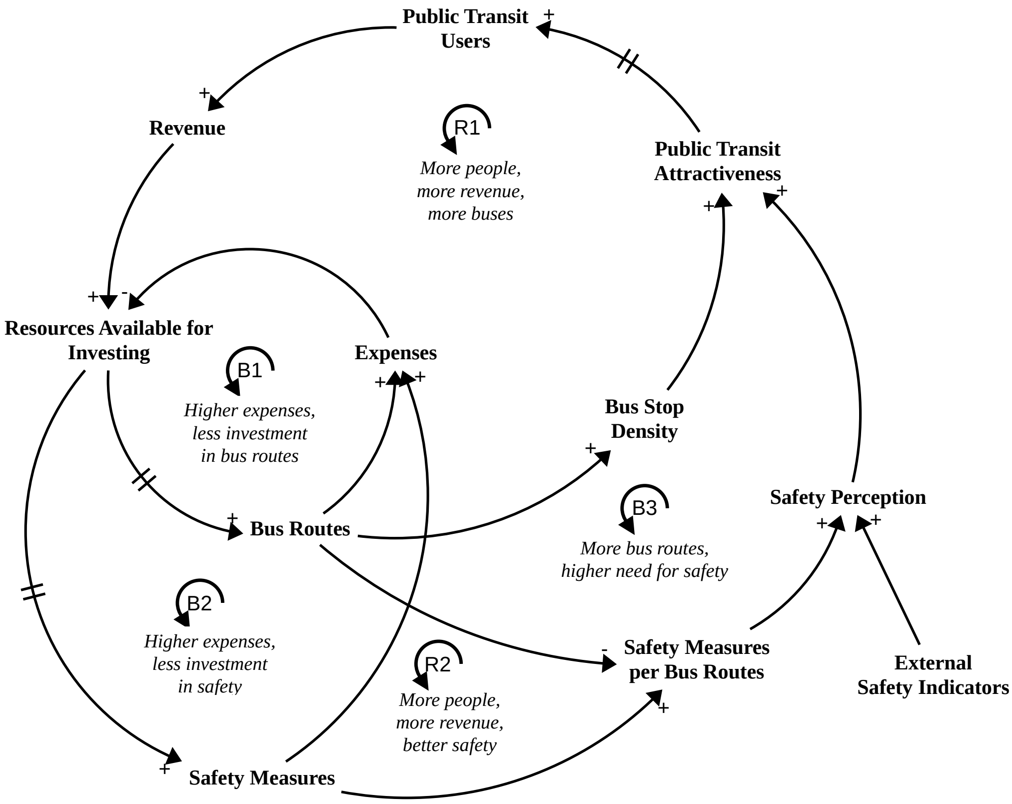

Fig. 1. Hypothesized feedback structure of safety perception in public transport usage.

In the first step, we show the dynamics of the problem. The two reinforcing loops R1 & R2, as shown in Fig. 1, influence the behavior in the same way: higher public transport usage leads to more revenue and therefore more money is available for investing, which either leads to more bus routes (R1) or more safety measures being implemented in the bus routes (R2). Both improve the attractiveness of using the bus and therefore lead to more public transport users.

B1 and B2 counteract the effect mentioned above since investing in bus routes and safety measures is followed by increased operational costs, which leads to less money being available for further investments.

B3 shows the interaction between bus routes and safety measures. An expansion of bus routes needs to be followed by an expansion of safety measures, otherwise, the average safety measurements implemented per bus route declines. Safety measures mostly have a local impact, so safety measures per bus route are hypothesized to be more important than the total amount. An increase in bus routes could therefore lead to a decrease in passengers, despite the increase in convenience it causes for passengers, if the balance between bus routes and safety measures declines and impacts potential passengers' safety perception.

2.2. Conceptual Simulation Model

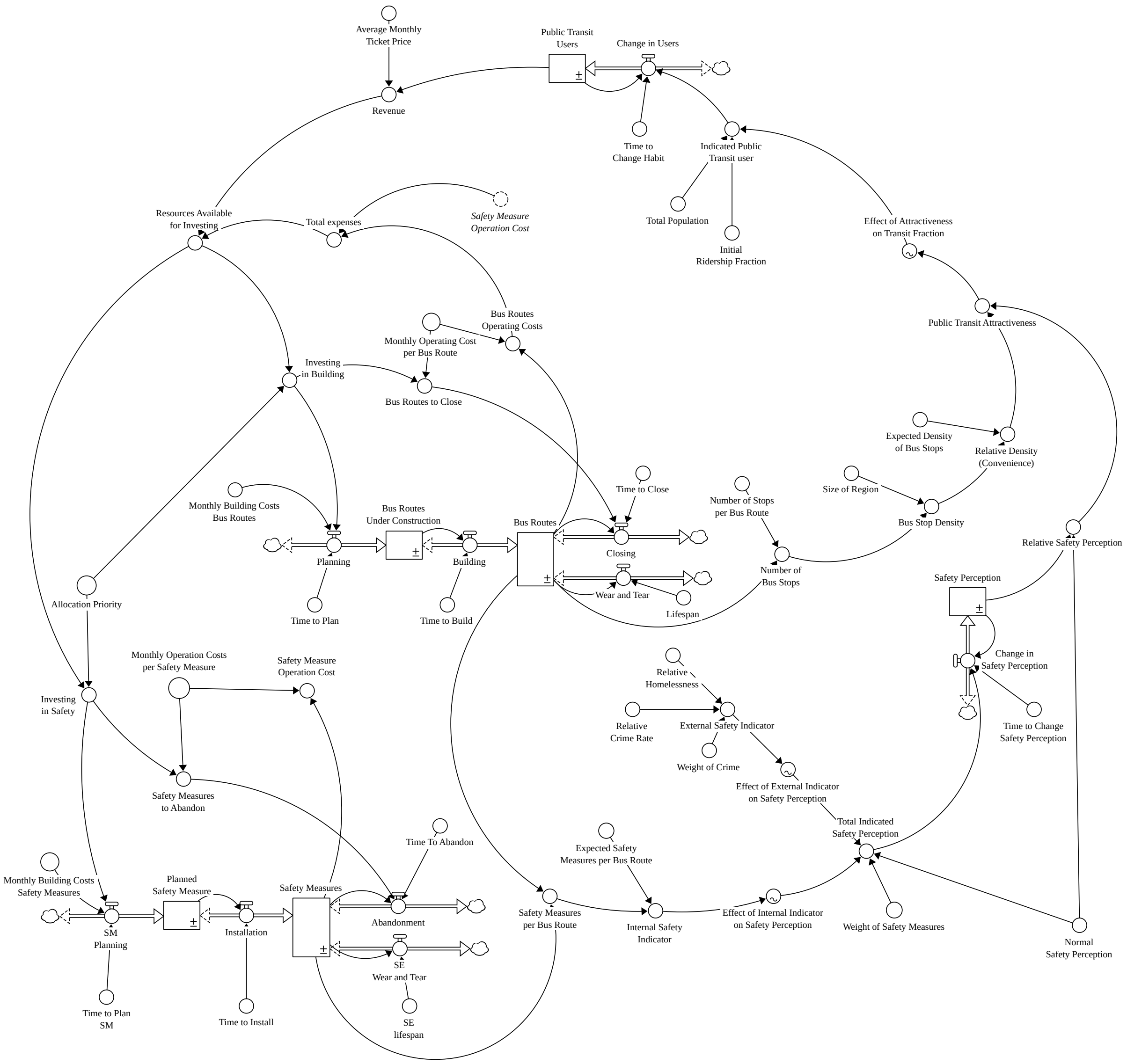

Fig. 2. Stock and flow diagram of conceptual public transport model with safety perception.

Public transportation models commonly capture the dynamics of transport usage with a stock of users that increases or decreases based on the attractiveness of public transport. For simplicity, we made public transport attractiveness a multiplicative function of bus stop density, as a proxy for convenience, as well as the average passenger's perception of safety on buses. To model convenience, we used the density of bus stops per squared kilometer of a certain region and normalized it to an expected density of 10 bus stops per squared kilometer. This relative density, then, represents passengers' accessibility to bus stops near them. For instance, if the relative density is less than 1, it indicates that public transportation is inconvenient and, by extension, less attractive. Bus stop density is determined by the product of the number of bus routes and the average number of bus stops per route. Bus routes are represented as a stock that depreciates with time (given the wear and tear of infrastructure that must be maintained) as well as a decision-rule for closing routes based on the net resources available for operation. When revenue is less than expenses, then a proportional number of routes is closed to balance the books of the transport operators. The bus routes increase with a construction delay based on the amount of resources available for investment. When there is a surplus of resources (Revenue – Expenses > 0), the operator is assumed to invest in building more routes and expand the public transport system. This sector is meant to be a simplified proxy for the public transport system, which has been represented with more detailed complexity in existing literature. The objective, here, is not to build a comprehensive model of a public transport system, but to simply test an initial conceptualization of passenger safety perception and consider how it could be added as a component to existing models.

Safety perception is operationalized as an intangible stock that varies from 0 to 1, where 1 represents the perception of 100% or maximum sense of safety. Relative safety perception is normalized to a normal value that is assumed to be 0.5. Public transport attractiveness increases when safety perception is more than 50% and vice versa. The indicated safety perception is determined by two equally weighted effects from external safety indicator and internal safety indicator. Passenger perceptions of safety for taking public transport is influenced by the social environment. Here, we operationalized external safety as a relative measure of a region's crime rate and homelessness, which are proxies for the perceived danger in the social environment.

The rapid increase of homeless people has been suggested to contribute to the fall in transport ridership in Los Angeles (Manville et al. 2018, 44). As public spaces, public transport as well as public transport stops can offer shelter from the elements, which makes them attractive for homeless people. Most transport agencies report issues with homeless people, for example regarding behavioral issues sometimes in combination with mental illness. According to them, it affects other transport users' ability to use public transport facilities (National Academies of Sciences, Engineering, and Medicine 2016, 7-18). However, we want to emphasize that the literature cited only suggests a relationship between the presence of homeless people in public transport facilities and perceived fear and discomfort, but not actual incidents. While homelessness is a major issue in many cities, there are also other indicators for social problems that influence perceived safety, e.g., drug use, that could be used instead, depending on the depicted city. The relative measure of a region's crime rate influences the region's reputation as safe or unsafe, which affects passengers' perception of safety on public transport as opposed to personal transportation.

When these environmental indicators are set to 1, it means that the region is not any more dangerous or safer than the norm (e.g., national average). When these are set to more than 1, then passengers experience a more than normal sense of danger, which would in turn negatively affect their public transport safety perception. The internal safety indicator is a normalized value of the average number of safety measures per bus route to an expected normal number assumed to be 3. The effect of both the internal and external indicators are simply modelled as a logistic function, where the effect on safety perception increases decreasingly to a maximum of 2 when the relative indicator increases above 1; and decreases decreasingly toward 0 when the relative indicator decreases below 1.

Safety measures are represented as a stock with a similar structure to bus routes. It depreciates over time and may be abandoned if there is a deficit in the resources available. It increases with a delay when there is a surplus of resources available for investing and installing safety measures. Here, the variable, *safety measures*, is a proxy for more specific measures such as installation of equipment (e.g., security cameras) or other forms of measures like policing. Especially installing lights and the presence of security staff have been proven to increase the perceived safety feeling at nighttime (Loewen et al. 1993; Yavuz and Welch 2010 2495-2496). The amount of resources available for investment is allocated proportionally between building more routes and implementing more safety measures. Allocation priority is a parameter that can be set between 0 to 1 range, which indicates the weight of building bus routes.

3. Analysis

The model was simulated on Stella Architect (version 3.2) over a time horizon of 240 months with a time-step of 1/8 using Euler integration. In this conceptual model, the total population size was held constant at 4 million with an initial fractional ridership of 0.25, and the size of the region was set to 1000 squared kilometers. The stocks for the bus routes and safety measures were initialized at a quarter of the long-term equilibrium value of the system, to correspond the size of the initial public transport system to the initial fractional ridership. We generated a baseline scenario and two divergent scenarios to show the reaction of the system to different circumstances, as shown in table 1.

Additionally, a sensitivity analysis has been conducted and documented in the appendix. It showed that the model is mostly appropriately sensitive to the constant parameters and only changes behavior where expected, with the exception of changes in Initial Ridership Fraction and Weight of Safety Measure, which could be overcome with further modeling and are partly due to the model being a simplified and conceptual.

Scenario	Allocation Priority	Relative Crime	Relative Homelessness
Baseline Scenario	0,9	1	1
Scenario 1: Higher Priority for Safety Measures	0,6	1	1
Scenario 2: Low External Safety in Environment	0,6	1,5	1,5

Tab. 1 Scenario parameter overview

3.1. Baseline Behavior

To generate a baseline for the system, we set the relative crime rate and relative homelessness to 1 (normal). In addition, we set allocation priority as 0.9 to represent a much higher weight given to building routes at the expense of safety measures (0.1).

With reference to Fig. 3, public transport ridership increases for a short-lived period before decreasing decreasingly toward 0 by the end of the simulation duration. This development is explained by public transport attractiveness, which starts out high before it starts declining. With 90% resource allocation to building bus routes, we observe that the bus routes stock starts out with exponential growth as more and more is being invested there as opposed to safety measures (R1). Correspondingly, we observe that safety measures decline continuously over the time horizon since there is insufficient investment in this aspect of the transport system (B2). Since the number of bus routes increases, bus stop density increases and the convenience factor for public transportation is high (R1 – virtuous circle). However, the declining safety measures translates to a decline in safety perception, which in turn scales down the overall public transport attractiveness despite the high convenience (R2 – vicious circle). This accounts for the slow decline in attractiveness for the first part of the simulation.

As attractiveness continues to decline over time, public transport ridership begins declining as well. A reduction in ridership results in lowered revenue and thus less resources available for investment. Moreover, expansion of bus routes also incurs higher operational costs (B1). Eventually, bus route expansion is impeded by insufficient resources, which then triggers bus route closures and accounts for the sharp decline in bus routes after the growth spurt (R1 – vicious circle). In Fig. 3, we notice that safety perception increases as bus routes closes. This is an artifact of B3 since the rapid decline in bus routes results in an increase in the average safety measure per bus route. Regardless, public transport attractiveness is driven by R1 since the rapid decline in bus routes makes bus stop density, and by extension, convenience decline at a similar rate. And since the attractiveness is modelled as a multiplication of convenience and safety perception, an increase in safety perception alone will not lead to an increase in attractiveness. To sum up, the decline in public transport attractiveness over the time horizon is first driven by the declining safety perception (R2) and, later, by the declining bus stop density (R1).

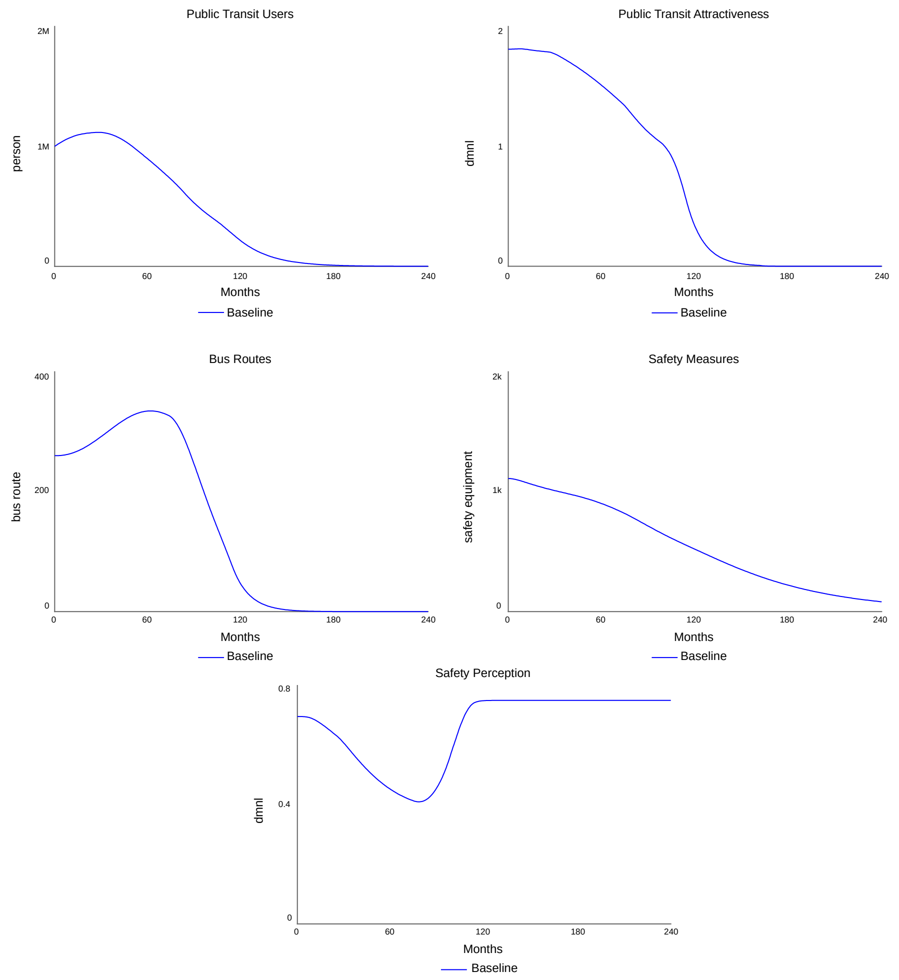

Fig. 3. Baseline simulation results of key indicators.

3.2. Scenario 1: Higher Priority for Safety Measures

When simulating the model with a higher priority for safety measures, but otherwise unchanged parameters, the behavior mode changes drastically. The allocation priority is set to 0.6 in the simulation for scenario 1, now 40% instead of 10% of the resources get invested into safety measures.

As seen in Fig. 4, the ridership increases increasingly at first, the development then slows down and the ridership continues to increase decreasingly until it reaches a ceiling of 3 million people towards the end of the simulation. The behavior starts with a similar increase in ridership as in the baseline scenario but in contrast to it, continues to increase above this initial growth spurt. The continued increase can be traced back to a continued increase in transport attractiveness. It increases due to an equal increase in bus routes as well as safety measures, caused by increased investment in both, due to the increasing revenue (R1 and R2 – virtuous cycle). The safety measures increase nearly equally to the bus routes, which causes an initial subtle increase and then a stable number of safety measures per bus routes, resulting in the same behavior for the safety perception.

The increase of bus routes is slower in comparison to the baseline scenario, due to the lower allocation priority, but it is also more sustainable since the positive ridership development provides an increasing revenue, that is necessary to not only invest, but also maintain the bus routes as well as the safety measures. It reaches a ceiling when the effect of attractiveness of the public transport on transport fraction reaches its ceiling and therefore all potential transport users become active users. We defined the effect as an S-shaped curve depending on the attractiveness. The ceiling at three quarters of the total population was an assumption set in the model to reflect that no matter the attractiveness, a part of the population will not switch to public transport for varying reasons.

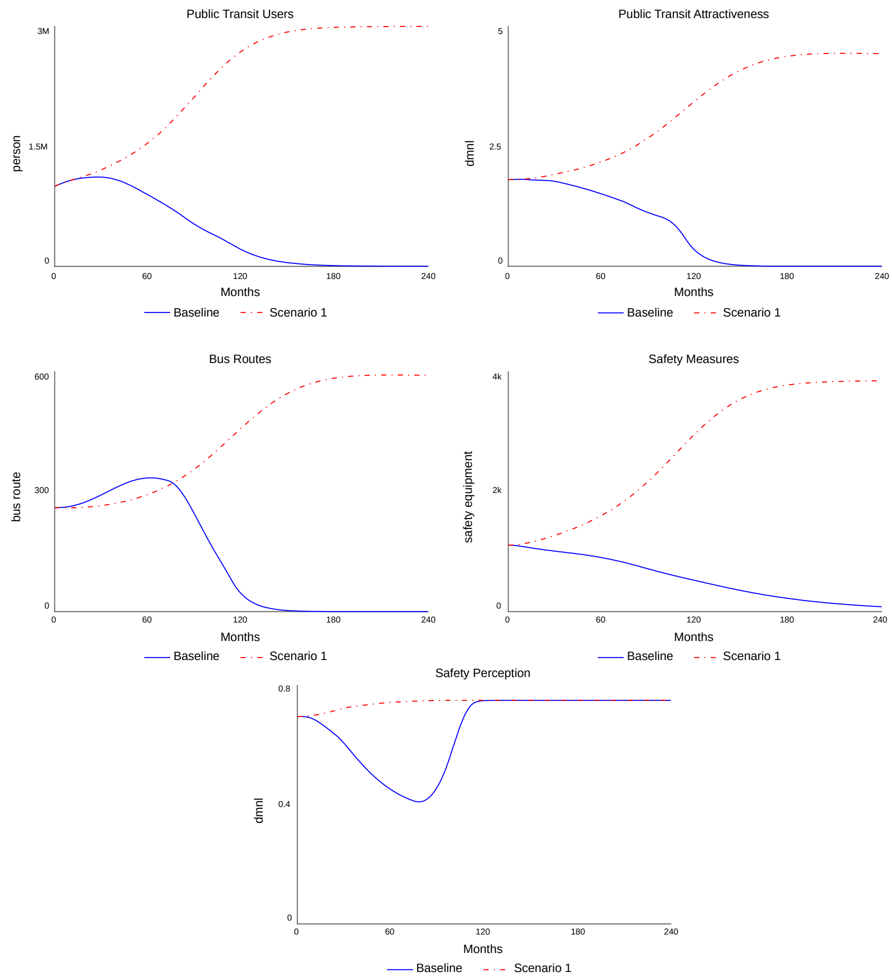

Fig. 4. Scenario 1 simulation results of key indicators.

3.3. Scenario 2: Low External Safety in Environment

The next scenario shows the influence of the embedded social environment on public transport usage. While maintaining the parameter values set in scenario 1, we further set the relative crime rate and the relative homelessness to 1.5 (above normal) for both. This scenario then represents a situation where the region modeled is perceived to be more dangerous than what was considered the norm for the nation. As a result, the low external safety indicator negatively influences the safety perception, resulting in an initially low perceived safety and consequently lower overall attractiveness of public transport and therefore fast decline in ridership (see Fig. 5).

The initially low value of attractiveness, compared to the previous scenarios, leads to an initial decrease in ridership and therefore revenue. Because of the declining revenue, the transport operator cannot invest in measures to increase the attractiveness. Instead, bus routes decline when the transport operator can no longer afford to keep them operational and abandons them as well as the normal wear and tear. As a result, the convenience and as follows the attractiveness decreases (R1 – vicious cycle). The declining attractiveness leads to a further decrease in ridership, until it reaches zero, at about 70 months.

The safety perception stays stable at first. Despite the decrease in revenue, the safety measurements decrease slower, due to the larger share of investment (40%) into safety measures as well as a lower building and operational costs. As already observed in the baseline scenario, the safety perception begins to increase slightly with the decline of bus routes, due to B3. The faster decline of bus routes in comparison to safety measures leads to an increase in the average safety measure per bus route. However, safety perception increases to a much lower equilibrium than the other two scenarios because of the more social environment that affects users' valuation of safety. Regardless, the overall public transport attractiveness continues to shrink, since the behavior is dominated by the rapidly declining bus stop density, and by extension convenience (R1). The ridership approaches 0 at about 80 months, significantly earlier than in the baseline scenario. Unlike the baseline, both safety perception and bus stop density (convenience) are decreasing from the get-go. Once this dynamic sets in, it leads to a fast downwards spiral.

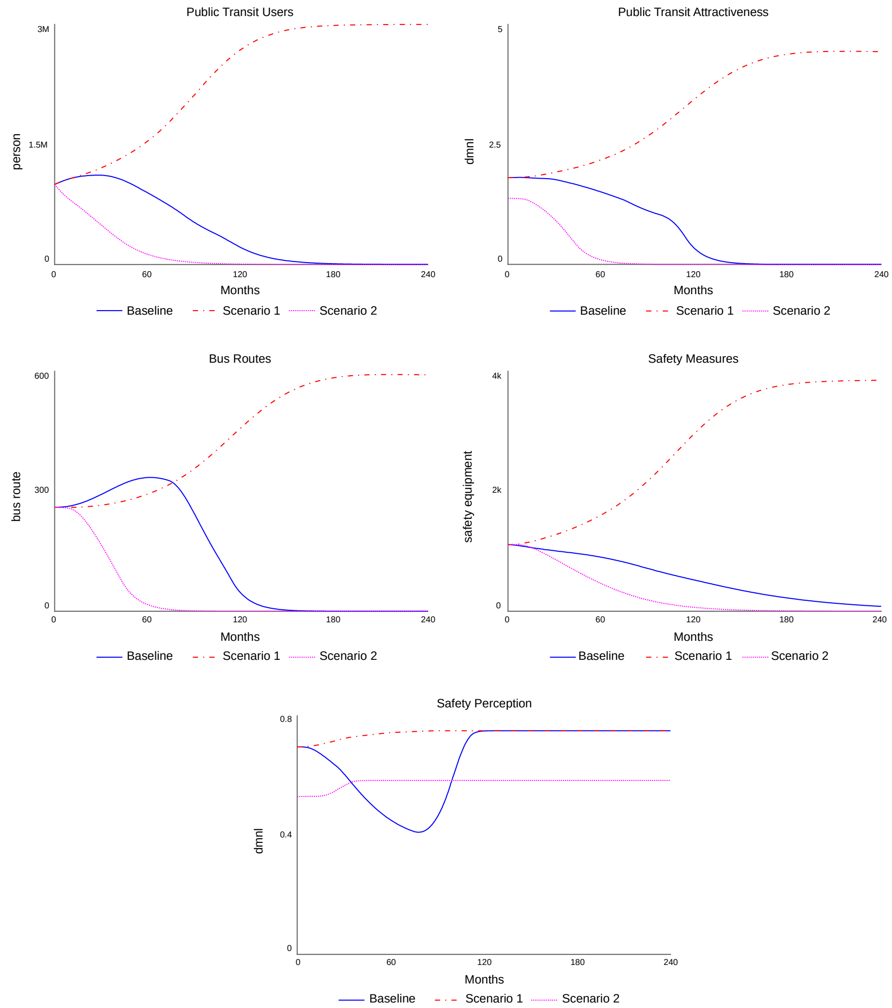

Fig. 5. Scenario 2 simulation results of key indicators.

4. Discussion

Based on the above scenario analyses, we can conclude that the model shows a strong sensitivity to changes in safety perception, when other factors stay stable. While a high safety perception only results in a high ridership when convenience is also at a satisfactory level, this relationship also persists in the other direction. Public transport is only attractive when both factors meet the minimum standard expected of users. The results produced by the conceptual model finds support for Manville (2018) theory that without changes to perceptions of public transport safety, expansion of the transport system would not significantly influence ridership.

High-leverage policies for increasing ridership would, consequently, seek to ensure that both convenience and safety are sufficiently addressed. Safety perception consist of two important factors, internal and external safety indicators. As the model is sensitive to changes in both, it points towards their importance in the system. Decision-makers could seek to amass internal safety perception by ensuring sufficient resource allocation for implementing safety measures. Yet, if the embedded social environment is perceived to be too dangerous, then perhaps internal measures might not be sufficient to overcome the risk-averse behavior of potential users. This calls for public policies to address more systemic problems like crime and homelessness, that have significant impact on safety perception and thus ridership. These preliminary policy insights, however, should be tested with more robust empirical modelling that is beyond the scope of this conceptual model.

It is important to note that the model excludes many external influences on public transit attractiveness and only depicts a limited part of the many influences on the use of public transportation.

The main limitation of the model is that safety measures accumulate solely based on resources allocated to safety, independent of the number of existing bus routes. When bus routes are closed due to operating budget issues, the implemented safety measures do not get abandoned proportionally. This resulted in increased safety perception as more and more of the bus routes are closed. This does not significantly affect the system's performance as the model compensates by reducing bus stop density and thus the attractiveness of public transport. Nevertheless, this issue can be overcome with further modelling; for instance, safety measures abandonment could be made to correspond to the rate of bus routes closures. Safety measures and bus routes could also be modeled as co-flow structures. Future research seeking to integrate safety perception in transport models could benefit from this added layer of complexity.

Another issue is the aggregation of safety measures into a single stock. Safety measures like lights, security personnel, or security cameras all have different costs and different impacts on the safety perception. The impact does not always correspond with the costs. Other measures, like reliable information about departure times, have also been described as improving the perception of safety (Lättman et al. 2020), but might not be seen as typical safety measures by transport operators. Therefore, further differentiation might be necessary to give a more accurate reflection of the influence of the measures on the perceived safety.

While there is a need to further improve the structure of the model, as well as to specify the safety measures and their impact in order to make the model more empirical, this is beyond the scope of this paper. Our purpose here is to demonstrate the significance of safety perception in public transport ridership with a simple conceptual model, which is supported by our simulation results. That is to say that it is important to capture this additional layer of complexity in public transport users' decision-making in existing and future models, especially for regions where public safety is a privilege rather than a norm. Models that only consider convenience factors in the decision-rule for ridership changes are arguably an oversimplification. We contend that safety indicators and perceptions should be added to the model boundary in order to better analyze potential public transport policies.

5. Concluding Remarks

In this paper, we have presented a conceptual model of public transportation attractiveness and its influence on ridership, which includes safety perception as a deciding factor for the attractiveness of using public transportation. We included different influences on safety perception, such as external safety indicators and internal safety measurements to account for different circumstances. The simulation results showed the importance of safety perception for ridership and the success of a public transportation system in the long run.

Therefore, we concluded that safety perception is a factor that should be included in future public transportation models. It is a so far neglected influence. Our model is largely simplified and meant to be a conceptual framework to inspire the inclusion of safety elements in future models depicting public transportation in a more complete way.

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Appendix A: Model Documentation

Variable	Equation	Units	Documentation
Bus_Routes(t)	Bus_Routes(t - dt) + (Building - Closing - Wear_and_Tear) * dt INIT Bus_Routes = 1040*0,25	bus route	The stock represents the number of bus routes that are operated by metro. Bus routes are defined as a stock as they accumulate by building and deplete due to wear and tear and closing.
Bus_Routes_Under_Construction(t)	Bus_Routes_Under_Construction(t - dt) + (Planning - Building) * dt INIT Bus_Routes_Under_Construction = 104*0,25	bus route	The stock Bus Routes under Construction contains planned but not yet built Bus Routes. This means they are in a state of conceptualization, preparation or construction. The stock represents a material delay. It increases by the inflow planning and decreases through the outflow building after a Time to Built.
Planned_Safety_Measure(t)	Planned_Safety_Measure(t - dt) + (SE_Planning - Installation) * dt INIT Planned_Safety_Measure = 222*0,25	safety equipment	The stock Planned Safety Measures contains planned but not yet installed/implemented Safety Equipment. This means it is in a state of conceptualization or preparation. The stock represents a material delay. It increases by the inflow planning and decreases through the outflow installation after a Time to Install.
Public_Transit_Users(t)	Public_Transit_Users(t - dt) + (Change_in_Users) * dt INIT Public_Transit_Users = Total_Population*Initial_Ridership_Fraction	person	Represents the amount of people that use the public transit system. It is represented as a stock because the users accumulate, since it takes a lot of time to rethink daily habits as for example the commute. The in- and outflow is Decision to Use Public Transit, which is influenced by the Indicated Amount of Transit Users.
Safety_Measures(t)	Safety_Measures(t - dt) + (Installation - Abandonment - SE_Wear_and_Tear) * dt INIT Safety_Measures = 4440*0,25	safety equipment	The stock Safety Measures represents all kind of safety measurements in public transit and around it, e.g. security cameras, security personal and lights.Safety Measures is defined as a stock as it accumulates by new installations and depletes due to wear and tear and abandonment.
Safety_Perception(t)	Safety_Perception(t - dt) + (Change_in_Safety_Perception) * dt INIT Safety_Perception = Total_Indicated_Safety_Perception	dmnl	The stock Perceived Safety Feeling represents the perceived feeling of safety of people using public transit. It changes through the inflow Change in Safety Perception. It is defined as a stock because it represents an information delay. When circumstances change the safety feeling, people need to time to perceive that by themselves or through talking to other people.
Abandonment	MIN(Safety_Measures/Time_To_Abandon; Safety_Measures_to_Abandon/Time_To_Abandon)	safety equipment/month	The outflow Abandonment represents the abandonment of Safety Equipment in case there is not enough money to further support these. The outflow is only active when the Safety Equipment Gap is negative, the higher the absolute value of the negative equipment gap, the higher the outflow.
Building	Bus_Routes_Under_Construction/Time_to_Build	bus route/month	Outflow of the stock Bus Routes Under Construction and inflow to Safety Equipment, represents the process of finishing the planning of Bus Routes and adding it to the stock of Bus Routes.It is delayed by Time to Build.
Change_in_Safety_Perception	(Total_Indicated_Safety_Perception-Safety_Perception)/Time_to_Change_Safety_Perception	Per Month	Inflow to Perceived Safety Feeling, represents the change of Perceived Safety Feeling and depends on the Indicated Safety Feeling and the Time to Change Safety Perception.

Change_in_Users	(Indicated_Public_Transit_user-Public_Transit_Users)/Time_to_Change_Habit	people/month	The in- and outflow Decision to Use Public Transit represents the number of persons that decide each month to stop or start using public transit on a regular basis. It is influenced by the Indicated Public Transit Users and the Time to Change Habit.
Closing	MIN(Bus_Routes/Time_to_Close; Bus_Routes_to_Close/Time_to_Close)	bus route/month	The outflow Closing represents the closing of bus routes in case there is not enough money to further support these. The outflow is only active when the Bus Route Gap is negative, the higher the absolute value of the negative bus route gap, the higher the outflow.
Installation	Planned_Safety_Measure/Time_to_Install	safety equipment/month	Outflow of the stock Planned Safety Measures and inflow to Safety Measures, represents the process of finishing the planning and implementing of Safety Equipment and adding it to the stock of Safety Equipment. It is delayed by Time to Install.
Planning	MAX(0; Investing_in_Building/Monthly_Building_Costs_Bus_Routes/Time_to_Plan)	bus route/month	Planning is the inflow toward Bus Routes Under Construction, it represents how many bus routes are getting planned and therefore added to the Bus Routes Under Construction stock. It is influenced by the Desired New Bus Routes times the Fraction of New Bus Routes Affordable.
SE_Planning	MAX(0; Investing_in_Safety/Monthly_Building_Costs_SE/Time_to_Plan_SE)	safety equipment/month	SE Planning is the inflow toward Planned Safety Equipment, it represents how much safety equipment is getting planned and therefore added to the BPlanned Safety Equipment stock. It is influenced by the Desired New Safety Equipment times the Fraction of New Safety Equipment Affordable.
SE_Wear_and_Tear	Safety_Measures/SE_lifespan	safety equipment/month	SE Wear and tear is an outflow that represents the decrease of Safety Equipment due to breakage at the end of the lifespan of the equipment.
Wear_and_Tear	Bus_Routes/Lifespan	bus route/month	Wear and tear is an outflow that represents the decrease of Bus Routes due to breakage at the end of the lifespan of the buses.
Allocation_Priority	0,9	dmnl	This constant represents the priority for Investing in Safety vs. Investing in Building. It can only range between 0 and 1 and represents the fraction of resources available for Investing that gets allocated to Investing in Building. Everything that does not get Invested in Building gets allocated to Investing in Safety instead.
Average_Monthly_Ticket_Price	100	$/person/month	The Monthly Ticket Price represents the average amount of money one person spends on tickets in a month.
Bus_Routes_Operating_Costs	Monthly_Operating_Cost_per_Bus_Route*Bus_Routes	$/month	Bus routes Operation Cost represents the monthly costs that arise from operating the bus routes installed in the public transit system. It is calculated by multiplying the bus routes with Monthly Costs per Bus route.
Bus_Routes_to_Close	IF Investing_in_Building<0 THEN - Investing_in_Building/Monthly_Operating_Cost_per_Bus_Route ELSE 0	bus route	The variable represents the gap between the amount of bus routes that are operating or in plannning, and the amount of bus routes that can be afforded with the monthly money dedicated to safety equipment. It is calculated by dividing Investing in Building by the Monthly Costs per Bus Route. When Investing in Building is positive, the variable is

			positive as well and influences planning positivly, if Investing in Building goes negative, the variable goes negative as well and influences Abandonment.
Bus_Stop_Density	Number_of_Bus_Stops/Size_of_Region	bus stops/Kilometers^2	The density of bus stops is an indicator for the density of the public transit network as a whole. It is influenced by the amount of bus stops and the size of the city.
Effect_of_Attractiveness_on_Transit_Fraction	GRAPH(Public_Transit_Attractiveness) Points: (0,000, 0,000), (0,400, 0,0379), (0,800, 0,1302), (1,200, 0,3496), (1,600, 0,8028), (2,000, 1,500), (2,400, 2,197), (2,800, 2,650), (3,200, 2,870), (3,600, 2,962), (4,000, 3,000)	dmnl	The Effect of Attractiveness on Transit Fraction translates the Public Transit Attractiveness into the effect it has on the Indicated Public Transit Users. It is a graphical function with an S-shape, indicating an effect between zero and three. The S-shape is reflecting the assumption, that nearly no one uses public transit, if it does not fulfill a certain standard of attractiveness and that even at a high attractiveness, there are people who cannot be convinced to use public transit. The higher the Indicator the higher is the effect.
Effect_of_External_Indicator_on_Safety_Perception	GRAPH(External_Safety_Indicator) Points: (0,000, 0,000), (0,200, 0,02526), (0,400, 0,08682), (0,600, 0,2331), (0,800, 0,5352), (1,000, 1,000), (1,200, 1,465), (1,400, 1,767), (1,600, 1,913), (1,800, 1,975), (2,000, 2,000)	dmnl	The Effect of the External Indicator on Safety Perception translates the External Safety Indicator into the effect it has on the Total Indicated Safety Perception. It is a graphical function with an S-shape, indicating an effect between zero and two. One is representing a normal situation. The higher the Indicator the higher is the effect.
Effect_of_Internal_Indicator_on_Safety_Perception	GRAPH(Internal_Safety_Indicator) Points: (0,000, 0,000), (0,200, 0,02526), (0,400, 0,08682), (0,600, 0,2331), (0,800, 0,5352), (1,000, 1,000), (1,200, 1,465), (1,400, 1,767), (1,600, 1,913), (1,800, 1,975), (2,000, 2,000)	dmnl	The Effect of the Internal Indicator on Safety Perception translates the Internal Safety Indicator into the effect it has on the Total Indicated Safety Perception. It is a graphical function with an S-shape, indicating an effect between zero and two. One is representing a normal situation. The higher the Indicator the higher is the effect.
Expected_Density_of_Bus_Stops	10	bus stops/Kilometers^2	The expected density of bus stops is a variable that represents the necessary density that reduces the walk to the next bus stop to a length that is acceptable for the average person. The number is an assumption.
Expected_Safety_Measures_per_Bus_Route	3	safety equipment/bus route	A constant that represents the amount of safety equipment the average person to find per bus route in order to feel safe.
External_Safety_Indicator	1/Relative_Crime_Rate*Weight_of_Crime + 1/Relative_Homelessness*(1-Weight_of_Crime)	dmnl	The External Safety Indicator combines external influences on safety. It is calculated summing up the weighted Relative Homelessness compared to the Normal Homelessness of one and the weighted Relative Crime Rate compared to the normal crime rate of one. If the Relative Crime Rate or the Relative Homelessness go up, the indicator goes down.
Indicated_Public_Transit_user	Initial_Ridership_Fraction*Total_Population*Effect_of_Attractiveness_on_Transit_Fraction	person	The Indicated Public Transit Users represent the number of people for which it is attractive to use public transit regular. It is calculated by the share of the population that public transit is attractive to according to the Effect of Attractiveness on Transit Fraction, the initial ridership fraction and the total population. If the Effect of Attractiveness on Transit Fraction is going up, the Indicated Public Transit Users increase. Since the

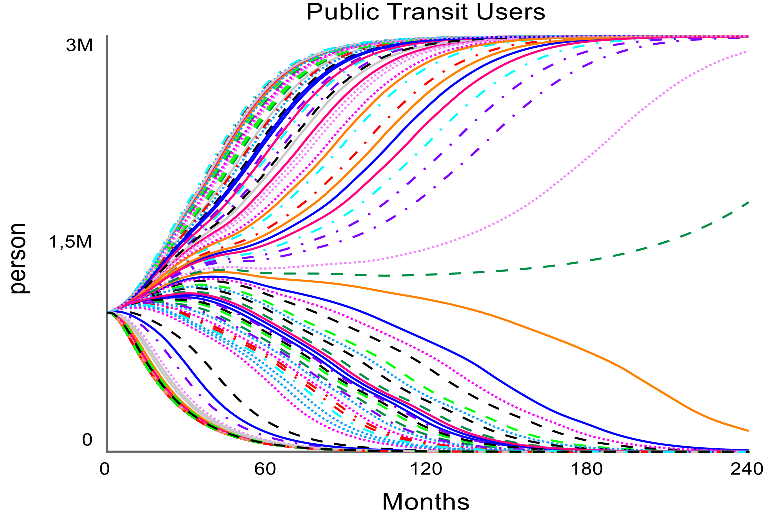
			initial ridership is 25% and the maximum Effect of Attractiveness on Transit Fraction is three, there is a maximum of 75% of the population that will use public transit.
Initial_Ridership_Fraction	0,25	dmnl	The initial fraction of the population that uses public transit is defined to be 25%.
Internal_Safety_Indicator	Safety_Equipment_per_Bus_Route/Expected_Safety_Measures_per_Bus_Route	dmnl	The Internal Safety Indicator represents the ratio of Safety Measures per Bus Route towards the Expected Safety Measures per Bus Route. This assumes that there is a certain level of safety equipment that passengers expect in public transit in order to feel safe. If the actual amount goes beyond that the Internal Safety Indicator goes above 1, if it is below that it goes below 1.
Investing_in_Building	Resources_Available_for_Investing*Allocation_Priority	$/month	The variable represents the monthly investing in building bus routes in public transit. It is influenced by the total Resources Available for Investing in public transit and the allocation priority which defines the fraction of the Resources is allocated to Investing in Building.
Investing_in_Safety	Resources_Available_for_Investing*(1-Allocation_Priority)	$/month	The variable represents the monthly investing in Safety Measures. It is influenced by the Resources Available for Investing and the Allocation Priority which defines which fraction of the Resources is allocated to Investing in Safety.
Lifespan	120	month	The average amount of time a bus route stays in the system before it closes due to wear and tear and needs to be renewed. The number is an assumption.
Monthly_Building_Costs_Bus_Routes	1000000	$/month/bus route	The monthly Cost of Building a Bus Route.
Monthly_Building_Costs_SE	100000	$/month/safety equipment	The monthly Cost of planning and installing new Safety Measures.
Monthly_Operating_Cost_per_Bus_Route	100000	$/month/bus route	The constant represents the average monthly costs of operating one bus route in US-dollars.
Monthly_Operation_Costs_per_Safety_Measure	50000	$/month/safety equipment	The constant represents the average monthly costs of operating one Safety Measurement in US-dollars.
Normal_Safety_Perception	0,5	dmnl	The Normal Safety Perception is a constant that represents the expected and necessary safety perception in order to go into public places without worrying for the average person.
Number_of_Bus_Stops	Bus_Routes*Number_of_Stops_per_Bus_Route	bus stops	The number of Bus Stops depends on the number of bus routes and the number of bus stops per Bus Route.
Number_of_Stops_per_Bus_Route	50	bus stops/bus route	The average number of stops per bus routes.
Public_Transit_Attractiveness	"Relative_Density_(Convenience)"*Relative_Safety_Perception	dmnl	The public transit attractiveness is a variable that represents how attractive it is overall to use the public transit system. It depends on the Convenience to use the bus and the Relative Safety Perception (while using the bus). The higher both of these values are the

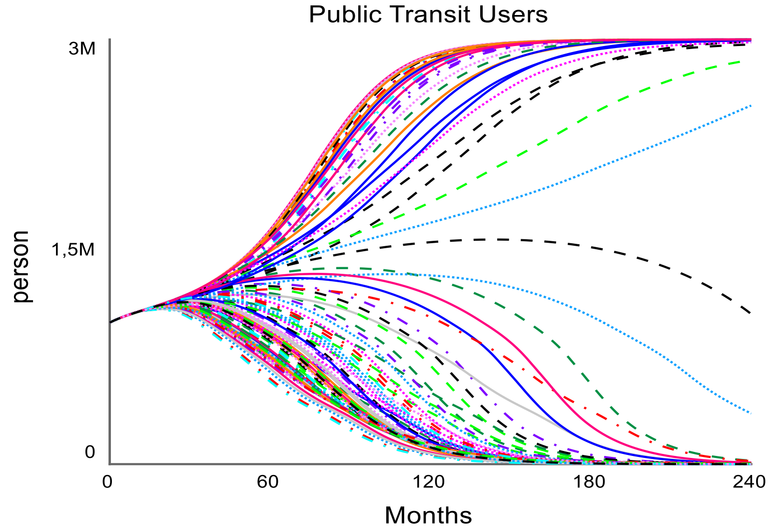
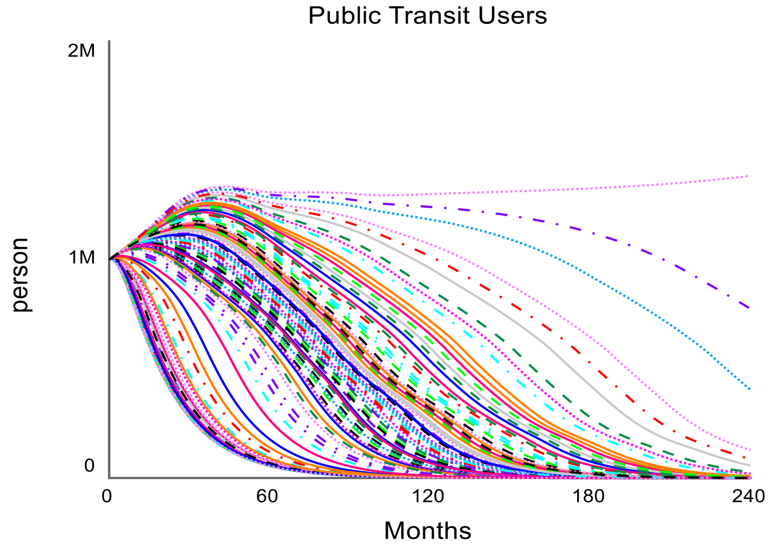
			higher is the public transit attractiveness. It depends on both variables, so if one of them is very low the overall attractiveness will also be low, as they cannot compensate for each other, both convenience and safety are necessary in order to make it attractive for people.
Relative_Crime_Rate	1	dmnl	The Relative Crime Rate represents the crime rate in comparison to the national average. One represents the average, above one represents more than the national average, below means less.
"Relative_Density_(Convenience)"	Bus_Stop_Density/Expected_Density_of_Bus_Stops	dmnl	The Convenience to Use Bus represents the ratio of Perceived Bus Stop Density to Expected Bus Stop Density. If the Perceived Bus Stop Density goes beyond the Expected the value goes above 1, otherwise below. The assumption behind this variable is that the average person is only willing to walk a certain distance in order to take Public Transit. Otherwise the person will try to find other means of transport.
Relative_Homelessness	1	dmnl	Relative Homelessness represents the perception of homelessness people in comparison to the national average. One represents the normal homelessness, above one represents more than the national average, below means less.
Relative_Safety_Perception	Safety_Perception/Normal_Safety_Perception	dmnl	The Safety Feeling Compared to Expectations represents the ratio of the Perceived Safety Feeling to the Normal Safety Feeling that is necessary to go to a place without concern.
Resources_Available_for_Investing	Revenue-Total_expenses	$/month	Resources Available for Investing represents the monthly amount of money that is not used for operating facilities and can therefore be invested in new bus routes or safety measures. It is calculated by subtracting the Total expenses from the Revenue.
Revenue	Public_Transit_Users*Average_Monthly_Ticket_Price	$/month	Revenue represents the monthly amount of money that the public transit generates. It is calculated by the Regular Public Transit Users times the Monthly Ticket Price.
Safety_Equipment_per_Bus_Route	Safety_Measures//Bus_Routes	safety equipment/bus route	The amount of Safety Equipment per Bus Route is calculated by dividing the bus routes by the number of safety equipment installed. In order to maintain a stable level of Safety Equipment per Bus Route the number of safety equipment and bus routes must rise at the same speed.
Safety_Measure_Operation_Cost	Safety_Measures*Monthly_Operation_Costs_per_Safety_Measure	$/month	Safety Measure Operation Cost represents the monthly costs that arise from operating the Safety Equipment installed in the public transit system. It is calculated by multiplying the Monthly Operation Costs per Safety Measure with the Safety Measures.
Safety_Measures_to_Abandon	IF Investing_in_Safety<0 THEN - Investing_in_Safety/Monthly_Operation_Costs_per_Safety_Measure ELSE 0	safety equipment	The variable represents the gap between the amount of bus routes that are operating or in planning, and the amount of bus routes that can be afforded with the monthly money dedicated to safety equipment. It is calculated by dividing Investing in Building by the Monthly Costs per Bus Route. When Investing in Building is positive, the variable is positive as well and influences planning positively, if Investing in Building goes negative, the variable goes negative as well and influences Abandonment.

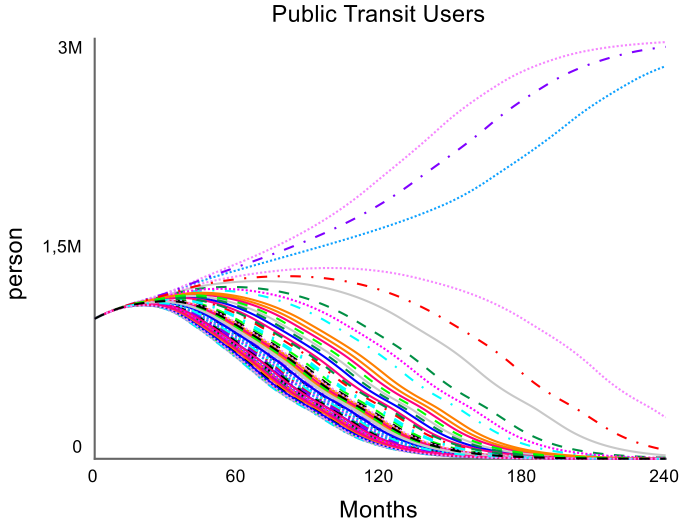
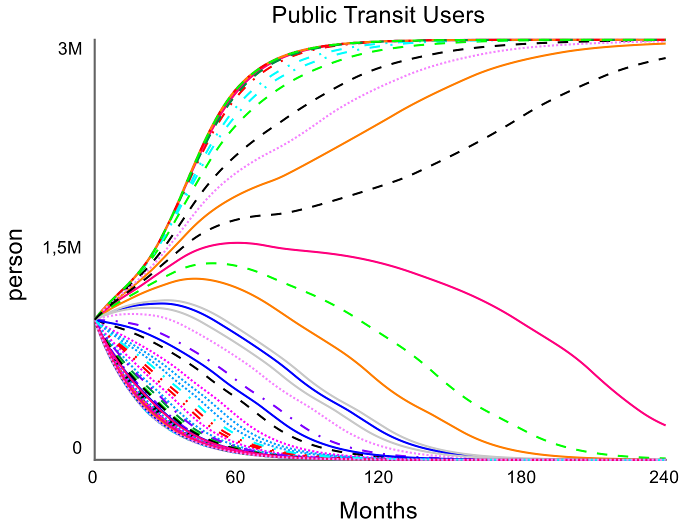
SE_lifespan	120	month	The average amount of time safety equipment stays in the system before it closes due to wear and tear and needs to be renewed.
Size_of_Region	1000	Km^2	The size of the area covered by the public transit.
Time_To_Abandon	12	month	The constant represents the time it takes for the transit operator to abandon Safety Measures, that includes time to uninstall equipment or lay off workers.
Time_to_Build	12	month	Represents the average amount of time it takes to build a bus route after it is build.
Time_to_Change_Habit	18	month	Time to Change Habit is a constant that represents the time it takes for people to re-evaluate their transit options in case of changed circumstances.
Time_to_Change_Safety_Perception	3	month	Average time it takes for people to change their perception of the safety situation in public transit.
Time_to_Close	12	month	The constant represents the time it takes for metro to close Bus Routes, that includes time to uninstall equipment or lay off workers. The number is an assumption.
Time_to_Install	6	month	This constant represents the average time it takes to install safety equipment.
Time_to_Plan	6	month	Represents the time it takes for bus routes to be planned.
Time_to_Plan_SE	6	month	This constant represents the average time it takes to start planning new safety equipment.
Total_expenses	Safety_Measure_Operation_Cost+Bus_Routes_Operating_Costs	$/month	The total monthly expenses consist of the operation costs of bus routes and the operating costs of safety equipment.
Total_Indicated_Safety_Perception	Normal_Safety_Perception*(Effect_of_Internal_Indicator_on_Safety_Perception*Weight_of_Safety_Measures + Effect_of_External_Indicator_on_Safety_Perception*(1-Weight_of_Safety_Measures))	dmnl	Indicated Safety Feeling represents the overall safety feeling of the people using public transit, it depends on the Normal Safety Perception as well as sum of the weighted Effect of External Indicator in Safety Perception and the weighted Effect of Internal Indicator on Safety Perception.
Total_Population	4e6	People	The constant is representing the total population in the transit area.
Weight_of_Crime	0,5	dmnl	The weight of Crookedness is a fraction that represents the importance of this factor for the Indicated Safety Feeling. It depends on the Weight of External SF and the relative distribution.
Weight_of_Safety_Measures	0,5	dmnl	The weight of Safety Measures is a fraction that represents the importance of the Effect of the Internal Indicator on Safety Perception.

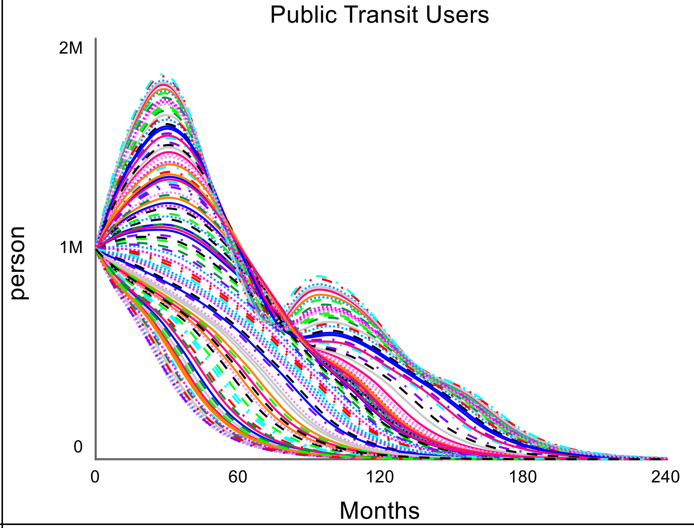
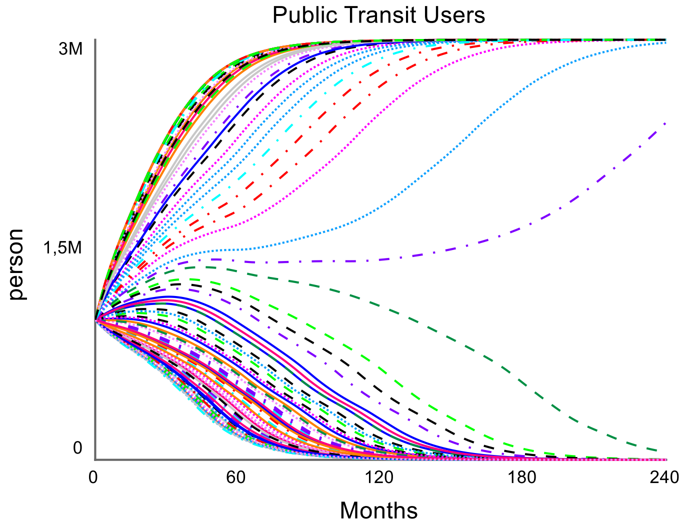
Appendix B:

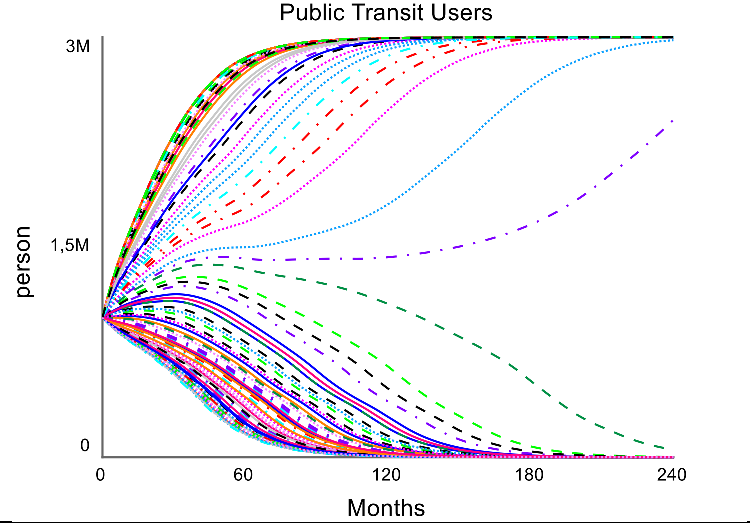
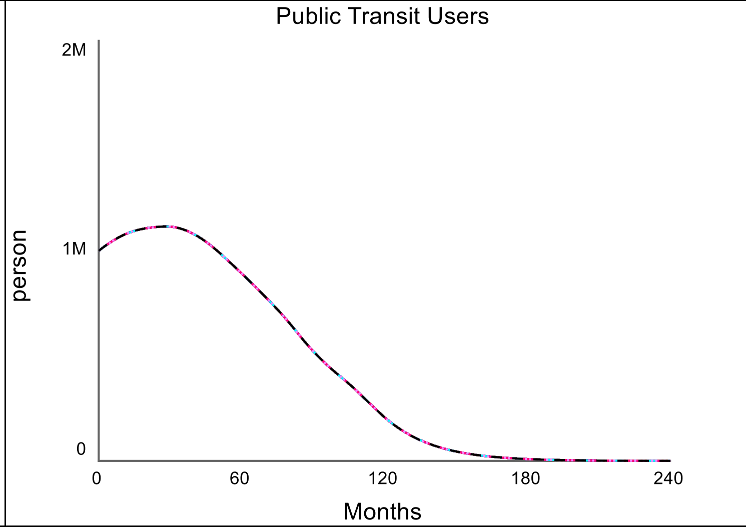
A sensitivity analysis has been conducted using the Stella Architect model analysis tool with following settings: Number of runs = 200
Method: Latin Hypercube Sampling
Distribution: Uniform

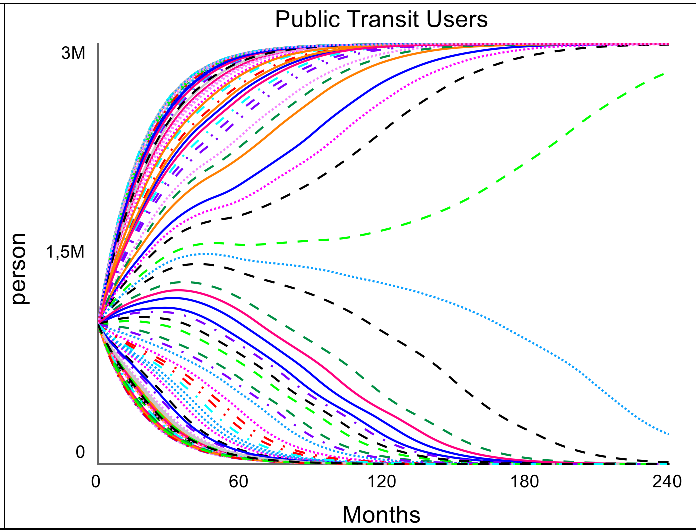
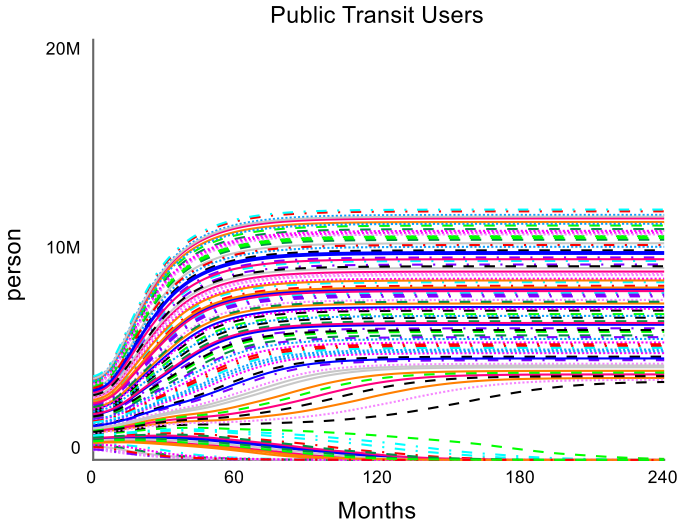
Variable Name and Values	**Results**	**Description**
Average Monthly Ticket Price Original Value = 100 Minimum Value = 10 Maximum Value = 200		The model is appropriately sensitive to the parameter. It has influence on the behavior and numerical sensitivity. It influences the model via the Revenue and Resources Available for Investing. Unlike in real life, it has no direct influence on the attractiveness of public transport, which could be improved in a more advanced model, but is a reasonable simplification for this conceptual model.

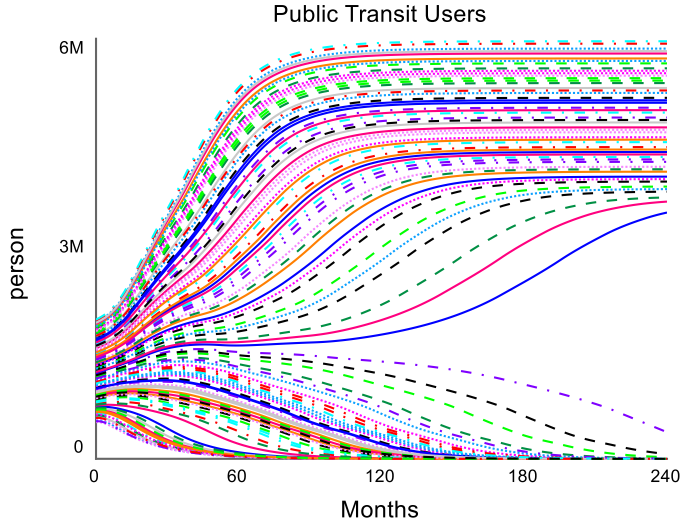
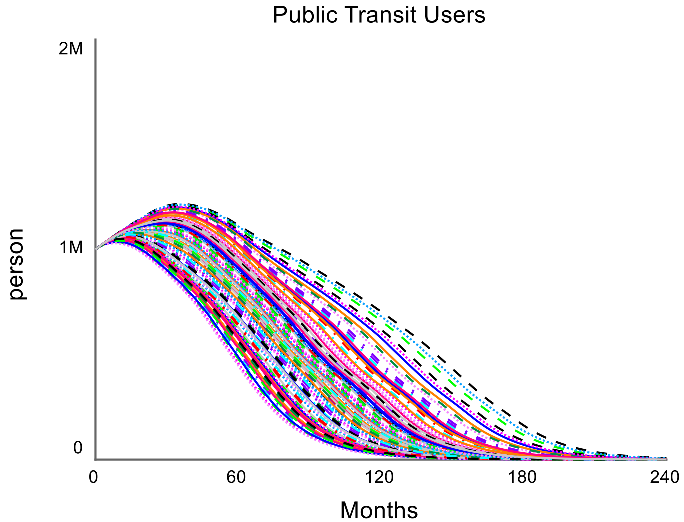
Allocation Priority Original Value = 0,9 Minimum Value = 0 Maximum Value = 1		The model reacts sensitively to changes in this parameter, it has an influence on the behavior and numerical sensitvity. The parameter is a possible point for intervention and therefore has also been discussed in the simulation results.
Monthly Operating Costs per Safety Measure Original Value = 50,000 Minimum Value = 25,000 Maximum Value = 100,000		The model is appropriately sensitive to the parameter. It has influence on the behavior and numerical sensitivity.

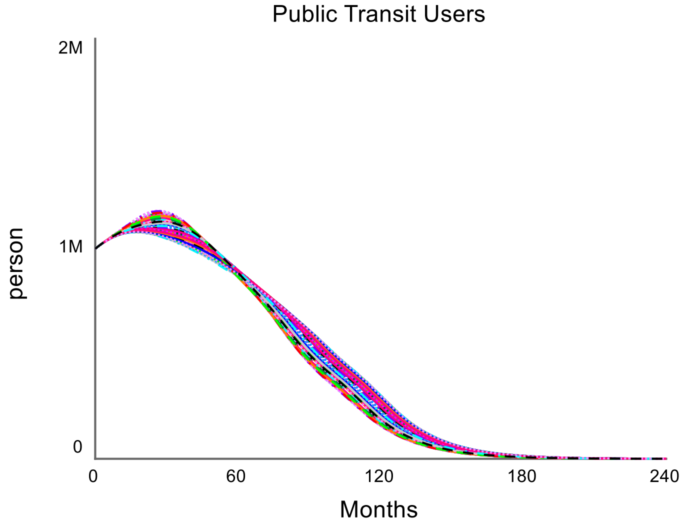
Monthly Building Costs per SE Original Value = 100,000 Minimum Value = 50,000 Maximum Value = 200,000		The model is appropriately sensitive to the parameter. It has influence on the behavior and numerical sensitivity.
Expected Safety Measures per Bus Route Original Value = 3 Minimum Value = 0 Maximum Value = 10		The model is appropriately sensitive to the parameter. It has influence on the behavior and numerical sensitivity.

Weight of Safety Measures Original Value = 0,5 Minimum Value = 0 Maximum Value = 1		The model reacts unexpectedly to changes in the parameter. It has influence on the behavior and numerical sensitivity. This point should be given further thought in the future.
Relative Crime Rate Original Value = 1 Minimum Value = 0 Maximum Value = 2		The model reacts sensitively to changes in this parameter, it has an influence on the behavior and numerical sensitvity. The parameter is a possible point for intervention and therefore has also been discussed in the simulation results.

Relative Homelessness Original Value = 1 Minimum Value = 0 Maximum Value = 2		The model reacts sensitively to changes in this parameter, it has an influence on the behavior and numerical sensitvity. The parameter is a possible point for intervention and therefore has also been discussed in the simulation results.
Normal Safety Perception Original Value = 0,5 Minimum Value = 0 Maximum Value = 1		The model is not sensitive to changes in the parameter, which was to be expected.

Number of Stops per Bus Route Original Value = 50 Minimum Value = 5 Maximum Value = 100		The model is appropriately sensitive to the parameter. It has influence on the behavior and numerical sensitivity.
Initial Ridership Fraction Original Value = 0,25 Minimum Value = 0,1 Maximum Value = 1		Changes in the parameter reveal problematic behavior. The amount of public transit users can go beyond the total population in the model when changing the parameter value. This problem can be overcome with further modeling in the future.

Total Population Original Value = 4,000,000 Minimum Value = 2,000,000 Maximum Value = 8,000,000		The model is appropriately sensitive to the parameter. It has influence on the behavior and numerical sensitivity.
Monthly Operating Costs Bus Routes Original Value = 100,000 Minimum Value = 50,000 Maximum Value = 200,000		The model is appropriately sensitive to the parameter. It is only numerical sensitive.

Monthly Building Costs per Bus Routes Original Value = 1,000,000 Minimum Value = 500,000 Maximum Value = 2,000,000		The model is not very sensitive to changes in the parameter.