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Simulation of rail replacement bus service in Oslo

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Abstract

This paper describes an applied simulation study on the flow of rail replacement buses in Oslo. We performed the studies using SIMADES, a newly developed multi-agent discrete event simulator. In the project, we enriched the simulator with agents representing entities commonly found in the urban mobility domain. Our study identified the main bottlenecks that limit the flow of buses through the road network under the traditional way of scheduling and dispatching buses. The study furthermore identified the best actions to implement that enable a significant increase of capacity for rail replacement buses. The conclusions are expected to lead to concrete changes in how the rail replacement bus service will be executed in Oslo during planned and unplanned maintenance of the rail network.

Introduction

With the population in the Oslo metropolitan area growing rapidly, there is increasing pressure on finding more sustainable urban mobility solutions. Already in 2013, an average of 11,500 people travelled out of the Oslo city centre by trains operated by NSB (the Norwegian State Railways) during the afternoon peak hour. At the same time, the Norwegian National Rail Administration is making large investments in the increased capacity of the rail infrastructure and the replacement of old signalling systems. Scheduled and unscheduled maintenance therefore, frequently leads to a need for rail replacement bus services. The current maximum capacity for buses in the Bjørvika area (near Oslo Central station) does not enable a sufficient volume of replacement buses, frequently resulting in chaotic situations that attract media attention, as in Mordt and Skarra (2015). The limitation is due to a number of complex factors restricting the flow of buses, such as the bus terminal layout, the obstructing flows of pedestrians, the congestion of buses at the staging area, the obstructing taxi stop, the intersections that include complex lane changes, and the short traffic signal timings for green lights. Therefore, in early 2015, NSB asked SINTEF (The Foundation for Scientific and Industrial Research) to perform a simulation study of alternative solutions with the goal of doubling the capacity of replacement buses. The main questions to be answered through simulation were:

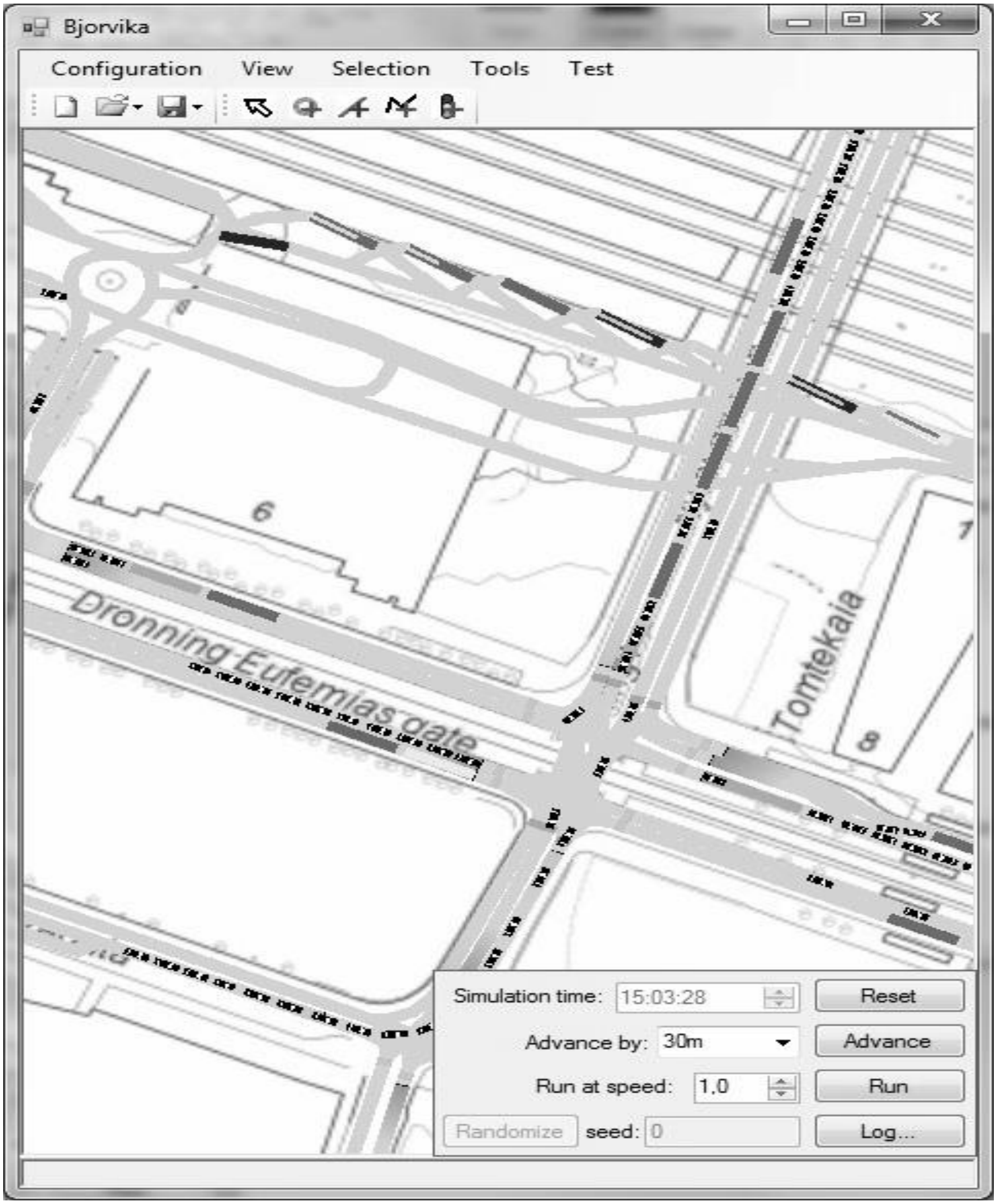
1. What are the best actions to implement that enable an increase of capacity for rail replacement buses in the short term, i.e., summer 2015, and what is the corresponding capacity during afternoon peak hours?
2. What are the best actions to implement that enable an increase of capacity in the long term, and what is the corresponding capacity during afternoon peak hours?

In this paper, we first introduce our agent-based microsimulation approach, implemented in SIMADES, SINTEF Multi-Agent Discrete Event Simulator, SINTEF (2016). We then explain how we modelled the road network and the flow of traffic in the Bjørvika area. Finally, we draw conclusions from the experimental result obtained.

Design of the simulator

The static environment of our simulation is the road network, represented as a directed graph. The edges in the graph are the paths the vehicles might drive along. Roads might have several edges in parallel, typically one for each lane, and always separate edges for opposite directions. Special edges are added for potential lane changes or different choice possibilities in crossings. The edges also hold various information like speed limits, restrictions on permitted vehicle types in a lane and priorities to model right-of-way, etc. The edges contain a set of specific positions representing stop lines for traffic lights or pedestrian crossings, or decision checkpoints for the vehicles. For visualisation, we also include maps as part of the static environment. In addition, to the static part of the environment, there are dynamic elements that change their state or position, like intersections controlled by light signals, where light colours change, pedestrian crossings, where pedestrians come and go, and different vehicles.

The *events*, marking state changes during the simulations, are processed in chronological order. Typical events are traffic light changes, vehicles passing decision points, pedestrians coming to or leaving pedestrian crossings and the deduction of possible conflicts, etc. The simulator holds a set of *agents* that listen to events taking place, make active decisions for the entity they represent and create new events. Some are intelligent agents that make decisions based on the simulation state and implemented logic; others are more deterministic. A special agent is the *heartbeat agent*, which regularly sends a heartbeat event, typically every 0.75 second.



Simulation time: 15:03:28

Advance by: 30m

Run at speed: 1,0

seed: 0

Figure 1. A screenshot from SIMADES with sawtooth layout at the bus terminal

Modelling the expected flow of vehicles and pedestrians

For the simulation to be realistic, there must be a representative flow of vehicles in the network. We based this on measured vehicle counts divided into 15-minute intervals. Most counts would include the number of vehicles of each type (electric, car, taxi or bus) passing through a lane in a road or an intersection during the time interval. However, some of the traffic counts would give only the total number of vehicles. The counts were collected on different days.

Agents called *vehicle sources* generate all vehicles in the simulation. They create vehicles from specific nodes entering the network. The nodes where vehicles exit the network are labelled *vehicle sinks*, and vehicles entering a sink are destroyed. The simulator generates optimal routes for each vehicle type where the vehicles can drive through the network, i.e., the fastest routes from all sources to all sinks. We manually excluded some routes that did not make sense, e.g., driving into the network then back out on the same road as the vehicle entered, or cars driving from one parking garage to another. To recreate a flow according to the measured vehicle counts, we also introduced some additional, but suboptimal, routes through the network.

In the real world, taxis will go to the terminal area, pick up passengers and then travel somewhere. Therefore, we also introduce *redirect points* to enable taxi routes to be generated from vehicle sources to the redirect points and further from the redirect points to the sinks. A special vehicle controller agent enables the simulated taxis to travel from a source to a redirect point where they wait for a stochastic amount of time before receiving a route to a sink. Based on the routes and the traffic count data, the simulator will compute the frequency of vehicles for each type and each route. This is calculated by solving a linear program where the objective is to minimise the total deviation of the generated vehicle flow from the vehicle counts. In our case, the vehicle counts were based on observations at different days. Therefore, it was not possible to eliminate all deviations, but in practice, we were able to keep the number and the magnitude of the deviations small. Finally, during the simulation run, the vehicle sources spawn vehicles at random intervals drawn from exponential probability distributions reflecting the computed frequencies.

Since our simulator primarily focuses on the flow of vehicles on roads, pedestrians and bus passengers are currently modelled only in a more simplified fashion. We added *pedestrian controller agents* to simulate pedestrian crossings and the states of pedestrians entering, traversing and leaving the crossing. The frequency and duration of such activity is drawn from probability distributions. The simulator models bus passengers merely by means of probability distributions for the duration of unloading and loading passengers at the bus stops.

Vehicle model

The simulator models each physical vehicle as a *vehicle agent* that represents the vehicle controlled by its driver. As the vehicle's route has already been decided, the driver's main concern is to control the vehicle's speed. At events generated by the heartbeat agent, the driver evaluates the traffic situation and decides on an acceleration or deceleration rate, which determines the vehicle's speed until the next heartbeat event. The considerations made by the driver are:

- Keep a speed suitable for the road
- Keep a distance to the vehicle ahead
- Stop for obstacles ahead
- Avoid collision with other vehicles

Each of these considerations will constrain the set of possible accelerations. The actual acceleration is then chosen as the possible acceleration, being as close as possible to the ideal acceleration, which would achieve a speed suitable for the road in the absence of traffic considerations.

To keep a distance to the vehicle ahead, the simulator uses a safety-distance model based on the Gipps model described in (Gipps 1981). The model uses Newtonian mechanics with assumed constant acceleration during each time interval, except if a vehicle reaches zero velocity. As in Gipps, based on the vehicle's current positions and speeds, and on the driver's desired maximal and minimal accelerations, our model computes a safe acceleration for the vehicle. In addition, we consider the actual physical maximal acceleration and deceleration for each vehicle. In certain cases, a driver might be forced to brake harder than he would prefer. For this reason, we also compute a maximal safe range of accelerations for which the vehicle will not crash into the leading vehicle, assuming the follower will brake at the physical maximum. Hence, we have extended the traditional safety-distance approach without losing the non-crash guarantee. A driver can choose any acceleration within the maximal range, but will prefer the one provided by the traditional vehicle-following model with the desired acceleration range. This flexibility is useful for modelling more dynamic and situation-dependent behaviours.

The consideration to stop for obstacles ahead, e.g., in front of a light or for a pedestrian, is a special case of keeping a distance to the vehicle ahead, but with an important difference. For both a traffic light and a pedestrian crossing, the driver will normally get advance notice about when the obstacles will appear on the road (he can see the yellow light or the approaching pedestrian). The driver can then either speed up to pass the area before it is blocked, or he can brake to stop in front of the obstacle.

To avoid collisions, the driver looks ahead on the route and finds other vehicles whose routes merge or cross within a reasonable time and distance. Each of these corresponds to a *conflict diagram*, a 2-dimensional diagram where each axis represents the distance driven by one of the two vehicles involved. The *collision region* is the region of the diagram where the two vehicles would be in physical contact. We have used a generalisation of the interval-halving method presented in Ericson (2004) to calculate the extreme points of the collision region. A choice of acceleration for each vehicle defines a curve in the conflict diagram, which may intersect the collision region or not. Assuming a specific acceleration behaviour from the other vehicle, the driver can evaluate possible accelerations and eliminate any interval of accelerations that leads to a collision, padded with safety distances in time and space.

A conflict is normally ignored if the other vehicle must yield due to being on a lower priority arc. However, conflicts unavoidable by the other vehicle are always considered. At low speeds, the driver will tend to yield when the other vehicle is closer to the conflict, even when it has the right-of-way. In this way, low speed lane changes and zipper merges are made possible.

Controlling the rail replacement buses

While most vehicles in the simulator simply follow the route assigned by the vehicle source agent, the task for the rail replacement buses is more complex. First, they may have to drive to the bus stop where they unload passengers before lining up at another bus stop for loading passengers, wait until the bus is loaded or the scheduled departure time, and finally drive to the destination of the trip. If another bus already occupies the bus stop, the bus may have to enter an off-street waiting area to avoid blocking other buses. The simulator supports this by assigning each bus to a *vehicle controller agent* responsible for high-level decisions according to actions defined in a separate scripting language. Example of such actions can be:

- **Drive to location**: The vehicle controller utilises a shortest path algorithm to extend the route to the given location in the road network.
- **Stop at location**: The vehicle controller performs a *drive to location* action and stops at the given location. When the vehicle has stopped, the vehicle agent sends a signal to the vehicle controller, and the vehicle controller can continue to process the next scripted action.
- **Wait**: The vehicle controller stops the vehicle (if not already stopped) and waits for the given duration. Where the bus has stopped to load passengers, the duration for the wait may be given as a probability distribution from which a value is drawn.
- **Choose**: The vehicle controller can decide among alternative actions based on a condition. This can represent the situation where the vehicle controller finds the bus stop to be occupied (the condition) and only then drives to the off-street waiting area (the conditional action). In general, the 'choose action' makes the simulator able to handle any dynamic model where an agent's strategy should be adjusted based on an observed situation.

Experiments and results

To be able to answer the main questions through simulation, we identified eight separate candidate actions to implement. The most important were:

1. Unloading of passengers: Traditionally, passengers were unloaded in an area near the bus terminal for loading passengers. This required empty buses to make an additional loop through Bjørvika through the same roads as the

in-service buses. An alternative location for unloading passengers was identified farther away from the central station, but there, the deadhead route avoided the most congested roads.
2. Bus stop design: The bus terminal next to the central station is narrow. Traditionally, the way of loading passengers was, therefore, to line up multiple buses into two parallel rows. This arrangement implies first in, first out as well as the simultaneous loading of the buses at the terminal. An alternative design of the bus stop that could enable a steady flow is to apply a *sawtooth* layout (see Figure 1) to achieve a more continuous flow of buses.
3. Staging area: The staging area for buses waiting for an available bus stop is limited to a maximum of 10-15 buses. With an increased flow, this may not be sufficient. Additional locations for staging buses were therefore identified.
4. Traffic signal control scheme: In the Bjørvika area, we identified 15 intersections controlled by traffic lights that the buses had to pass. Some alternative durations of the traffic light phases were simulated through an iterative process to achieve optimal traffic flows.

The data collected and used by the simulator were:

- Road information with lanes, turn based restrictions from the zoning plan for Oslo. The Bjørvika road system is currently under construction and changing from year to year. Therefore, the relevant road network had to be generated manually.
- Vehicle counts from January 2015 from the Norwegian Public Road Authorities, supplemented by additional traffic counts from March and April 2015. To be able to simulate the correct flow of vehicles in the separate bus lanes and to simulate scenarios with relocated taxi stops, the supplemental counts put vehicles into the four separate categories: buses, electrical vehicles, taxis and other vehicles.
- Traffic signal timing diagrams for the 15 intersections in Bjørvika from 2014 and 2015.

The time of the week considered most critical was weekday afternoons between 15:30 and 17:30. To be able to answer the main questions through simulation, we had to calibrate the simulator and verify the soundness of the model and available data. Hence, the first scenario we modelled was the base scenario representing the traditional way of rail replacement bus service. The base scenario was then fine-tuned through a process of comparing simulated performance with on-site observations and traffic counts. Thereafter, we simulated selected combinations of actions as separate scenarios. Each distinct combination was sampled as a Monte Carlo experiment with 20 two-hour simulations, making a total of 1,006 individual experiments. The results of five of these scenarios are listed in Table 1. The column 'Flow' gives the average number of vehicle agents that were created per hour. Hence, it indicates how replacement buses affect the flow of other vehicles in the area. The column 'Buses' gives the average number of rail replacement buses that were loaded per hour.

Table 1. Some results from selected simulation runs

No.	*Scenario description*	*Flow*	*Buses*
1	The base scenario	2948	40
2	As 1 but with optimised traffic signal scheme	2963	59
3	As 2 but with 20% reduction in taxis through the taxi stop	3077	69
4	As 3 but with relocated stop for unloading passengers	2725	82
5	As 4 but with a sawtooth layout at the bus terminal	2988	101
6	As 5 but without optimised traffic signal scheme	2701	58

The results of the simulation study were delivered to NSB in May 2015. According to Øystein Risan, Director of Traffic at NSB, the credibility of the simulation results was a crucial factor in the process of getting the final approval for modifications of the layout of the bus terminal, as the simulations confirmed that a doubling of capacity was possible.

Limitations

This work was a contract research project for NSB. They contacted us in January 2015 and by May 2015, they needed us to suggest how to get robust flow of replacement buses as well as calculate the corresponding capacity during afternoon peak hours. The vehicle counts were recorded at different dates on only a subset of the network. During data collection, there was road and construction work in the area, which affected the quality of the data. With more time and money, we would have simulated people entering and leaving the buses as well as added bicycles. In addition, we would improve the vehicle behaviour—currently, all vehicles move on fixed invisible tracks on the road. Involving more opportunistic driver behaviour would allow the vehicle to utilise traffic opportunities better. Our statistical approach for loading one bus was also used when several buses are loaded next to one another—this is a simplification. We would prefer to validate our model with additional simulations of the current layout against additional traffic measurement.

Conclusions

In early 2015, NSB asked SINTEF to perform a simulation study on the flow of rail replacement buses in Oslo. We performed the studies using SIMADES, a newly developed, multi-agent discrete event simulator. The simulation results showed that the best actions to increase the capacity for rail replacement buses in the short term is to relocate the stop for unloading passengers at the bus stop outside the Oslo Opera House; control that taxis do not block the exit from the bus terminal; and to apply the optimal traffic signal scheme. In the long term, the best actions are to relocate the stop for unloading passengers to a new permanent location; ensure that taxis do not block the exit from the bus terminal; apply the optimise traffic signal scheme; change the layout of stops at the bus terminal to a sawtooth design; and implement a strict dispatching strategy for the staging area. The simulation provided NSB with an estimate of the maximum capacity of buses that can pick up passengers during afternoon peak hours with current bus stop layout and with a sawtooth layout.

Future work

We are in discussion with NSB on how we could make the simulator available for training. Our idea is that the planners could use it to draw up streets and test scenarios by themselves. Testing scenarios becomes a combinatorial problem where the number of possible scenarios grows quickly when increasing the number of variables and their values. Since each simulation takes a long time, with limited time, only a small part of the plausible scenarios can be tested. We plan to investigate ways to select scenarios more intelligently using different inference and statistical techniques.

The agent-based microsimulation approach is not only very valuable to investigate road traffic. It could also be used in other areas. For example, at airports, there are typically similar bottlenecks (runways, gates, taxiways). SIMADES is built upon a framework that can easily be adapted for airports as well. This customisation is ongoing and will be used for simulations in SESAR 2020, a large Air Traffic Control European R&D program.

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