Final report: The risk for a gridlock and the macroscopic fundamental diagram

Report

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Final Report: The Risk for a Gridlock and the Macroscopic Fundamental Diagram

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1 Abstract of the Project & Goals of the Original Grant Application

A solid base for modeling traffic gridlocks and their avoidance by control techniques exists for the strand of aggregate transport modeling. However, transport modeling continuously shifts from aggregate (macroscopic) to disaggregate (microscopic) models in recent years as with the movement from extending to managing the infrastructure, many important new questions came up, which can only be answered having the higher resolution of the disaggregate models (Kitamura (1996, Section 2) and Daly (2013)).

In the present version, disaggregate models sometimes include gridlock situations. However, this states are often rather a flaw of the model than a consistent image of reality. For MATSim, for example, “artificial” gridlocks are observed for substantially jammed traffic conditions because of a certain lack of flexibility (or realism) of drivers’ en-route route choice behavior (Charypar (see also 2008; p.99) and Rieser and Nagel (2008)) describe gridlocks. At least, gridlocks events are typically too rare to be of concern of the travel demand modelers and, thus, the systematic analysis and consistent modeling of such events is scarce to date in these models.

But, recent events in Zürich and elsewhere have raised the question if and how the theoretical work on gridlocks and heavily jammed network states needs to be integrated in the models of “daily traffic” covering the typical range of demand situations. The potentially substantial economic impacts of such events do not allow to blindly neglect these issues anymore, in particular not in regions with rising demand-supply ratios.

With the multi-agent transport microsimulation MATSim (MATSim, 2014) an instance of disaggregate large-scale travel demand and traffic flow modeling systems is productive at the Institute for Transport Planning and Systems IVT and will be the base for this project. It will be handled as an example for other modern transport microsimulators. Calibrated and validated implementations are available for Switzerland as a whole (Balmer et al., 2010), and more detailed versions for region of Zürich (Balmer et al., 2009).

This project’s goal was to evaluate MATSim’s ability to model traffic gridlocks and highly congested states, to enhance the model at the most urgent places; a large traffic jam in Zurich was analyzed and set up as a real-world comparison base for modeling.

The original grant application also proposed to perform a meta analysis of gridlocks using MATSim and linking the previous improvements in form of a risk analysis of traffic performance in highly congested situations. Consideration of the aggregate base and physics-oriented
approaches for gridlock modeling (Al-Khudhairy et al., 2012; Mendes et al., 2014; Nagel and Herrmann, 1993; Mendes et al., 2012) was also suggested in that application.
2 Introduction

2.1 Gridlock: Definition

In strict terms, a gridlock is “a state of severe road congestion arising when continuous queues of vehicles block an entire network of intersecting streets, bringing traffic in all directions to a complete standstill.” (Oxford English Dictionary, 2014). This state is depicted in Figure 1, where the red cars are blocking the intersections.

In the transport field, however, gridlock is used inflationary, also for high traffic congestion states with small but positive flows.

Also in this report, the distinction between the two states was not strict, as it was not overly relevant for the assessment of overall traffic system performance.

Figure 1: Gridlock: Schematic. Note that MATSim does not model the interactions on the network nodes.
2.2 MATSim

The development of the Multi-Agent Transport SIMulation MATSim (MATSim, 2014; Bäumer et al., 2006) has started approximately a decade ago as a collaborative effort of Prof. Nagel (now: TU Berlin) and Prof. Axhausen (ETH Zurich). It has its roots in Axhausen (1988) and in the transport simulation TRANSIMS (Raney et al., 2002), which was developed by Prof. Nagel as research team leader at the Los Alamos National Laboratory. As shown on the web page (MATSim, 2013), MATSim has been applied by local research groups world-wide for a dozen different regions.

MATSim is an activity-based, extendable, multi-agent simulation toolkit implemented in JAVA. It is open-source and can be downloaded freely at (MATSim, 2014; SourceForge, 2014). The framework is especially designed for large-scale scenarios, meaning that, the features of all models are generally stripped down to efficiently handle the base functionality, where emphasis has been also been laid on parallelization. For the network loading simulation, for example, a queue-based model is implemented, leaving out the very complex car-following behavior.

MATSim is based on a co-evolutionary principle (Section 2.2.3). While being in a competition for space-time slots on the transportation infrastructure with all the other agents, every agent iteratively optimizes its daily activity chain. This is done by running through the MATSim loop as depicted on the left in Figure 2.

Every agent possesses a memory of a fixed number of day plans, where each plan is composed of a daily activity chain and an associated utility value (in MATSim called plan score). For now, MATSim is conceptually designed to model a single day, a common unit of analysis for activity-based models (see, for example, the review in Bowman (2009)). In other words, basically, MATSim is a cross-sectional model. Nevertheless, in principle a longitudinal model could be implemented.

In every iteration, prior to the simulation of the network loading (e.g., Cetin, 2005) (execution), every agent selects a plan from its memory. This selection is dependent on the plan utility. A certain share of the agents (often 10%) is allowed to clone the selected plan and modify this clone (replanning). For the method of successive averages (MSA) usually a decreasing share of travelers is reallocated to a new route to avoid oscillations. For MATSim, it has been shown that a variable replanning share can be productive as well and “increase overall performance of the system by a factor of three or more” (Charypar et al., 2006, p.7f). For the network load microsimulation step multiple simulations are available and configurable (Horni et al., 2011b, p.10f).
Plan modification is implemented in the *replanning* modules. Four choice dimensions are considered for now: time choice (Balmer et al., 2005), route choice (Lefebvre and Balmer, 2007), mode choice, and destination choice. If an agent ends up with too many plans (configurable), the plan with the lowest score (configurable) is removed from the memory of this agent. The agents, which have not undergone replanning select between existing plans. The selection model is configurable; in many MATSim investigations, a model that generates a logit distribution for plan selection is used.

An iteration is completed by evaluating the agent’s day described by the selected day plans (*scoring*). The applied utility function is described in Section 2.2.1.

Starting from an initial demand, the iterative process is repeated until the average population score stabilizes, where the definition of the stopping criterion is subject of ongoing research initialized by Meister (2011); Nagel and Flötteröd (2009).

MATSim offers considerable customizability through its modular design approach. Although, replacing core modules, such as the network loading simulation is associated with a substantial effort (MATSim Development Core Team, 2014; Section 2.4) in principle every module of the framework can be replaced.

### 2.2.1 MATSim’s Utility Function

The first and still basic MATSim utility function was formulated by Charypar and Nagel (2005) from the Vickrey model for road congestion as described in Vickrey (1969) and Arnott et al.
(1993). Originally, this formulation was established for departure time choice. However, all studies performed so far, indicated that the MATSim function is also appropriate for modeling the further choice dimensions.

For the basic function, the utility of a plan $U_{\text{plan}}$ is computed as the sum of all activity utilities $U_{\text{act},q}$ plus the sum of all travel (dis)utilities $U_{\text{trav},q}$:

$$U_{\text{plan}} = \sum_{q=1}^{n} U_{\text{act},q} + \sum_{q=2}^{n} U_{\text{trav},q}$$  \hspace{1cm} (1)

The utility of an activity $q$ is defined as follows (see also Charypar and Nagel (2005, p.377 ff)):

$$U_{\text{act},q} = U_{\text{dur},q} + U_{\text{wait},q} + U_{\text{late},ar,q} + U_{\text{early},dp,q} + U_{\text{short,dur},q},$$

where:

- $U_{\text{dur},q} = \beta_{\text{dur},q} \cdot t_{\text{typ},q} \cdot \ln(t_{\text{dur},q}/t_{0,q})$ is the utility of performing activity $q$, where opening times of activity locations are taken into account. $t_{\text{dur},q}$ is performed activity duration, $\beta_{\text{dur},q}$ is marginal utility of activity duration for its typical duration $t_{\text{typ},q}$ and $t_{0,q}$ is minimal duration, or in other words, the duration for which utility starts to be positive.

- $U_{\text{wait},q} = \beta_{\text{wait},q} \cdot t_{\text{wait},q}$

  denotes the waiting time spent for example in front of a yet closet store, where $\beta_{\text{wait},q}$ is marginal utility of waiting and $t_{\text{wait},q}$ is the waiting time.

- $U_{\text{late},ar,q} = \begin{cases} \beta_{\text{late},ar,q} \cdot (t_{\text{start},q} - t_{\text{latest},ar.q}) & \text{if } t_{\text{start},q} > t_{\text{latest},ar.q} \\ 0 & \text{else} \end{cases}$

  specifies the late arrival penalty, where $t_{\text{start},q}$ is the starting time of activity $q$ and $t_{\text{latest},ar}$ is the latest possible starting time of that activity for example given by opening times.

- $U_{\text{early},dp} = \begin{cases} \beta_{\text{early},dp.q} \cdot (t_{\text{earliest,dp},q} - t_{\text{end},q}) & \text{if } t_{\text{end},q} > t_{\text{earliest,dp},q} \\ 0 & \text{else} \end{cases}$

  defines the penalty for staying not long enough, where $t_{\text{end},q}$ is the ending time of the activity and $t_{\text{earliest,dp},q}$ is the earliest possible end time for activity $q$.

- $U_{\text{short,dur},q} = \begin{cases} \beta_{\text{short,dur},q} \cdot (t_{\text{short,dur},q} - t_{\text{dur},q}) & \text{if } t_{\text{dur},q} < t_{\text{short,dur},q} \\ 0 & \text{else} \end{cases}$

  is the penalty for a too short activity, where $t_{\text{short,dur}}$ is the shortest possible duration for the activity.

Travel disutility is given as

$$U_{\text{trav},q} = \beta_{\text{trav},q} \cdot t_{\text{trav},q}$$  \hspace{1cm} (2)

where:
• $\beta_{\text{trav},q}$ is the marginal utility of travel by mode (normally negative or zero), and
• $t_{\text{trav},q}$ gives the travel time between location of activity $q - 1$ and $q$

Note that the distance contributes to disutility in two ways. First, it is included in a direct manner via $\beta_{d,\text{mode},q}$, which is natural for modes with physical efforts such as walking or cycling. Second, distance is also included monetarily via $\beta_m \cdot \gamma_{d,\text{mode}}$ which is natural for mode car or pt, where monetary costs increase dependent on distance.

Further note that travel receives an additional implicit penalty from the opportunity cost of time: If a travel time could be reduced by $\Delta t_{\text{trav}}$, the person would not only gain from avoiding $\beta_{\text{trav}} \cdot \Delta t_{\text{trav}}$, but also from making activities longer.

### 2.2.2 MATSim’s Traffic Flow Model

MATSim provides two different internal mobility (or traffic) simulations (called mobsims): “QSim” and “Java Deterministic Event-Driven Queue-Based Traffic Flow Micro-Simulation” (JDEQSim). Furthermore, external mobility simulations can be plugged in. Some years ago the “Discrete Event Queue Simulation” (DEQSim) written in C++ and described by Charypar (2008); Charypar et al. (2007b; 2009; 2007a) was plugged into MATSim and frequently used. The multi-threaded QSim is the default mobsim (MATSim Development Core Team, 2014).

Charypar et al. (2009) distinguishes between

- physical microsimulation models, featuring detailed car following models,
- cellular automata, in which roads are discretized in cells,
- queue-based simulations, where traffic dynamics are modeled with waiting queues,
- mesoscopic models, using aggregates to determine travel speeds, and
- macroscopic models, based on flows rather than single traveler units (e.g., cars).

As MATSim is designed for large-scale scenarios it adopts an efficient queue-based approach (see Figure 3). A car entering a network link (i.e., a road segment) is added to the tail of the waiting queue. It remains there until the time for traveling the link with free flow has passed and until he or she is the head of the waiting queue and until the next destination link allows entering. The approach is very efficient, but clearly it comes at the price of reduced resolution, i.e., car following effects are not captured.

For computational reasons the waiting-queue approach is for JDEQSim combined with an event-based update step (Charypar et al., 2009). In other words, there is no time-step-based updating process of any agent in the scenario. Instead agents are only touched if they actually
require an action. For example, during the time an agent needs to pass a link (i.e., he is waiting in the queue), he does not need to be processed. Triggering of update events is managed by a global scheduler. QSim, however, is time-step based.

The MATSim traffic flow model, and as we will see also gridlock modeling, is heavily based on the two measures: storage capacity and flow capacity. Storage capacity defines the number of cars fitting onto a network link. It is a physical property and, thus, essentially fixed in the simulation. For sample scenarios, however, it needs to be scaled.

Flow capacity gives the outflow capacity of a link, i.e., how many travelers can leave the respective link. It is an individual measure per link. A maximum inflow capacity cannot be defined in one of the models. The many simulation experiments with QSim (and queueSimulation) have shown, that neglecting inflow capacity has not a substantial effect but further reduces model complexity.

The MATSim traffic flow model currently has several limitations, which directly influence gridlock modeling. They are listed in Section 5.1.5.

2.2.3 MATSim’s Co-Evolutionary Algorithm

As illustrated in Figure 4, the MATSim equilibrium is searched by a co-evolutionary algorithm. These algorithms co-evolve different species subject to interaction (e.g., competition). In
Figure 4: Adopting a co-evolutionary algorithm in MATSim

MATSim, the individuals are represented by the plans of a person, where a person represents a species. By applying the co-evolutionary algorithm, optimization is performed in terms of agents’ plans. Eventually, an equilibrium is reached subject to constraints, where the agents cannot further improve their plans unilaterally. When speaking in strict terms, there is a difference between application of an evolutionary algorithm and a co-evolutionary algorithm. An evolutionary algorithm would lead to a system optimum as optimization is applied with a global (or population) fitness function. The co-evolutionary algorithm instead leads to a user equilibrium as optimization is performed in terms of individual utility functions and within an agent’s set of plans. At the moment, the MATSim co-evolutionary algorithm only includes mutation; recombination may come into play when joint day plans of family members, for example, are included in the future.
3 Achievements and Advances Made During the Course of the Research Project

The project was divided into three work packages as follows.

**Work Package I: Congestion Events**

Detailed in Section 4, work package I looked at a congestion event in Zurich that took place before peak hour on an April 2013 evening (Tagesanzeiger, Pia Wertheimer, 2013). The event was chosen as it was to date the largest traffic jam in Zurich and as lots of gridlocks at least in the area around intersections could be expected. This analysis laid a base for comparisons with work package II’s and future simulations.

The analysis was based on count data available with reasonable effort. The analysis also revealed that for further gridlock modeling attempts, establishing a more complete and quickly updated data base about such events, maybe including camera data and aerial surveillance data is required. The classical planning data like count data or average working day surveys is of very limited use in this regard.

**Work Package II: MATSim Gridlock Modeling**

Detailed in Section 5, work package II analyzed MATSim’s capability to model gridlocks and highly jammed traffic states in general. It turned out, that this was actually a weak point of MATSim. Various analysis are shown in Section 5.1. The project lead to respective improvements. First, the implementation of a double-queued traffic simulation by the MATSim core team was triggered containing the back-traveling gaps at intersections which are crucial to model the jammed part of the macroscopic fundamental diagram (MFD) correctly. The project furthermore implemented a micro within-day replanning approach around heavily jammed intersections to reduce artificial gridlocks in MATSim stemming from a model flaw (Section 5.2.1). Driver’s instantaneous route choices are now modeled more realistically. The project also applied the sophisticated model by Grether (2014) to include traffic signals in the Zurich scenario—the most frequently used MATSim scenario—which improves future experiments of all kinds (Section 5.2.2).
Work Package III: How to Perform a Risk Assessment

Detailed in Section 6, work package roughly explored how to perform a gridlock risk assessment. As described in Section 7, here, future work can and should connect.
4 Work Package I: Congestion Events

This work package looked closer at a recent congestion event in Zurich that took place before peakhour on an April 2013 evening (Tagesanzeiger, Pia Wertheimer, 2013). Goal of this chapter was to create a comparison base for the simulations performed in work package II in terms of the event’s spatio-temporal characteristics. The event was chosen as it was to date the largest traffic jam in Zürich and as lots of gridlocks could be expected.

4.1 Analyses of the Traffic Jam

At 15:30 on 17th of April 2013 a truck damaged the south-west portal of tunnel Schöneich and lead to the blockage of both tunnels Schöneich and Milchbuck until the next morning. As these tunnels are on an north-east-bound arterial route, this lead to massive traffic jamming.

At the red square in Figure 7, in Kanonengasse close to Langstrasse, the first author’s engine could be frequently stopped for minutes while sitting in the traffic jam. This subjective impression confirmed through personal discussion with other drivers indicating a huge traffic jam with gridlocks, requires validation on a broader base. Thus, to begin with, count data provided by the city, the canton and ASTRA are evaluated. The accident happened at 17th of April 2013. Comparisons with the normal condition are based on the situation one week before, on the 10th of April. For simplicity the comparisons with 16th, 18th and 24th of April are omitted, but data is available and was inspected as well with little differences between these “normal condition” days.

A first look at a count station nearby the midpoint of the closed tunnel route, at Hirschwiesen-tunnel, indicates a heavy traffic jam (see Figure 5). The volumes are dramatically decreased after the blocking (Figure 5(a)) and the occupancy time, measuring the time a car needs to pass a detector, is heavily increased after the accident (Figure 5(b)). Similar patterns can be observed along the alternative eastbound arterial route (Hardbrücke, Rosengartenstrasse and interchange Aubrugg).

To widen the focus and include the dynamics, the volumes for different hours are charted in Figure 6. Count stations considered are plotted in Figure 7. The strong reduction of the volumes indicates a large jam, but to our evaluation, the count data do not indicate a city-wide gridlock as the average breakdown of volumes is moderate. However, the count data patterns of an actual gridlock are not known for Zürich nor is the term gridlock concisely defined in the literature for large traffic networks.
Figure 5: Hirschwiesentunnel

(a) Volumes

Hirschwiesentunnel: Volumes

(b) Occupancy Time is usually defined as $t_{oc} = \frac{1}{n} \sum_{i} \frac{l_i}{v_i}$, where $l_i$ is the length of car $i$ and $v_i$ is the speed of car $i$ and $n$ is the total measured number of cars. Obviously, a high occupancy times mean low speeds.

Hirschwiesentunnel: Occupancy Time
Figure 6: Count Data for the Gridlock Day and One Week Before

(a) Hour 14-15
(b) Hour 15-16
(c) Hour 16-17
(d) Hour 17-18
(e) Hour 18-19
(f) Hour 19-20
Figure 7: Overview of inner-city: As mentioned in the legend, red dots denote a volume reduction between 17 and 18 o’clock of more than 50% as compared to the volumes one week before the accident. The closed tunnels are printed with dashed black lines. The inner and outer circle areas denote the two different directions of a count station. The red circle shows the location considered worst by the first author.

Some count stations indicate a dramatic situation, thus, the spatial characteristics of the jam are analyzed as well. Figure 7 shows that measured volume reduction does not cover the complete inner-city but is relatively limited to the wider neighborhood of the tunnels.
4.2 Conclusions

The limited extent of the traffic jam represents a large discrepancy with the author’s subjective “rien-ne-va-plus” driver perspective, meaning that either the subjective perspective (from the eye of the tornado) was too dramatic or that count data do not tell the whole story. Finding different data sources such as video data, primarily, at police department Zurich is, thus, the next very important step. For future analyses, further and different data is urgently required to generate a more complete picture of the actual accident day network state. Furthermore, other huge traffic jams, such as the 2014 truck accident on the A1 in Aargau or the 2011 truck accident in Schwyz need to be included in the analysis.

Nevertheless, if such an important arterial road is blocked and the traffic jam still does not lead to full blockage (i.e., gridlocking) of the complete city area and its surroundings, then a stable and well-controlled traffic system must be assumed, which raises the question about the relevance of modeling in detail such events.

In any case, the analyses performed above can be used as a comparison base for the simulations performed in the next chapter.
5 Work Package II: MATSim Gridlock Modeling

The first part of this work package analyzed MATSim’s capability to model highly congested network states and gridlocks (Section 5.1).

MATSim is an agile software project. Insights into the fundamental traffic flow modeling characteristics and in particular into its shortcomings, clearly, quickly trigger corrections. The analyses thus did represent a snapshot valid for the time of the analysis. Substantial changes were made during project period. An important example are the very important “backward moving gaps” (explained below) that are currently inserted—besides others also triggered by the discussions in this project’s context.

As summarized in Section 5.1.5, MATSim’s traffic flow model has some limitations, that are significant for gridlock modeling. The following analyses looked at some of these issues and at MATSim’s general ability to model congested scenarios.

The first two analysis investigated MATSim’s volume-delay functions (Section 5.1.1) and its macroscopic fundamental diagram (MFD) (Section 5.1.2). Besides having a first picture of modeling congested states, in particular, the MFD analysis also gave insights into the issue of the backward moving gaps.

The next analysis, presented in Section 5.1.3, focused on MATSim results for the Zurich truck accident. Thereby, a closer look was also taken at the influence of the MATSim storage capacity parameter. The analysis presented in Section 5.1.4 looked at MATSim’s intersection modeling, which was missing traffic signals as an important network impedance.

The second part of this work package presented the simulation results for this project’s improvements of the MATSim traffic flow model (Section 5.2).

5.1 Problem Analyses

5.1.1 Volume-Delay Function Analysis

A common approach to model link travel times in aggregate models is using volume delay functions. They are related to MFDs but cannot be directly transformed into the other form. Assumption here was that deriving a volume-delay function for MATSim is helpful in assessing its capability to handle heavily congested or gridlocked network states. The reported experiments
were initialized by Horni and Montini (2013) and later extended together with Milos Balac, IVT.

The most frequently used volume-delay function is the BPR-function. It is defined as follows

The BPR function is defined as follows.

\[ t = t_0[1 + \alpha (V/C)^eta] \]

where \( t_0 \) is the free-flow travel time. \( \alpha \) and \( \beta \) are calibration parameters, where \( \beta \) usually lies between 5 and 11. In other words, a non-linear relation is usually assumed.\(^1\)

Figure 8(a) shows \( \alpha (V/C)^eta \) for \( \beta = 5.0 \) with \( \beta = 5.0 \) and varying demand and supply. The idea is to compare the MATSim functional form with this typical plot.

For this purpose the basic scenario depicted in Figure 9 was simulated with varying demand and supply. The network was initially empty. From 8 to 9 am a varied number of agents traveled from their home to the work locations with uniformly distributed start times. Trip travel times and link passing times for the center link (marked in the figure) were evaluated. No signal lights and back-traveling gaps were modeled. Simulation was run from midnight to midnight. One single iteration was performed including network load simulation and excluding replanning.

The simulation results are shown in Figure 10(a) and 10(b) for the link travel times and the trip travel times respectively. It can be clearly seen, that the MATSim function substantially differs from the BPR formulation using the common parameters in Figure 8(a). It looks more like a linear specification with \( \beta = 1 \) as shown in Figure 8(b).

For an even clearer picture, capacity was hold constant at \( C = 600 \) vehicles per hour (as an example) as shown in Figure 11, where also a linear relationship was observed. Functional form is very similar for both link and trip travel times. In other words, also the two intersections (i.e., network nodes) did not add substantial non-linearity here.

Although the scenario needs to be carefully treated due to its small size, it indicates, nevertheless, that MATSim’s capability to model high-demand or low capacity cases correctly is limited. To deepen the analysis and to look at the problem from a different perspective in the next section MFD analyses are presented.

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\(^1\) Remember the definition of linearity: \( y = m \cdot x \), i.e., two variables \( x, y \) are proportional with constant factor \( m \).
Figure 8: BPR-like specification of travel time

(a) $0.5 \cdot (V/C)^{\beta}$ with $\beta = 5.0$ (non-linear)

(b) $20.0 \cdot (V/C)^{\beta}$ with $\beta = 1.0$ (linear)
5.1.2 MFD Analyses

The MFD analysis is another formulation of aggregate network characteristics. The MATSim MFD analyses confirmed the problems found in the Volume-Delay-Function analysis, namely that the MATSim default mobsim (QSim) had difficulties to model highly congested scenarios. There were a couple of MFD analyses performed at IVT. The most recent one was done by Patrick Bösch for the Zurich scenario. The experiment was part of the NetCap project whose progress was reported in an unpublished interim report.

Slide 25 of this presentation, shown here in Figure 12 courtesy to Patrick Bösch and Francesco Ciari, clearly shows that the usually strong decrease in flow for the high density region was missing in late iterations. Very similar results were observed in Singapore by Pieter Fourie (personal communication). Slide 26 of this presentation came to the conclusion that in the Zurich city center “over a number of iterations, agents find a way around traffic jams”. Gridlocks thus cannot be modeled realistically. For toy scenarios, there were two studies, however, that were able to generate realistic MFDs. Importantly though, they were based on DEQSim and JDEQSim respectively, which both do include backward moving gaps.

Simoni (p.81ff2013) investigated MATSim’s ability to model macroscopic characteristics with
Figure 10: MATSim Travel Times for Barbell Scenario

(a) Link Times

(b) Trip Times
Figure 11: MATSim Travel Times for Barbell Scenario, Fixed Capacity

(a) Link Times

(b) Trip Times
a four link ring scenario. He found considerable influence of the back moving gaps speed on the form of the MFD. A speed of $-5 \text{ m/s}$ turned out to produce a quite realistic MFD. Charypar et al. (2009) also used a circular toy scenario. They also found the typical trapezoidal form for a broad range of network resolutions.

Natural conclusion here is, that backward moving gaps might be essential for generating a realistic MFD, in other words to realistically model to complete range of traffic conditions.

5.1.3 Zürich Truck Accident Traffic Jam Modeling: Storage Capacity Analysis

The analysis of the Zürich accident was presented at the Swiss Transport Conference 2014 and it is described by Horni and Axhausen (2014).

Simulation results for the Zürich truck accident were based on an 100% out-of-the-box Zürich scenario and configuration. The traffic crossing a 30 km radius around Zürich was simulated. Other modes than car were teleported. A navigation network was used. The runtime of an iteration roughly took 90 minutes with 70 GB of RAM and 20 CPU cores.

Technically, the demand was relaxed for some iterations. At 15:30, when the accident happened, Milcbuck- and Schöneichtunnel were closed by MATSim network change events setting capacity and speed to zero. To model drivers’ spontaneous route changes, the MATSim withinday
framework was applied (e.g., Dobler et al., 2012), where in the first 30 minutes, drivers around the tunnel portals were replanned. This area of replanning drivers was then increased continuously to a radius of 5 km around the tunnel midpoint.

The simulation results were compared against the comparison base created in work package I.

A first analysis looked at the MATSim storage capacity being an issue as detailed in Section 5.1.5. Our simulations confirmed that MATSim had a problem with modeling spill back, presumably in the mobsim and for the replanning. Running our 100% scenario with a storage capacity factor of 1.0 produced serious (artificial/unrealistic) gridlocks until midnight even for the normal case where no tunnels are closed as shown in Figure 13:

The second analysis continued the common work around for this issue by increasing the storage capacity (above the physically derived value). The storage capacity was increased by a factor
of 5, i.e., \( f_{sc} = 5.0 \). Figure 4 shows a snapshot at 6 o’clock pm for the regular situation with tunnels open and the accident situation with closed tunnels. The only significant differences occur along the eastbound arterial road serving as an alternative to the closed tunnels, no inner-city-wide gridlock is visible.

When comparing with the real-world analysis it can be seen that count data and the simulation tell a very similar story, while the question remains open if the count data analysis in work package I actually tells the whole story.

The conclusion drawn from the (first half) of the analysis above was, that MATSim actually had a problem with spill-back traffic, and thus also with heavily congested scenarios making necessary to tweak the storage capacity parameter. This was true for the mobsim (in every iteration an unrealistic traffic jam could be observed for open tunnels) but it is also for the replanning process (no convergence could be reached as people wildly replanned their route whenever possible). In other words, “the replanning process was blown up” (personal communication, Gunnar Flötteröd, 2014).

In the next section, a closer look is taken at MATSim intersection modeling, another weak link of MATSim.

### 5.1.4 MATSim Intersection Modeling: Missing Impedance Components

The analysis of MATSim intersection modeling was also presented at the Swiss Transport Conference 2014 and it is described by Horni and Axhausen (2014).

For gridlock modeling, capturing the intersection dynamics is essential. Unfortunately, as described in Section 5.1.5 MATSim’s intersection modeling is a weak link. Apart from an experimental traffic light module signals and other intersection characteristics (such as turn restrictions or lanes) were not considered systematically. In this project, we took the first step to extend this research by investigating Bucheggplatz a central and highly frequented multi-modal intersection. Bucheggplatz contains multiple car lanes, bus and bike lanes, crosswalks, signals, signal control cameras, public transport stops, and, it is part of an alternative route for Bucheggstrasse entering the Rosengartenstrasse, thus it is often blocked being a natural example to study gridlocks.

Goal in this analysis was simply to zoom into the full-network scenario and evaluate of morning hours showed the typical blocking of the intersection.

Figure 15 presents a simulation snapshot of Bucheggplatz at 7:00 am. In reality, at this time
Figure 14: Traffic Situation Snapshot at 18:00 with $f_{sc} = 5.0$

(a) Tunnels Open

(b) Tunnels Closed
of the day, Bucheggplatz is heavily loaded and its entering is associated with substantial delay. The simulation captured some congestion realistically, nevertheless, the corresponding video basically showed efficient roundabout dynamics. Especially, the entering into the circle from North (Radiostudio) and from East (Irchel) was not captured realistically.

This simply means, that network impedance was strongly underestimated in the simulation. This reductions’ effect on gridlock modeling is unclear however. The higher traffic flow into bottlenecks might accelerate the creation of gridlock nuclei, while it can also be argued, that jamming configurations are resolved quicker as traffic is also flowing off faster.
5.1.5 Problem Analysis Summary: What is Missing? What is Urgently Needed?

Above analyses show that MATSim had limited capability to realistically modeling gridlocks. This problem is complex, with solutions that might work antagonistically.

**Are the Agents Too Smart:** On the one hand, agents seem to be too intelligent in the replanning phase, as they circumvent traffic jams to an unrealistic extent. Reason is, that the rerouting process is (unrealistically) based on *global* knowledge of the situation and thus lets agents drive around jams in a very efficient manner. The VDF and MFD analyses show these capabilities. Note, that these analysis are based on increased storage capacities as detailed below.

**Are the Agents Not Clever Enough:** On the other hand, agents are too dumb in the traffic flow simulation. While in reality persons adapt their routes on-the-fly, MATSim agents strictly follow the routes defined in their plan. It obviously happens quite frequently, that in congested scenarios unrealistic artificial gridlocks are created due to the agents’ unrealistic non-responsiveness to the faced traffic situation (Charypar (see also 2008, p.99) and Rieser and Nagel (2007)). Agents are then unrealistically blocked forever. This severe problem has to date been “circumvented” by artificially increasing the link storage capacity (which is actually a physical measure) and by adding other work-around mechanisms to prevent unrealistic gridlocks and keep cars flowing. E.g., cars are forced to move even if the link to enter is overloaded after a certain waiting time (configured with the parameter “stuck time” sometimes also called “squeeze time”). Ash shown in Figure 16; this stuck time parameter has a strong influence on gridlock modeling.

While these solutions engineer out artificial gridlocks, at the same time, they also engineer out the ability to model *real* gridlocks, and in combination with missing signals and missing backward moving gaps maybe also the ability to model congested scenarios.

Besides this algorithmic problem intrinsic to the MATSim replanning and traffic flow modeling, the limited ability to model gridlocks probably also comes from missing network impedance components in the model. There is a module for traffic signals (Grether, 2014). For the current Swiss and Zurich scenarios, however, traffic signals are not taken into account. Other intersection dynamics are not considered likewise, turn restrictions are only covered if explicitly coded into the network.

Link dynamics, in particular slow drivers and overtaking, and mode interactions was not modeled until very recently. Backward moving gaps occurring when a car in queue accelerates are currently implemented by the MATSim core team. It seems, that adding backward moving
Figure 16: Stuck Time Evaluation: A low stuck time of 10 seconds produces a smooth score development without artificial gridlocks. A high stuck time of 100 seconds produces a zig-zag line score development with artificial gridlocks. Runs are performed on a planning net, the average executed plan score is shown.

The next Section tried to provide a solution to the algorithmic problem and to the most striking limitation of network impedance modeling, missing traffic signal lights.
5.2 Improvements & Simulation Results

5.2.1 Micro-Within Day Replanning

To relax the agents non-responsiveness to the faced traffic situation a micro-within-day replanning approach was implemented and tested. Idea was to give the agents the possibility to re-route whenever they face a certain “stuck time”. Figure 17 illustrates the principle in a toy scenario.

Clearly, this made the agents even more clever as criticized on Section refsec:summary. While the basic problem of “visionary” agents is inherent to the iterative structure of MATSim, their ability to foresee future traffic conditions was not increased by the micro-within-day-replanning approach. Thus it appeared as a productive approach to add more realism to the simulation, which actually solves the problem of unrealistic gridlocks. Figure 18 shows the simulation results for a scenario with and without on-the-fly rerouting. The zig-zag lines of the average population score development was strongly reduced.

However, this solution came at a price. Computation time is increased from around 1 minute per iteration to around 6-7 minutes.

Besides speed-up, future work concerns calibrating and tailoring the approach. Calibration has to be done in terms the share of agents allowed to re-route at a certain point in time. Algorithmically, a too high share causes oscillations. In behavioral terms, in reality, also not all drivers synchronously decide to re-route when stuck in jams. At the moment, agents are allowed to modify an arbitrary segment of their route. It would be more computationally efficient and maybe even more realistic to minimize the re-routed route segment, thereby legitimating the term micro-rerouting.

Technically, the approach can be included in MATSim in a straightforward way. Within-day replanning interfaces are available in the core code. As an indicator for being gridlocked the stuck time introduced above can be used.

5.2.2 Handling Network Impedance Components

As a first and natural network impedance signals were added to the Zurich scenario. The sophisticated but scarcely used model by Grether (2014) was adopted. Signal plans were derived from somewhat older (but available) signal data from city of Zurich (Stadt Zürich, Dienstabteilung Verkehr, 2008). In a first instance, the signals within the orange circles in
Figure 17: Toy Scenario: Within-day Replanning to Circumvent Overloaded Areas

(a) No within-day replanning

(b) Within-day replanning: Some of the stuck agents spontaneously re-route and take the upper route now.
Figure 18: Within-day Rerouting

![Graph showing score versus iteration for no on-the-fly rerouting and on-the-fly rerouting.]

As expected, signals reduce population score due to increased travel times (Figure 20). No further smoothing can be observed. As signals sometimes play an important role as drop counters preventing traffic jams, this is somewhat surprising.

### 5.3 Discussion and Conclusions

The approaches described above as well as the improvements triggered by the analyses besides others substantially enhanced MATSim’s capability to model gridlocks and highly jammed traffic network states. As soon as the double queue mobsim will be ready the experiments should...
be repeated including the micro withinday replanning approach and MATSim’s sophisticated signal system model calibrated with the data available for the city of Zurich. An open question is choice of a real-world gridlock example as analysis did not show a disastrous network state for the Zurich accident.

Furthermore, the focus shall be extended towards gridlock meta-analysis. Importantly, the difference between MATSim’s artificial gridlocks and real-world gridlocks has to be analyzed, e.g., evolve gridlocks from clearly identifiable nuclei, critical points, or from random network locations? Further looking at gridlocks’ risk might answer the question to what extent the high implementation and runtime costs (see Section 5.2.1) have to be taken in the models.

Besides double-queue simulation, that will be available soon, another important improvement of the mobility simulation QSim was achieved recently by the MATSim core team. QSim is now ready to simulate different modes and different vehicle types with first-in-first-out principle as well as in passing mode. This also makes possible to simulate the heterogeneity in people’s driving behavior, which might have an influence on jam formation (cf., “phantom traffic jams”).
Figure 20: core development with an without signals, with micro-withinday-replanning
6 Work Package III: How to Perform a Risk Assessment

This work package explores how to do a risk analysis of traffic performance in highly congested situations and for large-scale scenarios.

The gridlock risk \( r \), sums over the probabilities \( p(e) \) and costs \( c(e) \) of all possible gridlock events \( e \). The uncertainty can be quantified and thus converted into a risk by computing the distribution of \( p \) and calculating estimates for \( c \).

\[
 r = \sum_e p(e) \cdot c(e) \tag{3}
\]

Costs can be given as the difference between normal condition population travel times and jammed condition travel times, i.e., \( c(e) = \text{overall delay} = (tt_{\text{normal conditions}} - tt_{\text{gridlock,e}}) \).

Precondition for a gridlock is an abnormal pattern in supply or demand, i.e., an outage of some network components or a heavily increased demand maybe because of evacuation events.

In an approximate manner and for the first instance, one can thus focus on punctual network outages, i.e., an outage of a single network link. Outages probably mostly start out locally, e.g., due to an accident. Likewise in an approximate manner, one can assume that gridlocks events only differ in their nucleus, thus \( e \) corresponds with \( \bar{\lambda} \) being the outage of a specific link \( \lambda \). Thus, one might insert

\[
p(e) = p(\text{gridlock}|\bar{\lambda}) \cdot p(\bar{\lambda})
\]

in Equation\(^3\): \( p(\bar{\lambda}) \) is the probability that a blocking of link \( \lambda \) happens in the transport system over a specific period of time. It can be estimated by models such as Bodenmann et al. (2014) or by empirically deriving probabilities from accident data from e.g., ASTRA\(^2\) or BfS\(^3\) where information is available on accident probabilities dependent on the type of the road or on its extent of being an arterial road. A so-called Safety Performance Function dependent on the average daily traffic volume is available.

\( p(\text{gridlock}|\bar{\lambda}) \) is the conditional probability that a gridlock\(^4\) appears in case of link \( \lambda \) is blocked. Here, microsimulations enter the stage. They are a statistical tool, more precisely a Monte Carlo sampling method, thus they nicely mesh with risk assessments. Conceptually, microsimulations

\(^2\)http://www.astra.admin.ch/unfalldaten/
\(^3\)http://www.bfs.admin.ch/bfs/portal/de/index/themen/11/06/blank/01/aktuelle;
\(^4\)Clearly, here a precise definition of gridlock as it is available in e.g., computer science but not in transport needs to be established (Section 2.1). But this is an undertaking going well beyond the scope of this project.
can be directly used to estimate the probability $p(\text{gridlock}|\tilde{\lambda})$. In practice, however, where even the low-resolution planning networks easily have 60,000 links, this requires further adaptations. As gridlocks most probably are a highly non-linear phenomenon and a strict a priori reduction of the network links to a set of “critical links” seems inappropriate in particular as it also is against the idea of risk computation. Instead, the simulation process needs to be made more efficient.

Surrogate model as described by Sudret (2012) become ever more popular in risk analysis to generate approximate estimates by generating a “faster model of the model”. In MATSim such a surrogate model is available with “PSim” introduced by Fourie et al. (2013, 2012). Future MATSim gridlock research should connect at this point.

Still a large—maybe prohibitively large—computational effort might result, in particular due to the fact of microsimulations being a statistical tool associated with a substantial results variability (Horni et al., 2011a). A hierarchical approach evaluating clusters of links stepping into more detailed evaluation in case of high risk might be productive here. Future work might also consult Erath et al. (2009).

The results of this analysis of networks and their level of service (LOS), can be used to derive decisions on investment and control strategies productive in the future for multi-modal networks.
7 Conclusions & Reasons for not Achieving All Original Goals

The project improved disaggregate modeling for the MFD’s jammed part substantially using the example of MATSim. Improvements are direct (e.g., micro-within-day replanning) and indirect by triggering simulator improvements by the core developer group such as the implementation of the double-queue mobsim (not yet fully completed). Next step would be to compare with and possibly transfer the findings to similar simulation frameworks such as the “TRansportation ANalysis and SIMulation System” (TRANSIMS) (FHW A, 2013).

An original goal only partly met is a detailed meta-analysis of gridlocks—in particular transport system risk analyses—using MATSim as a tool and not the being the research subject and drawing on Al-Khudhairy et al. (e.g., 2012); Mendes et al. (e.g., 2014); Nagel and Herrmann (e.g., 1993); Mendes et al. (e.g., 2012). Comparison to physical concepts might further enlighten the complex phenomenon. Obvious reason for not meeting this goal completely is MATSim’s limited ability to model highly jammed states before the project.
8 References


