Analysis and Evaluation of Ramp Metering Algorithms

A Summary of the Latest Algorithms and the Development of an Evaluation Concept for the Effectiveness of Ramp Metering Strategies

Master Thesis

In

Civil Engineering

by

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Third Examiner: Dr.-Ing. Edgar Kienlein
Abstract

The last comprehensive summary of ramp metering algorithms was completed in 1999 by Bogenberger and May. This thesis summarizes the history and the current state of existing ramp metering algorithms. The general method of ramp metering is explained with its implementations and further approaches. To illustrate the importance of ramp metering in the world, an overview of existing algorithms and a detailed summary of the current number of metered ramps in the world is given. Because of the lack of a unified way to implement this strategy, this thesis describes the important influencing factors on ramp metering and gives a framework for a feasible evaluation process. The purpose of this thesis was to develop a foundation for future research on ramp metering; summarizing all of the existing history and methodologies.

Keywords: ramp metering, master’s thesis, standardized evaluation concept, algorithms
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At first I want to thank my research supervisors Prof. Dr. Klaus Bogenberger, who co-ordinated the contacts and provided me the opportunity to work on my thesis abroad, and Prof. Dr. Robert L. Bertini, who hosted me for the time in the US and supported my work on every step by providing contacts, advices and a vivid social life. Thank you both for all your efforts, I really enjoyed working for you.

Because this thesis is a large general overview about a specialized topic, many other researchers and experts on this field helped me to gather all the data and to summarize it to receive a fully completed work. Especially I want to thank:

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<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADOT</td>
<td>Arizona Department of Transportation</td>
</tr>
<tr>
<td>AHP</td>
<td>Analytic Hierarchy Process</td>
</tr>
<tr>
<td>ALINEA</td>
<td>Asservissement Linéaire d'entrée Autoroutière</td>
</tr>
<tr>
<td>ANN</td>
<td>Artificial Neural Network</td>
</tr>
<tr>
<td>ARMS</td>
<td>Advanced Real-time Metering System</td>
</tr>
<tr>
<td>Caltrans</td>
<td>California Department of Transportation</td>
</tr>
<tr>
<td>CBA</td>
<td>Cost Benefit Analysis</td>
</tr>
<tr>
<td>CCTV</td>
<td>Closed circuit television</td>
</tr>
<tr>
<td>CES</td>
<td>Cost Effectiveness Studies</td>
</tr>
<tr>
<td>CMS</td>
<td>Changeable Message Sign</td>
</tr>
<tr>
<td>CSM</td>
<td>Congestion Management System</td>
</tr>
<tr>
<td>CUA</td>
<td>Cost Utility Analysis</td>
</tr>
<tr>
<td>DoT</td>
<td>Department of Transportation</td>
</tr>
<tr>
<td>FHWA</td>
<td>Federal Highway Administration</td>
</tr>
<tr>
<td>FSP</td>
<td>Freeway Service Patrol</td>
</tr>
<tr>
<td>HAR</td>
<td>Highway Advisory Radio</td>
</tr>
<tr>
<td>HERO</td>
<td>Heuristic Ramp Metering Coordination</td>
</tr>
<tr>
<td>HOV</td>
<td>High Occupancy Vehicle</td>
</tr>
<tr>
<td>LOC</td>
<td>Level of Congestion</td>
</tr>
<tr>
<td>LOS</td>
<td>Level of Service</td>
</tr>
<tr>
<td>Mbottleneck</td>
<td>Modified Bottleneck</td>
</tr>
</tbody>
</table>
MILOS  Multi, Objective, Integrated, Large-Scale, Optimized, System
MnDoT  Minnesota Department of Transportation
OD    Origin-Destination
ODOT  Oregon Department of Transportation
OOCS  Overlapped Occupancy Control Strategy
OR    Oregon
PC-RT Predictive-Cooperative Real-Time Rate Regulation
PLC   Programmable Logic Controller
PORTAL  Portland Oregon Transportation Archive Listings
1 Introduction

This chapter gives a short overview about the motivation and the structure of this thesis. The task is to explain why this topic should be studied in more detail and what the general scope of this research is.

1.1 Motivation

Today, traffic is still a growing subject in the world and it is handled on existing streets embedded in mostly fixed urban scenarios. It is not possible to widen the space for traffic in such environment. Nevertheless, there is a demand which has to be satisfied for economic growth and welfare. Since the middle of the 20th century there have been aspirations to increase the capacity of existing roads by controlling the flow on the freeway or highway system. The selected method was to regulate the flow of traffic which joins the mainline through the ramps, first implemented on Eisenhower expressway in Chicago in 1963 [1](p.5). The success of this system lead to an implementation in other states and countries and to automation of this system, called ramp metering, with traffic signals at the on-ramps, splitting up platoons of merging vehicles and controls the flow on the mainline. The operational system to calculate such a procedure consists of seven following individual algorithms [2](p.8):

- Release algorithm
- Arbitration algorithm
- Switch on/-off algorithm
- Ramp metering algorithm
- Queue override algorithm
- Queue management algorithm
- Data filtering algorithm

The main focus of this thesis lays on the original ramp metering algorithm, which calculates cycle times of traffic signals on the on-ramp, correlating with the number of vehicles joining the mainline. Besides, it is not possible to exclude completely other parts of this system like the queue override mechanism or the switch on/-off algorithm. Information concerning these other parts of this structure shall be additional information to fill some gaps and cannot depict the completeness of these individual algorithms.

The goal is to give a latest overview and summary of all ramp metering algorithms for traffic engineers to decide future deployments in their area of response. In addition to complete this review of the algorithms, it is also necessary to explain which factors are
necessary to evaluate the ramp metering system and what boundaries may occur. The way, how this goal is going to be fulfilled through this thesis is explained in the following chapter about the structure of this work.

1.2 Structure

The used ramp metering systems have become more sophisticated and vary in their syntax. These algorithms shall be summarized in this master’s thesis for the latest overview about the situation of ramp metering in the world. The task is, to explain how they work and where they are deployed. At least there is an approach for an unified evaluation process, developed on former evaluation processes and real freeway data, which shall be an example for current techniques and problems in the field of ramp metering, today.

The structure of this thesis is a linear path from the general introduction to the more detailed concrete examples. It starts in the first chapter with a general explanation of ramp metering and how it is defined.

In the second chapter, the basic knowledge is given for a unified utilization of terminology and to clarify the several definitions and variations of ramp metering adaptations. It follows the direction to explain the general goals and operation methods of ramp metering in general and concludes with a brief overview of special mathematical methods which are often implemented into ramp metering algorithms.

The third chapter is the overview of all algorithms, which were known and explained to date. The list contains over 25 strategies to control the traffic on freeway entrance ramps to maintain free flow on the mainline. Most of them are deployed or were deployed in the past, but this list also describes the algorithms which were tested by simulations but never in the field. The general structure is divided into sub-chapters about their area of influence, either if it is a local or coordinated algorithm with their particular specials cases. The described algorithms in these sub-chapters are sorted by the year of their publication.

After that, the brief history of ramp metering is explained to show clearly the development of these strategies. The importance of these algorithms is presented in a worldwide summary of their deployment with a short comparison to the development in the past to present the growing demand and the trend to use such a system on the freeway. This overview includes how many ramps are metered in each country, and which algorithm is used for this task. A short review about the local characteristics and possible plans to develop the existing system is given in a more detailed textural explanation. Since the USA is the leading country in ramp metering and the several states treat this
topic in different ways, a more detailed explanation about the use of ramp metering is
given after the world-wide view.

The fifth chapter is about the second part of this thesis, a standardized evaluation con-
cept for future examinations of cities and governments about their ramp metering sys-
tem. To construct such a concept, two former greater evaluations were given as an ex-
ample to clarify which are the boundaries and the difficulties of such a study. In fact,
this is on the one hand Minnesota’s shutdown experiment and on the other it is the em-
pirical evaluation of the ramp metering system in Portland. Analyzing these is the main
foundation of the approach to give a standardized overview for upcoming evaluations to
improve the efficiency and to simplify this complex project. This concept is given af-
terwards and shall help future operators to have an overview of the efforts concerning to
the size and the depths of their planned project.

The sixth and following chapters are a summary of the investigations made in this thesis
and an overview of the cited works and the appendix with contents which did not fit
appropriately into the thesis.
2 Literature Review

This chapter serves the reader as a short overview about the basics of ramp metering and is a reflection of the current state of technology in this field. It will be described what the actual value of ramp metering is and which abilities this strategy, for improving freeway flow, has. These general explanations are the foundation for the following chapters, which assume a common understanding on this field.

2.1 Goals and Benefits of Ramp Metering

Ramp metering is an often used system to avoid or respond to congestion on freeways around the world. There are many different strategies to achieve this goal with a variety of equipment, techniques and philosophies to handle the external circumstances. All have in common to ensure free flow on the mainline. Therefore are the following subordinate strategies in different intensity in use to guarantee this main goal [3]-(p.1), [4]-(p.4):

- Break up platoons of joining vehicles to facilitate merging on to the freeway
- Avoid spillback from the ramp on to arterial roads
- Find equilibrium between on-ramp congestion and mainline flow

These goals lead to benefits according to ramp metering. The impacts are far-ranging, depending on the used algorithm, the traffic demand, local peculiarities and other various properties of the used technique just as well the environment of the metered ramp. Following list concludes studied advantages of ramp metering as average benefits: [1]-(p.10f), [5]-(p.11), [6]-(p.4f)

Table 1 Benefits of Ramp Metering [7]-(p.3f)

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mainline Speed</td>
<td>20%</td>
</tr>
<tr>
<td>Freeway Capacity</td>
<td>4%</td>
</tr>
<tr>
<td>Travel Time</td>
<td>20%</td>
</tr>
<tr>
<td>Crashes</td>
<td>30%</td>
</tr>
</tbody>
</table>

Also, there are studies which show decreased ecological damage, because of less fuel consumption and emissions.
In comparison between several algorithms is no consistent result which could lead to a preferred algorithm, but every study led to an improved mainline flow in comparison to a system without ramp metering. These results hardly depend on the evaluated parameters, because, like in other sciences, e.g. the law of conservation of energy or the second Maxwell theorem [8], the major delay is often moved from the mainline to the on-ramp. The high diversity of algorithms, which try to handle this situation in an appropriate way, could be explained by a variable performance of these, depending on many environmental boundaries, e.g. the general driver’s behavior, the quality of the merging area or the available space.

2.2  Ramp Metering Implementations

Depending on the local situation of traffic demand, environmental boundaries, historical situations or political decisions, ramp metering systems can be modified by adding or removing solely abilities. The chosen features of a ramp metering system depend at first on the ability of the basic algorithms to implement an option, which shall be explained in a later chapter. After that, the here explained features can be evaluated by their weight of fulfilling a pre-defined strategy to satisfy the traffic demand, which contains that some options exclude or improve the value of other. The following explanations are an overview about the state of technology and serve the reader to clarify and unify the used terminology. The Figure 1 below is an opportunity to understand the whole system and after that, the itemized blocks are explained in their working method and how they are used in the field.
2.2.1 Working Modes

An algorithm has for the most part three options to act under the influence of the given data. It could be a static mode, which depends on historic data with no consideration of the actual traffic or it could be a real-time mode which reacts directly to its environment by gathering and calculating the latest traffic information. This last method divides into an option to just react on this collected data, and into a forecast model with computed reaction to solve bottlenecks which might arise in the future. Especially the pre-timed strategy is going to be superseded by the real-time traffic responsive algorithms, because its invention was based on the former state of technology. At the moment there is no preference on a predictive or a reactive model because both have their advantages and disadvantages concerning the capacity for real time calculations and the boundaries on the quality of measured data. Following, these modes are named and explained in more detail.
2.2.1.1 Pre-Timed

{or fixed-time, time-of-day, preset operation} The basis of any calculations of metering rates is historical data, which is accumulated over time, and merge into a common, recurrent pattern for driver behavior. According to that, the algorithm meters the ramp under the assumption that the current traffic is the average of its data. This technique is only useful for recurrent congestion (e.g. commuter peaks AM and PM on weekdays), but even then, there is no reliability that the metering rate fits the actual traffic demand. [5]-(p.30), [9]-(p.1)

2.2.1.2 Adaptive

{or traffic-responsive} Adaptive is a method to react to the actual traffic on the mainline and ramps. The data has to be provided in real-time, which determines constantly the metering rate. Depending on the algorithm there is a need of data, e.g. speed, flow, density or occupancy to calculate the metering rate. [5]-(30), [9]-(p.6)

2.2.1.3 Predictive

With a predictive algorithm the existing real-time data are analyzed and result in a short-term forecast of the traffic growth. With that information the algorithm meters the ramps to keep the density or capacity under its saturation over the whole time. Although it will not react on real-time data, it will react on predicted data which will be probably provided sometime later. [5]-(p.30)

Table 2 below provides an overview about the described advantages and disadvantages for better clarity in a direct comparison.

Table 2 Summary of the Working Modes

<table>
<thead>
<tr>
<th></th>
<th>Pre-Timed</th>
<th>Adaptive</th>
<th>Predictive</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td>- Easy to implement</td>
<td>- Reacts to current situation</td>
<td>- More than reacting</td>
</tr>
<tr>
<td></td>
<td>- Good enough for recurrent congestion (commuter peaks)</td>
<td></td>
<td>- Ability to avoid congestion</td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td>- No reliability on current metering rate</td>
<td>- High data input</td>
<td>- Real-time calculation</td>
</tr>
<tr>
<td></td>
<td>- No flexibility on changed circumstances</td>
<td>- Possibility to react to on-ramp queues</td>
<td>- High data input</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Possibility to work with on-ramp queues</td>
</tr>
</tbody>
</table>
2.2.2 Level of Detail

There are algorithms on a different level and with different level of detail. It is possible to calculate independent metering rates based on a single ramp, but there are also options to take a broader view and compare computed local metering rates with others to find a global equilibrium. This larger system can be added with further information or possibilities to react to the current situation. The implementation of ramp metering systems started obviously with local algorithms and developed to the more sophisticated ones. But there are still a lot of local ramp metering algorithms in use whether due to easier for implementation or because they are a part of area-wide algorithms. Not every more sophisticated strategy simply works better, because there are a lot of possibilities of mistuning them or maybe there are conditions which do not need a more complex approach. The following levels of detail represent the latest stages which were computed for ramp metering algorithms.

2.2.2.1 Local

{or isolated} The local approach describes an algorithm which calculates the metering rates detached from its environment. It is dependent on the data which directly belongs to its ramp only, and establishes no connection to previous or following ramps. [4]-(p.6), [9]-(p.5), [10]-(p.14), [11]-(p.2)

2.2.2.2 Coordinated

{or system wide} Combines several ramps as a unit to consider what impact a metering rate to one location has on another. This superior system determines the metering rates at local positions to have a wider impact. This could be useful at sections with a bottleneck at the end, because it increases the storage capacity of this section since no longer only the first ramp has to react to this bottleneck with its limited capacity to store vehicles. [4]-(p.6), [9]-(p.5), [10]-(p.14), [11]-(p.2)

The Table 3 below provides an overview about the described advantages and disadvantages for better clarity in a direct comparison.
Table 3 Summary of the Grade of Detail

<table>
<thead>
<tr>
<th></th>
<th>Local</th>
<th>Coordinated</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td>- Easy to implement</td>
<td>- Uses more on-ramp storage capacity (section-wide allocation)</td>
</tr>
<tr>
<td></td>
<td>- Often “good enough”</td>
<td>- Solves wider problems (bottlenecks)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Consistency in metering tactic to handle one section</td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td>- Cannot solve wider problems</td>
<td>- Higher data flow</td>
</tr>
<tr>
<td></td>
<td>- Last ramp before bottleneck gets handicapped</td>
<td>- Sometimes last ramp before bottleneck still handicapped (too reactive)</td>
</tr>
</tbody>
</table>

2.2.3 Relationships Between Metered Ramps

Apart from local ramp metering algorithms, where the ramps do not communicate with each other, there are three possibilities for coordinated algorithms to connect the computed metering cycles for an improved, global solution. Depending on the superior system, each tactic has its advantages and disadvantages and is mostly preset by the used algorithm.

2.2.3.1 Cooperative

A cooperative algorithm is described by calculated metering rates which extend each other with data or reactive possibilities when one of the ramps reaches its limits. [4]-(p.6), [9]-(p.5)

2.2.3.2 Competitive

The competitive strategy calculates at first several metering rates independent of each other at area of response to choose after that the most restrictive calculated metering rate out of all solutions which finally gets deployed. [4]-(p.6), [9]-(p.5)

2.2.3.3 Integral

The integral relationship between different levels is characterized by separate computed metering rates which are compared to find the best working consensus of these strategies. [4]-(p.6), [9]-(p.5)

2.2.4 Activation Time

It was proven that ramp metering only has a visible impact on the mainline flow, then there is an increased traffic demand. Nevertheless there are aspirations to keep the ramp
metering system ready for incidents and more flexibility. The following list shows the latest common possibilities for using a ramp metering system. In general it is a question of costs over time compared to the use of the gained flexibility. [12]

2.2.4.1 Daytime

The ramp metering system gets activated after a fixed schedule. The switch-on and –off times are depending on historical data about commuting behavior or recurrent, well-known incidents. [13]-(p.101)

2.2.4.2 Dynamic

Dynamic activation describes a strategy where the actual traffic conditions determines that the ramp metering system will be switched-on after the mainline reaches a certain threshold, which is sensitively calibrated to get a chance to avoid congestion and not only to react to it. [13]-(p.101)

2.2.4.3 Incident

The incident activation is characterized by a certain incident on the mainline. The ramp metering system can be switched-on to support the evacuation of the mainline or to support a temporary changed situation, e.g. during roadwork, accidents or lane closures. [13]-(p.101)

2.2.4.4 Manual

The manual activation strategy is an option to respond to exceptional circumstances. It can be the opportunity to over-ride the algorithm by an operator, e.g. to clear a ramp before an ambulance arrives. [13]-(p.101)

2.2.5 Field Deployment

In general, it is an uncommon possibility to implement a ramp metering system on a new constructed freeway which is designed for the needs of ramp metering. Thus, the conditions of the profile and traffic demand are given as a task to solve. Options to handle the initial situation are rare and depend mostly on the existing space around the ramp. The following models are opportunities to respond to the circumstances which have an impact on the metered ramp.

2.2.5.1 Single lane, one vehicle per green

The typical option to meter an on-ramp is to let pass one car per cycle to the mainline. This version supports all goals of ramp metering as far as the demand from the arterial road is not too high. [1]-(p.6)
2.2.5.2 Single lane, multiple vehicles per green

{or *bulk metering, platoon metering*} It describes a strategy to handle a higher demand. There is also the possibility to let pass more than one car per cycle on the mainline. It is not possible to double the flow rate of the version with one car per green because of longer green and red phases to avoid uncertainty of the drivers. [14]-{(p.7) This option is in contrast to the goal of ramp metering to split arriving platoons into single units. It is not recommended to let more than 3 cars pass the ramp at once. [1]-{(p.6)

2.2.5.3 Dual lane metering

If there is enough space, it is a good method to increase the storage capacity of a ramp by adding a second lane to it. It is also useful by mainlines with high occupancy vehicle (HOV) lanes or public transport through the mainline. The green cycle should not be simultaneously to avoid further conflicts. [1]-{(p.6)

The Table 4 below provides an overview about the described advantages and disadvantages for a better clarity in a direct comparison.
Table 4 Summary of the Field Deployment

<table>
<thead>
<tr>
<th></th>
<th>Single lane, one vehicle</th>
<th>Single lane, multiple vehicles</th>
<th>Dual lane</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td>- Supports all goals of</td>
<td>- Higher traffic flow to clear</td>
<td>- Favoritism on HOV-</td>
</tr>
<tr>
<td></td>
<td>ramp metering</td>
<td>the ramp</td>
<td>lanes and public</td>
</tr>
<tr>
<td></td>
<td>- Easy to calculate</td>
<td>- More reactive to high traffic</td>
<td>transport on freeway</td>
</tr>
<tr>
<td></td>
<td>- Easy to understand/use</td>
<td>demand and arterial spillback</td>
<td>- Higher traffic flow</td>
</tr>
<tr>
<td></td>
<td>for drivers</td>
<td></td>
<td>- Higher ramp storage</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>capacity</td>
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<tr>
<td><strong>Disadvantages</strong></td>
<td>- Sometimes restricted</td>
<td>- No double output in</td>
<td>- Needs more space</td>
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<tr>
<td></td>
<td>for traffic demand</td>
<td>comparison to one vehicle</td>
<td>- Increased computing to</td>
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<td></td>
<td></td>
<td>- “Dilemma zone” how many</td>
<td>avoid simultaneous green</td>
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<td></td>
<td></td>
<td>vehicles are allowed to pass</td>
<td>cycles</td>
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<td></td>
<td></td>
<td>- Additional traffic sign to</td>
<td>- Spacious ramps</td>
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<tr>
<td></td>
<td></td>
<td>explain multiple vehicles</td>
<td></td>
</tr>
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<td></td>
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<td>- In contrast to avoid pla-</td>
<td></td>
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<td>toons</td>
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<tr>
<td><strong>Possible</strong></td>
<td>- First type to use, for</td>
<td>- Freeway to freeway meter-</td>
<td>- High traffic demand and</td>
</tr>
<tr>
<td><strong>Deployment</strong></td>
<td>most of the ramps</td>
<td>ing</td>
<td>additional space is avail-</td>
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<td>able</td>
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<td></td>
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<td></td>
<td>- HOV-lanes or public</td>
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<td></td>
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<td></td>
<td>transport on freeway</td>
</tr>
</tbody>
</table>

2.2.6 Further Explanations

2.2.6.1 Kalman Filter

Is a typical online mathematical tool to filter the noise of measurements and estimates statistically the real system in a more appropriate way, which is described as “the calibration problem: Least squared errors and maximum likelihood.” [15]-(p.304) It is founded on the assumption that the failures are Gaussian-distributed. [16]
2.2.6.2 Rolling Horizon

Many predictive ramp metering algorithms use the rolling horizon to improve the quality of their prediction. The idea is to smooth the basis for the forecasting model by forming the average of a pre-defined amount of previous measured data and take this as the basis for the following calculations. This method avoids jumps in the prediction which occurs regularly by changing traffic situations. [17]

2.2.6.3 Godunov Scheme

This method is a numerical tool to solve partial differential equations with a finite-volume approach and was developed by Godunov in 1959. The conservative variables are piecewise constant over the cells at each time step and the time evolution is determined by solving the Riemann problem. [18]

2.2.6.4 Kinematic Wave Model

The kinematic wave model was first mentioned by Lighthill and Whitham in 1955. They assume that on a long, crowded roadway the vehicles behave like the flow of water. The foundation is the relationship between flow and concentration, which is today better known as density. The assumption is that a changed flow causes a “kinematic wave” upstream with the difference that the height of the wave because of the incompressibility of water is represented by a higher density of the mainline flow. This model only works for a large number of vehicles because of its basis which are simple continuum models. [19]

2.2.6.5 Feedforward- and Feedback-Control

Feedforward-Control

Feedforward-Control, also known as open loop control or non-feedback control, is a simplified system to regulate a certain behavior in the current state and the predicted result. In cases of ramp metering, an example would be the measured traffic demand on the mainline and on the on-ramp, which results in a pre-defined cycle time for such a situation. At the next measurement cycle, the system only works with the current traffic situation of the next step what is shown as a process in Figure 2. Such a behavior can easily lead to an oscillating behavior because the calculation is not smoothed by historic data or an evaluation of what its decision caused. [20]-(p.24f)
Feedback-Control

Feedback-Control, also known as closed loop control, works with an evaluation component, which influences the decision of the next step by integrating the results of the previous decision into the calculation. An example for ramp metering would be an upstream measured mainline demand and an on-ramp demand, which results into a cycle time. The influenced situation is measured downstream and this data is included into the next cycle time calculation which is summarized in Figure 3 below. This behavior probably slows the process down because the algorithm reacts more smoothened on the future demand, but in general it works more robust and reliable. [20]-(p.12f)

The advantages and drawbacks are summarized for a better overview in Table 5 below.

Table 5 Comparison Feedforward-Feedback Control

<table>
<thead>
<tr>
<th></th>
<th>Feedforward Control</th>
<th>Feedback Control</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td>- Simple system</td>
<td>- More robust</td>
</tr>
<tr>
<td></td>
<td>- Active control</td>
<td>- Smoothened behavior because of influenced input</td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td>- Instable</td>
<td>- Reactive</td>
</tr>
<tr>
<td></td>
<td>- Inconsistent</td>
<td>- Can improve undesirable properties of the system</td>
</tr>
<tr>
<td></td>
<td>- No reaction on changed system</td>
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</tbody>
</table>
Feedforward-back Controller

In general, both controllers are often combined to balance the advantages and drawbacks of the single systems, which leads to a fast reaction because of the feedforward controller and to a more robust result because of the feedback component of the closed loop controller, as shown in Figure 4. [20]-(p.27) In the field of ramp metering, the use of this approach is new and is only implemented in one algorithm, see 3.105.1.

![Figure 4 Feedforward-Feedback Controller](image)

2.2.6.6 Origin-Destination Approach

To analyze traffic patterns, some ramp metering algorithms base their calculations on the assumption which ways the macroscopic traffic flow takes. This is called Origin-Destination (OD) estimation and can be realized through different approaches which estimate the route choices of single vehicles. Examples to determine this basic data set are traffic surveys which are expensive in time and costs, growth factor models, synthetic techniques or spatial interaction models, e.g. the connection of gravity centers through routes which are defined by time and cost functions. [21]-(p.14)

The analyzed relationships of the origins and destinations which influences the metered corridor are gathered in a OD matrix and serves the algorithm for traffic pattern assumptions.

2.2.6.7 Evaluation of Individual Algorithms

Distributed over this master’s thesis, there will be some evaluations and alignments. In the beginning it is to say that ramp metering systems with their various algorithms are not as consistent as desirable because they depend on too many influences in different combinations which distort the unambiguity. The alignments are approximate conclusions of many previous field tests and studies of other researchers and are a summarized block to estimate the value and possible deployments of several ramp metering algorithms and their components. To have a concrete view on a specific algorithm, the at-
tached literature includes tests of nearly all described algorithms, in which the perform-
ance, the advantages and disadvantages of the several strategies become obvious.

2.3 Conclusion of the Literature Review

This chapter is a short overview of the basic possibilities of ramp metering algorithms. It shows that the several opportunities to implement features to the solely algorithms, extends their flexibility and improves their behavior on the local circumstances. It is possible to react on existing boundaries, e.g. the storage capacity of each ramp or the merging quality in the area where the on-ramp joins the mainline. The reaction to the described parameters could be an implementation of a dual lane system or a multiple vehicle per green strategy. Also, there is the possibility to decide how much effort is needed to achieve a certain level of service (LOS). The resulting decision would be a choice of a pre-defined operating schedule with a static activation time, depending on the time of day, or it could be an adaptive algorithm which activates automatically, when the traffic demand on the mainline starts to increase. The last option would conclude in a continuously monitoring process with a lot of examined data and a constant measuring process which needs a lot of resources, e.g. manual operator or power, to run appropriately.

This diversity and flexibility of ramp metering strategies is one block of their success but it is also a hindrance for a best field-implementation because all these parameters should be recognized in the pre-evaluation process. How this could be implemented in reality is explained in the next chapter about the concrete algorithms.
3 Algorithms

3.1 Introduction

The number of algorithms grows with the innovations on the field of data collecting and processing. There are several algorithms which reacted on gathered experiences and technical improvements. Some are still in use and some are replaced by sequels or better working algorithms. To get an overview about the latest situation, this chapter summarizes and explains the algorithms which were developed and deployed over time. They are sorted by their characteristic grade of detail either local or which is also an imprecise order for their time of creation since the development of these algorithms leads to more complex and system wide strategies. For the beginning and a better overview Figure 5 illustrates chapter 3 in its actual order. The algorithms which are highlighted in red letters are not mentioned in the compendium of Bogenberger and May.
3.2 Local ramp-metering algorithms

Ramp metering of the local level is an essential block of all following ramp metering strategies. Former algorithms back to the beginning of ramp metering controlled the ramp solely at the local level. Even though, at first sight more coordinated ramp metering algorithms are used and seem to be more efficient because of their sophisticated structure, there is every time a local algorithm included solving the local level on-ramp and mainline demand. This is shown in many variations of these local algorithms, e.g. ALINEA, which is transferred in many coordinated systems as a robust and reliable ramp metering algorithm on the local level. [22]-[p.19], [23]

3.2.1 Demand-Capacity

This adaptive algorithm simply computes the gap between measured upstream occupancy and downstream critical capacity which leads to a number of vehicles which were allowed to enter the mainline. The Demand-Capacity (DC) method is a fundamental basis for many other algorithms because of the plausible and transparent idea. This foundation can be flexibly extended, e.g. by setting a minimum metering rate to avoid a permanent red signal at the on-ramp if the critical occupancy is exceeded [10]-[p.16]. The syntax including the described example might be like:

{\text{IF}} \ O_{in} \leq O_{crit} \ {\text{THEN}} \ r(t) = \max(q_{cap} - q_{in}, r_{min}) \\
{\text{ELSE}} \ r(t) = r_{min}

\begin{align*}
O_{in} & = \text{measured mainline occupancy upstream} \\
O_{crit} & = \text{pre-defined critical mainline capacity downstream} \\
r(t) & = \text{computed metering rate} \\
q_{cap} & = \text{pre-defined critical mainline flow} \\
q_{in} & = \text{measured mainline flow upstream} \\
r_{min} & = \text{pre-defined minimum metering rate}
\end{align*}

[24]-[p.7]

3.2.1.1 TANA

The TAngenziale de Napoli (TANA) is a comprehensive road management system, which included VMS, CCTVC and ramp metering and was established in Napoli in
1973. [25]-(p.542) The several parts of the system are not connected with each other automatically but through a manual operator.

The core algorithm itself seems to be the first installed ramp metering algorithm in the world and is based on the DC theory. [25]-(p.546) This strategy measures the demand and compares it with a six pre-defined classes. The lowest class, identified with a zero, induces a permanent green phase with the peculiarity that the traffic light is set to red but instantly changes to green, when a vehicle arrives in the front of the traffic signal. This setting avoids uncertainties for arriving vehicles, which do not know when this traffic light could jump to a red phase instantly. This algorithm also contains a queue override detection, which sets the latest cycle class one step lower, when the queue detector is occupied, to slowly clear the ramp. [25]-(p.547) Every part of the TANA strategy can be overridden by the manual operator, who might react more quickly to incidents observed through the CCTV or made experiences. [25]-(p.554)

3.2.1.2 RWS (Rijkswaterstat)

RWS, named after “the commissioning organization” [26]-(p.1) is a variation of the DC method and was developed in the Netherlands. The algorithm measures flow and uses speed instead of occupancy. The target is to keep the actual flow below the critical flow at the inflection point as visible in Figure 6 below.

![Figure 6 Visualization of Traffic-Inflexion Point](image)

Figure 6 Visualization of Traffic-Inflexion Point [24]-(p.10)

The metering rate results from a comparison of the pre-defined capacity and the measured flow of the previous time step.

\[ r_t = C - I_t - 1 \]

\[ r_t = \text{computed metering rate} \]
3.2.2 Occupancy Control

The occupancy control (OC) strategy is a basic approach for a local ramp metering algorithm and is the standard isolated part of the Bottleneck algorithm 3.59.2.

OC is an adaptive system which compares the actual computed solutions, based on measured occupancy data on the mainline by upstream detector loops, with predetermined metering rates corresponding to these occupancy values. The estimated metering rates are created on the assumption of a relationship between the measured occupancy and the actual volume on the freeway. The calculations are feed-forward based and thereby not as robust as feedback strategies as ALINEA 3.16.1, because it does not include previous calculations in its equations. Because of that, the metering rates can be sometimes inconsistent. [22]-(p.11f)

In some simulations the OC method was compared directly with the ALINEA algorithm, e.g. as the local part of the Bottleneck strategy, and it was shown, that ALINEA is every time an improvement. Because of that, this algorithm is not used anymore as a standard strategy for ramp metering. [4]-(p.33)

3.2.3 Zone

The Zone algorithm was first deployed in Minneapolis, Minnesota, USA as a pre-timed algorithm, but was updated later to an adaptive system. The region of the Twin Cities is well-known for its aspirations in researching ramp metering like an evaluation of their system by an 8-week shut-off experiment in fall 2000 shows. [27]

As the name provides, the Zone algorithm divides the mainline into zones, which were characterized by several metered and some unmetered on- and exit-ramps, an area with low incidents upstream and a potential bottleneck downstream. [4]-(p.41)

The idea is to control the functionality of the zone by measuring the incoming and leaving traffic over the whole section with the downstream bottleneck capacity as the regulating factor [11]-(p.3). This equation is described by:

\[ A + U + M + F = X + B + S \]
3.3 \( A \) 3.4 = upstream mainline volume (measured)
3.5 \( U \) 3.6 = sum of unmetered entrance ramp volumes (measured)
3.7 \( M \) 3.8 = sum of metered ramp volumes (controlled)
3.9 \( F \) 3.10 = sum of metered freeway to freeway ramp volumes (controlled)
3.11 \( X \) 3.12 = sum of exit ramp volumes (measured)
3.13 \( B \) 3.14 = downstream bottleneck capacity
3.15 \( S \) 3.16 = space available within the zone (computed volume based on measured variables)

For a more obvious presentation of the possibilities of the algorithm it is necessary to transform the equation any which is dependent on the metered ramp volumes. With the assumption that \( S \) is equal to zero this leads to:

\[
M + F = (X + B) - (A + U)
\]

[14]-(p.15)

3.16.1 ALINEA

The Asservissement Linéaire d’Entrée Autoroutière (ALINEA) algorithm developed by Papageorgiou is a robust and often used local ramp metering algorithm. It is proposed in 1997 and is or was deployed in Paris, Amsterdam, Munich and is often an improvement on the local area of coordinated ramp metering algorithms, e.g. in test situations for Bottleneck, SWARM or as the standard local algorithm of HERO. [22]-(p.19), [23]

The idea is to keep the traffic under a static, pre-evaluated occupancy and increase thereby the mainline throughput. It is based on the feedback theory and computes the metering rates in a way that the traffic flow remains under the system capacity. The metering rate is calculated with the equation below:

\[
r(t) = r(t - 1) + K_R (O_C - O_{out}(t))
\]

\( r(t) \) = meter rate (volume) in time interval \( t \)
\( K_R \) = weighting factor >0 to adjust the feedback control
\( O_C \) = local occupancy at ramp (measured by one mainline detector)
\( O_{out} \) = pre-defined occupancy value at capacity (varies, depends on local philosophy)
This equation is a closed-loop equation, thus \( r(t) \) is a function of \( r(t-1) \), an advantage in contrast to open-loop algorithms because of a certain consistency in metering rates and a robust behavior in calculations. [3]-(p.39f), [4]-(p.26), [11]-(p.28)

There are many regional variations, improvements and extensions to this algorithm and some of them shall be explained here. It is to summarize that every modification of the original ALINEA led to a worse result in comparison to the original algorithm, except for ALINEA/Q. The deployment of these changed algorithms is explained by the attempt to avoid construction work on the freeway to implement new detector systems by using the existing material. [10]-(30)

3.16.1.1 ALINEA/Q

The additional Q is an additional feature of ALINEA to count the number of vehicles which are stored in a queue or entering the ramp via video monitoring. This extension allows ALINEA to take reference to the queue, which was not possible up to this point and one of the most drawbacks because the mainline flow was guaranteed at the expanse of the arterial network. This extension can be implemented to every ALINEA algorithm including the existing modifications. [10]-(30)

3.16.1.2 MALINEA

MALINEA is an improvement made in 2001, which solves two disadvantages of the original ALINEA. At first the problem, that the congestion could arises upstream (and ALINEA just computes metering rates concerning to the downstream occupancy) and the second problem is the localization of the perfect place for the measuring detectors. Both of these subjects are handled in the following revised equation:

\[
Q'(t+1) = (O_u(t + n + 1) - O_u(t)) \cdot \frac{K}{A} + Q'(t - n)
\]

\( Q'(t+1) \) = calculated metering rate for next time step
\( O_u \) = measured upstream occupancy
\( n \) = pre-defined time lag between up- and downstream measurements
\( K \) = regulating factor
\( A \) = derivation of downstream and upstream occupancies relationship

[10]-(p.18)
3.16.1.3 FL-ALINEA

This adjusted ALINEA from 2003 replaced the downstream occupancy input data with the downstream flow measurements to overcome a lack of data. The original ALINEA equation is, thus modified in a way that occupancy input is replaced by flow data. A little extension is the connection to a minimum metering rate, which becomes deployed when the freeway capacity is exceeded. [10]-p.19

3.16.1.4 UP-ALINEA

The name suggests it rightly that the input occupancy data is measured upstream of the entrance ramp and is forecasted to a downstream occupancy. This additional step of calculation should only be implemented if there are already upstream detectors, e.g. from former algorithms which were using upstream data like demand-capacity). The predicted downstream occupancy is calculated by following equation:

$$
\tilde{O}_{\text{out}}(k) = O_{\text{in}}(k) \times \left(1 + \frac{Q_{\text{ramp}}(k)}{Q_{\text{in}}(k)} \right) \times \frac{\lambda_{\text{in}}}{\lambda_{\text{out}}}
$$

- $\tilde{O}_{\text{out}}(k)$ = estimated occupancy downstream at time step k
- $O_{\text{in}}(k)$ = measured occupancy upstream at time step k
- $Q_{\text{ramp}}(k)$ = measured flow from the on-ramp at time step k
- $Q_{\text{in}}(k)$ = measured flow on the mainline at time step k
- $\lambda_{\text{in}}$ = number of mainline lanes upstream
- $\lambda_{\text{out}}$ = number of mainline lanes downstream

This calculated downstream occupancy replaces the measured occupancy of the normal ALINEA. The rest of the original equation does not change. [10]-19)

3.22.1.1 UF-ALINEA

This modification of ALINEA is an extent to the FL-ALINEA. It uses the same equation as described above but with the difference that the insert downstream flow is not measured but calculated. It is a simply summation of the measured upstream flow and the on-ramp flow. This step extents the applicability of ALINEA without any modifications on the roadside. [10]-p.20
3.22.2 Local metering using neural networks

This algorithm is comparable to ALINEA with the difference that it is using Artificial Neural Networks (ANN) to work with input data. This method assigns input data a weight before it solves the function to get metering rates as output. The traffic is assumed as a kinematic wave which is a good description for the traffic flow. This based hydrodynamic model is a similarity to ALINEA as the use of feedback regulation to keep the actual situation on the freeway below the critical occupancy. The following scheme, Figure 7, shows the sequence of events for the feedback control of the algorithm.

![Figure 7 Non-Linear Feedback Control Process](image)

If there is any congestion solving problems can occur because of the lack of a queue override strategy. In this state the computed metering rate would be restrictively overridden which leads to an alternating behavior during congestion. [11]-(p.31)

All in all, this algorithm is as well as ALINEA still ranked as good. [4]-(p.8)

3.22.3 MIXCROS

MIXCROS is originally a local feedback-based algorithm of 2003 which treats explicitly ramp queues in its metering rate calculation. Because of the retarded possibilities to influence the mainline flow on the local level, there were already expansions to transform MIXCROS into a coordinated algorithm. [28]-(p.73)

The local version of MIXCROS is the basis for the adaptations in their syntax and assumptions. The idea is to maintaining the traffic density on the mainline to maximize its throughput, while reducing queues at the on-ramp. The importance of these two influenced areas is weighted by factors for each ramp and is reflected in the following error-equation [28]-(p.73):

\[ e(k) = w_1 * |\rho(k) - \rho_{cr}| + w_2 * queue_{ramp} \]

\[ e(k) \quad 3.23 \quad = \text{error-function to combine the situation on the ramp and the} \]
The calculated e(k)-factor is finally included into the calculation of how many vehicles shall be allowed to enter the mainline from an on-ramp. This procedure can be described by:

\[ u(k) = \frac{-F(k) - K \cdot e(k)}{G} \]

With

\[ F(k) = \text{sign}(\rho(k) - \rho_{cr}) \cdot w_1 \cdot \left[ \rho(k) - \rho_{cr} + \frac{T}{L_f} \cdot \left( f_1(k) - q_{out}(k) \right) \right] \]

\[ G = \text{sign}(\rho(k) - \rho_{cr}) \cdot w_1 \cdot \frac{T}{L_f} - w_2 \cdot \frac{T}{L_r} \]

\[ \text{sign}(\rho(k) - \rho_{cr}) = \begin{cases} 1, & \rho(k) > \rho_{cr} \\ -1, & \rho(k) \leq \rho_{cr} \end{cases} \]

\[ u(k) = \text{computed metering rate in} \ \left[ \frac{\text{veh}}{h} \right] \]

\[ k = \text{actual time step} \]

\[ K = \text{defined control gain} \]

\[ T = \text{time step duration} \]

\[ L_f = \text{length of the freeway section} \]

\[ f_1 = \text{measured incoming flow on the mainline} \]

\[ q_{out} = \text{measured flow leaving the section} \]

\[ L_r = \text{length of the entrance ramp} \]

This set of equations is the basis for the coordinated MIXCROS algorithms which exist in a coupled and in a decoupled version [28]-(p.80).
3.28.1.1 D-MIXCROS

The decoupled variant is quite similar to the local MIXCROS algorithm with the difference that the control gain factor K is constant over a whole section to produce a certain unity in the calculations of the several ramps. The equation for n ramps in a section would be described by [28]-(p.82):

$$u_n(k) = \frac{-F(k)n - K \cdot e_n(k)}{G_n}$$

As the calculation is the same as the local version of MIXCROS, the advantage of the decoupled variant is that it is easier to implement because of the constant control gain factor.

3.28.1.2 C-MIXCROS

This expansion of the MIXCROS algorithm is the coupled version which combines the weights of several ramps in a section on the foundation of the basic equation of the original algorithm. The calculation is described by the following equation:

$$u_n(k) = \frac{\alpha_n \cdot (-F(k) - K \cdot e(k))}{G_n}$$

The main extension is the weighting factor α which is a certain percent weight for every ramp and must be accumulated equal to 1. With that variable it is possible to react on different conditions on the several ramps by distributing the burden to other ramps in real-time [28]-(p.80f).

3.28.2 PRO

The Proaktive Rampenoptimierung (PRO) is an algorithm which was first described in 2006 in Germany and has been implemented into the ramp metering system of Baden-Wuerttemberg since 2012. [29]-(p.118) It is a local and predictive strategy which tries to handle the mainline flow and the on-ramp demand equally.

The origin algorithm consists of the unique ramp metering algorithm itself and additional components which calibrate the equation for the use in the reality. [30]-(p.81) At first, the core of this strategy shall be explained by the equation and its assumptions:

$$q_{HZS} = q_{Nachfrage mak} \cdot \left( \frac{q_{HF,max}}{q_{HF, max}} \cdot f_q \right)^{\lambda}$$

$$Q_{esz}$$ 3.29 = calculated metering rate
The weighting factor $\lambda$ is a possibility to influence the sensitivity of the algorithm. It could be possible to force a higher sensitivity to the current situation on the mainline, when $\lambda$ is set greater than 1. This would lead to higher fluctuations of the metering rate. If $\lambda$ is set smaller than 1, the metering rates becoming more stable and there is less reaction on the current traffic demand. Tests have shown that $\lambda$ has a different impact on the quality at different traffic demand, e.g. does it has a positive influence on the system, when $\lambda$ is small at situation with raising on-ramp demand. [30]-(p.81)

The correcting factor $f_q$ describes the opportunity to calibrate the algorithm to the local boundaries of the freeway system and is a result of the unique forecasting part of PRO. In contrast to other predictive algorithms, which are calculating a future demand by analyzing the data of the near past, PRO is predictive because of a second set of detector loops in a certain distance upstream the on-ramp. $f_q$ refers to inaccuracies in the estimated travel time from the detector loops which are further away, because of lane changing manoeuvres and deviations from the pre-set average travel speed. The mentioned input data of the different sets of detector loops are implemented into the equation via $q_{HFB,mik}$ as the current situation and $q_{HFB,mak}$ as the forecasted part. [30]-(p.81)

At the origin PRO algorithm the time lag between on-ramp entrance and detector loop for the current traffic situation is set to 15s. The time lag between the on-ramp entrance and the detector loop for the forecasted situation is set to 60s. The referring distance to the amount of time is calculated by the following equation: [30]-(p.84)

$$D = (T_{HFB,x} + T_{Schaltung} + T_{Einfahrt}) \cdot v_{prog}$$

$T_{HFB,x}$ 3.35 = time between detector loop and on-ramp entrance

$T_{Schaltung}$ 3.36 = estimated time for the data transmission and cycle time calculation

$T_{Einfahrt}$ 3.37 = average time for a car to reach the freeway from the on-ramp meter
The origin PRO algorithm works standardized with $T_{\text{Schaltung}} = 5$ s, which is an estimated period of time for the transmission of the measured data at the detector loop to the calculating station and includes the time for the algorithm to compute the metering rate. $T_{\text{Einfahrt}}$ is determined to 15 s and $v_{\text{prog}}$ is estimated to $80 \, \frac{\text{km}}{\text{h}}$ and can be adjusted referring to the real situation on the freeway. These assumptions are leading to a distance measured from the on-ramp to the first detector loop upstream of 770 m and to the second detector loop of 1760 m. [30]- (p.84) After implementing this ramp metering system on the road, the control scheme of PRO is working as visualized in Figure 8 below.

![Figure 8 PRO Flow Chart](p.123)
The description above is all about the core algorithm of PRO. Additional features are explained in the following paragraph. These features are independent of the algorithm itself and could be used for other strategies, too. In general, none of these improves the results of the algorithm, but partly they are necessary to implement it into a real system.

The minimum cycle time is pre-defined to 4.5s and it leads to a constant green when the computed cycle time is below this threshold. [30]-(p.84) The maximum cycle time is set to 36s which is equal to 100 vehicles per hour as a minimum flow on to the mainline [30]-(p.85) but tests were conducted with a maximum cycle time of 30s. PRO also includes strategies to react to incidents on the freeway. To hinder an occurring congestion, PRO sets the cycle time spontaneously to 30s for a short time, to relieve the impact on the freeway. [30]-(p.86) But this feature turned out as not as effective as desired. [30]-(p.132) If congestion has already occurred and the average speed is about $40 \frac{km}{h}$, PRO turns off automatically because of different driver behavior at this lower speed level and the assumption that ramp metering cannot support the system appropriately anymore. [30]-(p.86) The most important feature of PRO is the queue control which avoids queue spillbacks on to the arterial network and increases the equity between drivers on the on-ramp and on the mainline. The assumption is that a measured occupancy at the critical point greater than 20% would lead to a spillback. To clear the ramp, the metering rate can be increased step by step or it can be set to the minimum cycle time of 4.5s. [30]-(p.85)

All in all, depending on the tested load on the mainline and on the on-ramp, the algorithm has shown in micro simulations no further improvements to the zero-case study in cases like travel time and emission producing. [30]-(p.111f) This is because the benefits on the freeway always were comparable to the drawbacks on the on-ramps. In this study, ALINEA and a pre-fixed strategy were compared with PRO, too, with the same results. Nevertheless, the last two strategies were worse because of higher probabilities of queue spillback on to the arterial network. The advantage of PRO was a statistical reduction of 21.3% of crashes which was explained by an improved mainline flow through easier merging situations. [30]-(p.113) The new strategy to predict the future traffic demand seems to be very stable if it is matched to the local freeway situation, but the implementation includes the installation of this specific detection structure to fulfill the boundaries of the algorithm. An implementation in Baden-Württemberg has shown positive results, this includes an increase of the mainline speed and the mainline capacity as well as a decrease of the travel time. [29]-(p.134)
3.39 Coordinated ramp-metering algorithms

To improve local ramp metering strategies it was necessary to expand the possibilities of the algorithms. The new idea is to connect the local levels to get an earlier impact on bottlenecks and to enlarge the space to store vehicles on ramps. Coordinated ramp metering algorithms are a common way to avoid congestion and ease the impact on bottlenecks. There are 3 options how the local ramps can communicate with each other and with the system-wide algorithm, which will be explained based on the associated algorithms of this kind.

3.40 Cooperative

After computing the metering rate at the local level, the solution gets evaluated as independently solvable or as a critical threshold which leads to a communication to other ramps. In general, the previous ramp upstream reacts to the locally unsolvable situation downstream with a reduction of its metering rate to support the following ramp.

3.40.1 Linked-ramp

The original system of the Linked-ramp algorithm was deployed in San Diego, California, USA in 1968 and runs under the name of the San Diego Ramp Metering System (SDRMS). The calibration of this system is based on a pre-evaluation of the section and its influencing sections on previous areas. [10]-(p.23)

The maximum metering rate depends on the capacity of its local area which is affected by the input flow of the mainline and the previous located ramps. This information has to be selected from historical data. The minimum metering rate depends as well as the maximum metering rate on historical traffic flow data. The (mostly commuter) peaks were analyzed under the consideration of the local possibilities of the ramp to store vehicles. [10]-(p. 39)

This demand-capacity method is at the SDRMS for example divided into 16 segments of possible metering rates. It is a simplified system of the calculated period between the maximum and the minimum metering rate divided by the number of segments. The actual metering rate is given by: [4]-(p.10)

\[
\text{Metering rate} = \text{Target flow rate} - \text{Upstream flow rate}
\]

The highest flow rate is reached by a free flow rate where the ramp meter is frozen at green. If the local situation leads to one of the 3 lowest metering rates, the algorithm activates its cooperative part and carries the next previous ramp to lower its metering.
rate. This reaction is repeated until all possibilities of the linked-ramps in this section are spent or the traffic demand decreases again. [11]-(p.17)

3.4.0.2 Helper

The Helper algorithm was first deployed in Denver, Colorado, USA in early 1981 and consists of a local ramp metering algorithm and a superior coordinated algorithm. The freeway is divided into groups consisting of one to seven metered ramps per group which define the section the algorithm can work with.

On the local level the algorithm computes its metering rates based on the upstream mainline occupancy near the ramp and the data of the queue override detector. If the last one detects an approaching spillback on to the arterial roads, the metering rate is increased for one step per cycle time as long the queue override detector is occupied.

In addition to this local reaction on possible spillback, the coordinated algorithm reacts to this signal. With the Linked-ramp algorithm, the Helper algorithm distributes the load on the previous ramp upstream to relieve the impact on the mainline which would increase because of the self-solving reaction of the local algorithm to increase the metering rate to clear the ramp and avoid arterial spillback. The difference with the Linked-ramp algorithm is the separation of this local solution and the coordinated solution.

In general, this separate coordinated part of the Helper algorithm monitors the ramps of its group and categorizes them as critical or not-critical. It considers in a fixed cycle time the two possible events when a ramp would need some help of the other in this section. It checks the metering rate and the queue detector. If one of these two conditions were violated the coordinated algorithm reacts with a distribution of the load on the next upstream ramp. If that leads to a critical condition, the distribution on the next previous ramp gets repeated and so on as visualized in Figure 9. [11]-(p.5)

![Figure 9 Working Mode of the Helper Algorithm](image-url)
This algorithm is considered as sophisticated to calibrate but robust in its syntax. [4]-(p.9)

3.40.3 MILOS

The Multi-Objective, Integrated, Large-Scale, Optimized System (MILOS) is a predictive area-wide algorithm which was developed by the Arizona Department of Transportation (ADOT) during the RHODES-ITMS project in 1999. It is predictive, traffic responsive and interacts between the local and coordinated level in a cooperative way. It uses a macroscopic model to estimate the traffic and solves the optimization with quadratic programming (QP). The algorithm uses measured flow data and computes density and speed for further calculations. [32]

The structure of MILOS is based on a classification of the influenced area of the certain modules which have different technologies to handle their area of response. This ranking consists of the strategic, the tactical and the operational strategies which shall be explained in more detail. [33]-(p.21)

**Strategic**: it is the widest level which controls the whole section and has a horizon of hours, days or seasonal changes. The main task of the strategic view is to update the slowly varying parameters like the overall increase of traffic demand and to transfer the information about sub-networks and other superior data to the lower levels. It contains the modules of anomaly detection and the sub-network identifier.

**Tactical**: the tactical level operates on a horizon of hours and minutes and is described by the coordinated algorithm which reacts on short-term fluctuation, non-recurrent congestion and controls the queues in the section. This level consists of the anomaly detection and the area wide coordination. The computed solutions were fed to the lower level.

**Operational**: this level acts in a horizon of minutes and is responsible for the local level control algorithm which computes on the base of the superior levels an improved strategy for its retarded area. The goal is to reduce ramp queues by reacting on short-term fluctuations forecasted by local predictions.

As mentioned, these classifications consist of different modules themselves which shall be explained in more detail including their tasks and syntax. The sub-network identifier module is only briefly explained how it should work, but at the time of the research there was no functioning algorithm implemented in the complete system of MILOS. The description of the modules begins with the normal structure of system-wide and local algorithm and is followed by the additional features of statistical process control (SPC) anomaly detection and sub-network identifier. [33]-(p.19)
**Area wide coordination**: this part computes metering rates based on an optimization of queue lengths and mainline throughput maximization. The calculated rates for the system-wide level are given to the next lower level, the local ramp metering algorithm. Under the assumption that the first freeway input cannot be controlled, the following ramps were metered by the quadratic optimization problem below [33]-(p.39f):

\[
\max \sum_{i=1}^{N} (1 + 2\beta \gamma c_i d_i) \ast r_i - \beta \gamma c_i r_i^2 - \beta_2 \gamma c_i z_i^2
\]

- \(i\) = number of a certain ramp within the section
- \(N\) = total number of ramps within one section
- \(r\) = computed metering rate
- \(\gamma\) = ratio of the minimum flow entering the mainline from the on-ramps of the section
- \(\beta\) = weighting factor to determine the importance of mainline flow and ramp queues
- \(c_i\) = weighting factor to reflect the congestion conditions at each interchange
- \(d_i\) = on-ramp demand of ramp \(i\)
- \(\beta_2\) = scaling constant of \(\beta\) to optimize queuing behavior in the section
- \(z_i\) = factor to reflect extra capacity of ramp \(i\) to accommodate the flow at that ramp

The equations which are the basis for this optimization follow below with the itemization of the different variables. The text explanation of a variable is only given once starting at the equation above, to minimize the overview.

\[
\sum_{i=1}^{j} (A_{ij} \ast r_i) \leq CAP_j \ \forall \ j
\]

- \(i\) = defines ramp \(i\)
- \(j\) = defines section \(j\)
- \(A_{ij}\) = matrix with flow proportion entering at ramp \(i\) through section \(j\)
- \(r_i\) = metering rate for ramp \(i\)
- \(CAP_j\) = capacity of section \(j\)
\[(d_i - r_i) \cdot T - z_i \leq Q_i \quad \forall \ i\]

\(T\) 3.46 = optimization Time horizon

\(Q_i\) 3.47 = number of vehicles which can be queued on the on-ramp, assuming an average vehicle length

\[
c_i = \frac{\sum_{m=1}^{M} V_{m,i}}{\max_i(c_i)} \quad \forall \ i
\]

\(V_{m,i}\) 3.48 = offered volume for phase m at ramp i

\(C_{m,i}\) 3.49 = capacity of phase m at ramp i

\[
\gamma = \frac{\sum_{i=1}^{N} d_i}{\sum_{i=1}^{N} (c_i \cdot (d_i - r_{i, \text{min}}))^2}
\]

\(r_{i, \text{min}}\) 3.50 = minimum metering rate at ramp i

\[
d_i = \rho_{R,NB} \cdot d_{NB} + \rho_{L,SB} \cdot (1 - \rho_{R,SB}) \cdot d_{SB} + \rho_{T,EB} \cdot d_{EB} + \frac{q_i(0)}{T} \quad \forall \ i
\]

\(\rho_{R,NB}\) 3.51 = probability to turn right, northbound to enter the on-ramp from arterial road

\(d_{NB}\) 3.52 = demand of the arterial road, northbound

\(\rho_{L,SB}\) 3.53 = probability to turn left, southbound to enter the on-ramp from arterial road

\(\rho_{R,SB}\) 3.54 = probability to turn right, southbound to enter the on-ramp from arterial road

\(d_{SB}\) 3.55 = demand of the arterial road, southbound

\(\rho_{T,EB}\) 3.56 = probability to go through, eastbound to enter the on-ramp from arterial road

\(d_{EB}\) 3.57 = demand of the arterial road, eastbound

\(q_i(0)\) 3.58 = queue length at the beginning of the optimization iteration
Because this contemplation to involve the turning probabilities to evaluate the real-time ramp flow by minding real-time arterial network demand, the following Figure 10 shall give a better overview about the explained parameters above.

![Figure 10 Visualization of Turning Propabilities](image)

**Figure 10 Visualization of Turning Propabilities [33]-(p.44)**

The whole system maintains itself with the anomaly detector and reacts to infeasible equations, which can occur when an incident on the mainline decreases the capacity, by allowing spillback on to the arterial network.

The capacity of each section can be determined by analyzing historical volume-density curves or calculated with input data about saturation flow rates, number of lanes, merge area restrictions and other information. The goal is to maintain a real-time mainline capacity slightly below the critical capacity for the section to avoid oscillating congestion waves. The actual computed metering rate is between a pre-defined minimum and maximum rate and is automatically set to one of these boundaries when the calculation exceeds the interval. The goal is to maximize the metering rates to minimize the total travel time of the complete freeway system. The computed metering rates were fed to the next lower level, thus the local algorithm can improve this rate for the more detailed situation at each ramp.

**Local algorithm:** This part of the MILOS system is an optimization tool to improve the suggested metering rates of the upper levels by minding local peculiarities. The main task is to maintain the on-ramp queue and to extend the accuracy by a predictive-cooperative real-time rate regulation (PC-RT) which is only included at the local level to minimize the complexity of the whole system. The prediction refers to the on-ramp demand as well as to the mainline demand and has a horizon of 5 to 7 minutes, but will
be re-evaluated after 1 to 2 minutes to improve the metering rates and the forecast as their basis. These predictions do not need to be completely accurate but they must represent the dynamic and the range of the possibilities of the system. The computed metering rate replaces only the coordinated rate if it improves the system travel time and is adjusted to the calculations of the level above over a pre-defined interval $\varepsilon$ in which the local level is allowed to overwrite the coordinated metering rate.

**Anomaly detection:** this SPC-based module is a feature of MILOS to maintain itself and is therefore only activated when the measured data significantly differ from the average of the last assumptions and predictions. This difference is defined by a lower and upper limit with the presumption of an approximately constant demand, which cannot be right at peak periods. For this special occasion, the anomaly detector has implemented jumps to react appropriately on this recurrent traffic behavior. In general, the anomaly detection forces a re-evaluation depending on the detected difference. If a point is exceeded, the PC-RT will re-calculate the metering rate and if a trend is exceeded, the area-wide coordination algorithm will re-evaluate its results. [33]-(p.94f)

**Sub-network identification:** normally, the sub-network is pre-defined by a manual operator who regards his decision on local boundaries, e.g. state boarders or influence area of traffic control centers. The idea is to include such an automatically identifier into the structure of MILOS, but there is no further explanation available how it could be evolved and how it should work, thus there is no implementation of such a system, yet.

MILOS is a sophisticated algorithm with a lot of possibilities to react to upcoming traffic demand. It is new that the queue treatment is directly included and determining the metering rate and that for this feature the data collection is expanded to the arterial network. This input data has the advantage in comparison to queue override detector loops that an oscillating metering rate is avoided because there is no certain threshold which determines a change in the computing. It is rather a smooth calculation as known for mainline-based metering rates. The cooperative basis of the algorithm and the two-layer improvement of the metering rate, with a more sophisticated approach on a more detailed level, making MILOS very accurate and flexible in situations of infeasible equations. E.g. if the PC-RT has an infeasible equation, then it will re-activate the area-wide algorithm, which creates on this new input an improved metering rate. This behavior is supported by the different structure of the local and the area-wide level. Additional features, like the reaction on an incident by decreasing the real-time mainline capacity or the idea of the sub-network identifier making MILOS to an interesting project. But all these good ideas leading to their disadvantages that MILOS needs a lot of data even about the arterial network, which can be a huge problem, as tests with SWARM has
shown. Furthermore there are a lot of sophisticated real-time calculations with a high data transfer from the upper to the lower level.

The algorithm was only tested by ADOT in computer simulations in which the algorithm has shown good results, slightly better than LP.

3.59 Competitive

This mechanism is based on a direct comparison between computed metering rates where the most restrictive rate gets deployed and the other rate has to bow to it. It is often deployed in situations where one important single on-ramp would lead to a collapse of the whole system if it would not be well maintained.

3.59.1 Compass

This algorithm was first deployed in Toronto, Canada in 1975 and is a good example for decisions based on the most restrictive data, i.e. it is a competitive algorithm on local as well as on the system wide level. The ramp metering algorithm is only one part of the whole COMPASS system, which is installed in Toronto, Mississauga, Burlington and Ottawa and contains vehicle detector stations, closed circuit television (CCTV) cameras, changeable message signs and other opportunities for an operator at the traffic control center to have an impact on the traffic on the freeway.

The included algorithm uses the mainline occupancy data near to the ramp, the downstream mainline occupancy and the upstream mainline volume. This information is combined with pre-set thresholds on the local level, downstream occupancies and upstream volume to result in a value which will be compared with a look-up table. Depending on the calculated value of the measurements, the look-up table will lead to the most restrictive metering rate depending on the local and downstream occupancy and the upstream volume and has a resolution of 17 steps. This pre-defined simplified method for data classification is the largest drawback of this method.

Besides the local level, there is an additional off-line optimized metering rate which is influenced by the system wide level. This metering rate is also compared with the metering rate at the local level and again, the most restrictive will be implemented.

In addition, this algorithm includes ramp queue handling which means that the calculated metering rate is set up one level higher than computed. This superior restrictive decision shall lead to a ramp clearance to a value below the on-ramp occupancy threshold. [11]-(p.11)
This algorithm is not as robust as other traffic responsive algorithms because of the pre-defined look-up tables, but it is eventually categorized as a good algorithm. [4]-(p.11)
The algorithm was replaced by ALINEA in 2012 in Ontario and thus, there is no location known where the Compass algorithm is still in use. [34]

3.59.2 Bottleneck

This algorithm was first implemented by the Washington Department of Transportation (WDOT) on the I-5 north of Seattle, Washington, USA in 1981. It consists of two layers, which are computing metering rates on their certain level, and a comparison of these afterwards. It is a competitive algorithm which means that the most restrictive of these metering rates gets implemented and a well-known representative is the FLOW algorithm of Seattle. The following sequence of events in Figure 11 is an overview about the typical calculation steps of a bottleneck algorithm.
At the local level, this algorithm uses the measured real-time upstream occupancy to transfer to a local metering rate. This transition is set up by a pre-defined look-up table made of historical data, which connects the occupancy to a certain volume which can be compared with the local estimated downstream capacity. Finally, the computed metering rate lets pass a number of vehicles per minute to match the gap between real-time measurement and capacity to create a high LOS. [11]-(p.7)
The system-wide part is activated when 2 criteria are fulfilled. First, it localizes a violation of a pre-defined occupancy threshold at a bottleneck on the freeway, which represents a demand above the capacity, and second, the section upstream of the bottleneck is already storing vehicles, which indicates that more vehicles are joining the freeway than leaving it. The coordinated algorithm determines the gap between demand and supply and reduces the volume of the influencing section by dispersing the burden of storing vehicles to the on-ramps based on a weighting factor. This procedure can be explained with the following equations, at first the reduction of the freeway volume upstream [14]-(p.15):

\[ U_i(t + 1) = (q_{in} + q_{on}) - (q_{out} + q_{off}) \]

\[ U_i(t+1) \quad 3.60 \quad = \text{metering rate reduction for section } i \text{ for next time step} \]

\[ q_{in} \quad 3.61 \quad = \text{measured flow on the freeway} \]

\[ q_{on} \quad 3.62 \quad = \text{measured on-ramp flow} \]

\[ q_{out} \quad 3.63 \quad = \text{measured flow leaving the bottleneck} \]

\[ q_{off} \quad 3.64 \quad = \text{measured flow leaving the section on the exit ramps} \]

This reduction has to be dispersed on to the upstream on-ramps, weighted because of environmental circumstances:

\[ BMR_{ji}(t + 1) = U_i(t + 1) \times \frac{WF_j}{\sum_{j=1}^{n}(WF_{ji})} \]

\[ BMR_{ji}(t+1) \quad 3.65 \quad = \text{bottleneck metering rate reduction at section } i \text{ for ramp } j \text{ for next time step} \]

\[ WF_j \quad 3.66 \quad = \text{weighting factor to value ramp } j \]

Finally, the computed reduction has to be subtracted from the pre-measured on-ramp flow at each certain ramp:

\[ BMR_{ji}(t + 1) = q_{ON} - BMR_{Rji}(t + 1) \]

\[ BMR_{ji}(t+1) \quad = \text{bottleneck metering rate for each section } i \text{ and ramp } j \text{ at next time step} \]

Bottleneck was ranked as a very good algorithm even though there are some improvements available like the implementation of the ALINEA algorithm at the local level.
instead of the original local Bottleneck algorithm. This is tested in an examination as a small benefit and is called modified Bottleneck (MBottleneck). In the direct comparison the MBottleneck is as good as the ALINEA which could indicate that the effort for the coordinated part of this algorithm has no influence in this certain test. [4]-(p.33)

3.66.1 SWARM

The System Wide Adaptive Ramp Metering (SWARM) algorithm has been developed since 1996 and was tested and implemented in Orange County, California and Portland, Oregon (OR), USA. This algorithm consists of two separate operating levels, the system-wide algorithm SWARM1 and on the local level any isolated traffic-responsive ramp metering algorithm. The freeway is divided into several sections, which includes a detected bottleneck at the beginning and at the end of it. Between these two bottlenecks there are several entrance and exit ramps. [9]-(p.7), [11]-(p.22)

SWARM1: This part operates on the area-wide level with a predicted traffic demand which is generated through measured data of a few minutes earlier, thus it is pro-active to the actual traffic demand and does not use historical data. The input data, which this algorithm needs, is the density and a pre-defined critical density, called saturation density, when congestion starts to occur in this section. SWARM1 predicts the density of a pre-defined period of time and compares it to the saturation value of the bottleneck. An exceeding of this threshold leads to a dispersion of the vehicles, correlated to that density, on the ramp storage, thus the saturation density will not be exceeded after the computed amount of time, named $T_{\text{crit}}$. Figure 12 and the equations below represent this process in a plausible way. [4]-(p.48f)
Figure 12 Visualization of SWARM Forecast Operation [11]-(p.23)

\[ d_{\text{tar}} = d_{\text{curr}} - \frac{d_{\text{exc}}}{T_{\text{crit}}} \]

- \( d_{\text{tar}} \) 3.67 = computed density to stay below saturation value
- \( d_{\text{curr}} \) 3.68 = measured section mainline density
- \( d_{\text{exc}} \) 3.69 = computed density above the saturation value
- \( T_{\text{crit}} \) 3.70 = computed time, when the saturation density is going to be exceeded

\[ V_{\text{red}} = (d_{\text{loc}} - d_{\text{tar}}) * n * l \]

- \( V_{\text{red}} \) 3.71 = computed value, how much the mainline volume has to be reduced
- \( d_{\text{loc}} \) 3.72 = measured local mainline density
- \( n \) 3.73 = number of lanes at the local area
- \( l \) 3.74 = distance to the next ramp

**Local SWARM Algorithm:** as mentioned is every local ramp metering algorithm feasible, e.g. ALINEA (MSWARMI), SWARM 2a and SWARM 2b developed for Orange County or SWARM 2c developed for Portland, OR, where there are no exit ramp detec-
tors, thus it leads to a modification of the algorithms deployed in California. [4]-(p.87), [35]-(p.9f)

The two computed metering rates out of the system-wide and the local perspective are compared and the most restrictive rate gets deployed. SWARM uses an internal algorithm to exclude inappropriate data from defect detectors, because it needs a reliable basis for an adequate prediction. At the same moment, this seems to be the largest drawback of this algorithm because of its high reliability on the demanded data. In the deployed time in Portland, OR, it shows that there are invalid data around 10%, which is a lot in comparison to 1% invalid data at the time of using a fixed-time algorithm. [9]-(p.42)

3.74.1 SZM

The stratified zone metering (SZM) algorithm was first implemented in Minnesota, USA in 2002, as the replacement for the local algorithm ZONE, which is the basis for the new one. The progression was demanded by the publicity after discomfort about too long waiting periods on the entrance ramps which led firstly to the shut-down experiment in 2000, which has shown that ramp metering is still an improvement in comparison to an unmetered ramp situation, and secondly it led to a wish that the waiting time on the on-ramp should be decreased. The SZM includes a calculation method comparable to the original ZONE algorithm and furthermore, it takes the on-ramp waiting times into account. [27]-(p.1f)

In general, the freeway section is divided into zones which may overlap and include different numbers of metered entrance ramps. The several detector stations shall have a distance of a half a mile with maximum 7 stations in one zone, which leads to a highest zone length of 3 miles. Comparable zones are gathered in layers, e.g. every zone with 2 metered on-ramps belongs to layer 1 and layer 2 includes zones which contain 3 metered on-ramps and so on, visualized in Figure 13 below.
The computed metering rates are based on the idea to keep the current capacity under a certain threshold. For the coordinated level, this is determined through:

\[ M \leq B + X + S - A - U \]

- \( M \) = total allowed volume entering the freeway through entrance ramps
- \( B \) = pre-defined downstream mainline capacity (not an especially bottleneck)
- \( X \) = total measured off-ramp volume
- \( S \) = calculated spare capacity
- \( A \) = measured upstream mainline volume
- \( U \) = total measured volume entering the freeway through non-metered ramps

The spare capacity minds extra absorption ability during a time of free flowing on the mainline with low traffic. It is calculated through:

\[ S = (d_{\text{full}} - d_{\text{cur}}) \times n_l \]

- \( d_{\text{full}} \) = pre-estimated full zone density, approximately 32 vehicles per mile, per lane
- \( d_{\text{cur}} \) = measured current density
- \( n_l \) = number of lanes within the zone

At the local level, every ramp computes a minimum metering rate to mention a maximum waiting time on the on-ramp. This upper limit is determined through public surveys to estimate an accepted period of time. For Minnesota, this is on ordinary entrance
ramps a maximum waiting time of 4 minutes and on freeway to freeway ramps is the limit set to 2 minutes. These thresholds determine continuously a minimum metering rate through the following equation:

\[ R_{min} = \frac{N}{T_{max}} \]

\( R_{min} \) = computed restrictive minimum metering rate
\( N \) = stored vehicles on the on-ramp
\( T_{max} \) = pre-determined maximum waiting time

This minimum metering rate allows the last vehicle on the ramp to enter the freeway after the pre-determined maximum waiting time. The weight of this boundary is very high which is represented through the additional behavior of the algorithm, that it increases the metering rate if the queue detector is for 25% of the time occupied, which indicates an upcoming or still existing queue length which cannot guarantee the maximum waiting time. The metering rate is set every time step one level higher, which means that 150 more vehicles per hour can leave the ramp to establish the promised time again. [27]-(p.3)

\[ D_t = D_{t-1} + 150 \]

\( D_t \) = number of leaving vehicles at time step t
\( D_{t-1} \) = number of leaving vehicles at the previous time step

The new metering rate is calculated every 30 seconds which leads to the maximum release rate of 1716 vehicles per hour within 5 minutes when it has to start its calculation form the lowest limit of 240 vehicles per hour. The upper limit is pre-determined through the fixed minimum cycle times and the circumstance that Minnesota has a two-lane on ramp system.

In the end, every computed metering rate for one ramp will be compared and the most restrictive one gets deployed. This is a huge redundancy because every ramp belongs to multiple zones. On top of that, the algorithm excludes solely zones if the detectors provide invalid data or then the density between two measurements drops spontaneously more than 50 vehicles per hour which implies an incident. [27]-(p.3f)

All in all, this algorithm outperformed the ZONE algorithm. Although it led to an increased mainline delay, the total travel time was reduced because of the decreased ramp delay. It is not evaluated, yet, if the increased stops on the mainline would lead to more
accidents. But in general, this algorithm represents the transition of DOTs to put more effort in a fair distribution of waiting time by restricting the mainline flow. [27]-p.8

3.87 Integral

The most sophisticated approach to link the systems to each other would be to compute metering rates separately at the local level and then to compare the results on an open perspective. The goal of the comparison would be to find a consensus which fits in the local and system wide situation best. The advantage of this method is that no computed solution gets lost by too restrictive boundaries. [4]-p.12f

3.87.1 Linear programming

Linear programing is in general a mathematical technique to solve a problem of several variables fixed in linear inequalities to define the maximum or minimum of this system.

As a ramp metering algorithm it is first deployed in Kobe, Japan in 1970 on the Hanshin Expressway. This algorithm needs the occupancy and demand data of the mainline accurately and at a high resolution to solve the constraint equations simultaneously and in an adequate way. The several equations represent the ramps and the function to minimize or maximize these, leading to an optimal metering rate, according to the mainline flow. In addition it is possible to tune the boundaries, e.g. with weighted ramps to vary their importance in the section or it would be feasible to calculate the real-time capacity for the sections to react even if the congestion already occurred. [11]-p.15f

The algorithm follows the pattern below: [11]-p.16f

1. The roadway is divided into segments (h) between ramps (i)
2. Speed-detection \( Y_h \) for each section \( \rightarrow \) calculate real-time capacity due to congestion results in real-time capacity for each section \( C_h \)
3. Detection of queue length \( N_i \) and determine ramp demand \( D_i \) from historical data or queue detection
4. Pre-define storage capacity of a ramp \( \rightarrow \) queue length maximum \( L_i \)
5. Pre-define weight-factor \( Q_{ih} \) with historical occupancy and demand data \( \rightarrow \) scales the traffic flow from \( i \) to the mainline downstream flow on \( h \)
6. Pre-define weighting factor \( A \) to estimate the importance of the ramps \( \rightarrow \) guide drivers behavior by penalize unfavorably ramps
7. Maximize function for ramp flow at each ramp \( U_i \)

\[
Z = \sum_{i=1}^{n} (A_n * U_n)
\]

The constraints for this equation are listed below:
\[
Q_{\text{main}} \cdot U_i + \sum_{n=1}^{i} (Q_{nh} \cdot U_n) \leq C_h \quad \forall \ h
\]
\[
\land
\]
\[
(0 \leq U_i \leq N_i + D_i) \lor (\text{ramp demand + ramp queue} \leq \text{ramp flow rate})
\]
\[
(N_i + D_i - U_i \leq L_i) \lor (\text{ramp queue + ramp demand} - \text{ramp flow rate} \leq L_i)
\]
\[
(U_{\text{min}} \leq U_i \leq U_{\text{max}}) \lor (\text{minimum rate} \leq \text{metering rate} \leq \text{maximum rate})
\]

The disadvantages of linear programming are as always for coordinated algorithms the accuracy of the occupancy and demand data and the equations are pre-defined and static. It works with the assumption that the travel time is a constant. Nevertheless, the algorithm is ranked as good. [4]- (p.14)

### 3.8.7.2 Sperry

The Sperry algorithm, 1999 deployed in Arlington, Virginia, USA works on the system wide level in a so called restrictive mode where it solves a demand-capacity equation to ensure that the critical capacity is not exceeded by the demand. The data for that equation is provided by detectors at each ramp (entrance and exit) to keep an overview about the total number of vehicles in the section. The algorithm distributes the vehicles on the ramps in an average way to keep the demand below the critical mainline capacity which is pre-defined for certain weather conditions. If there is a violated queue length threshold on a ramp, the algorithm switches into the non-restrictive mode to avoid a spillback on to the arterial roads by increasing the metering rate for the affected ramp. [4]- (p.13)

Special features of Sperry are to react to manual operation by adjusting previous ramps downstream in an adequate way or that the algorithm can interact with other sources like variable message signs (VMS). In general, it is trained to prefer the mainline by keeping the metering rate a little bit under its possibility to maintain a higher level of service (LOS) on the freeway. Furthermore the algorithm has the ability to work with predictive traffic flow information and beyond it adjusts its metering rates in an appro-
priate way, thus the more restrictive rate is set in a time it is really needed and not prematurely. [11]-(p.10)

The disadvantages of Sperry are obvious the solely use of volumes and pre-defined capacities. Which is harder to handle and depending on the variable capacities, which often do not match the reality.

### 3.87.3 METALINE

This algorithm is an expansion of the ALINEA and is developed in Paris, France in 1991, shortly after publishing the local traffic responsive ramp metering algorithm ALINEA. The additional element is the system-wide algorithm which causes a transition from scalar values to vectors and matrix. The rest is similarly build to ALINEA, a closed loop algorithm which compares measured occupancies with defined capacities and uses the ramp storage to keep the actual situation below the critical capacity. The modified equation to determine the metering rate is given below: [11]-(p.19f), [36]-(p.28)

\[
\vec{r}(k) = \vec{r}(k-1) - \mathbf{K}_1 (\vec{\delta}(k) - \vec{\delta}(k-1)) - \mathbf{K}_2 (\vec{\bar{O}}(k) - \vec{\bar{O}}c)
\]

- \(\vec{r}\) 3.88 = vector of metering rates for several ramps at time interval \(k\)
- \(k\) 3.89 = time interval
- \(\vec{\delta}\) 3.90 = vector of measured occupancies in the section
- \(\vec{\bar{O}}\) 3.91 = vector of measured occupancies downstream of each ramp (\(O \subseteq o\))
- \(\vec{\bar{O}}c\) 3.92 = vector of corresponding (to occupancy) capacity values
- \(\mathbf{K}\) 3.93 = matrix of weighting factors for the impact of a station on a certain ramp

The area-wide level is established through the matrix \(\mathbf{K}_1\) and \(\mathbf{K}_2\) of weighting factors. These factors determine how much impact one detector should have on the metering rate of a certain ramp. In fact, the \(\mathbf{K}_1\) matrix contains the importance of the measured occupancy of a detector on a certain ramp and the \(\mathbf{K}_2\) matrix determines the impact of the critical detectors to the metered rates at each ramp. If one measurement shall not have any impact on a certain ramp, this value is to set to zero. This weight of the several detectors and their influence on the system in certain areas determines the efficacy of the algorithm. [10]-(p.22), [11]-(p.20)
3.93.1 ARMS

The Advanced Real-time Metering System (ARMS) is developed by the Texas Transportation Institute, USA in 1993 and is defined in contrast to other algorithms to risk actively congestion. This algorithm is divided in two calculating (or even three, if the predictive algorithm is counted as an own) parts. The sequence of events in Figure 14 presents how these individual algorithms work together within the ARMS strategy.

The first part computes a mainline free flow over the whole section and is pictured on the right side of the operational chart. The calculated boundaries are allocated to the several ramps by analyzing the traffic-occupancy and demand data. This process is supported by a predictive algorithm which has a dynamic foundation to improve its own forecast based on patterns and adjusting it with real time measurements. The second part handles a congestion which is already occurred as seen on the left side of the chart. The algorithm estimates the congestion clearance time and computes the storage of vehicles in that section. After that, the burden of storing vehicles is dispersed over the sev-

Figure 14 ARMS Operational Flow Chart [11]-(p.29)
eral ramps regarding the occupancy and demand information as in the first part. This additional level is probably due to the implemented congestion risk of the first part. [4]-(p.16), [11]-(p.28f)

ARMS is not implemented in any real system, yet.

3.93.2 RAMBO

Ramp Adaptive Metering Bottleneck Optimization is an in two parts divided algorithm developed in Texas in 1991. These two parts are called RAMBO I for the local level and RAMBO II for the system wide calculation of ramp metering rates. Originally both are DOS stand-alone applications which are also implementable on Windows. The unique characteristic is that this tool does not have a direct impact on the ramp metering rate. It is a planning tool which provides ramp metering plans, which can be implemented into the system manually by an operator or to pre-evaluate the functionality of a ramp metering system project. [14]-(p.15), [37]-(p.1)

**RAMBO I**

This local algorithm computes metering plans for single or groups of isolated ramps. An operator has to type in the demanded information about traffic flow, the target capacity downstream and general boundaries on which the algorithm will calculate 4 different metering plans. [37]-(p.1) It is the decision of the operator to change the input data or to choose one of those plans or a variety which he wants to implement on the real system. [37]-(p.3)

**RAMBO II**

The coordinated part of the RAMBO system can control up to 12 metered on-ramps and other 12 exit ramps in one section. It is a predictive algorithm which uses linear programming. This program needs like RAMBO I certain information about the geometry of the mainline and the ramps, e.g. number of lanes, distance between ramps, definition if it is an exit or an on-ramp. Also it needs the traffic data and other factors like merge quality, capacity analysis or the maximum queue length. [14]-(p.25f), [37]-(p.31f)

All in all, this algorithm is not in use anymore because of its dependence on a manual operator, thus it stays being a mix of a pre-timed algorithm and a slow adaptive ramp metering system. The modeling of the freeway with its conditions also has some aspects of a simulation tool. This diversity and the lack of detailed information about its structure made it hard to categorize this algorithm in an adequate way and the goal of listing it here is to have a mostly complete list of every developed ramp metering algorithm.
3.93.3 Metering model for non-recurrent congestion

This algorithm is a standard scheme for ramp control, first explained in 1994 and includes most of the features which can possibly implement. It computes the traffic flow as a kinematic wave and has predictive parts in it to estimate forecasted densities, which are the basis to maintain the mainline flow on its highest possible throughput. The algorithm considers also the ramp queue length and creates metering rates based on all named conditions. The data is smoothened by Kalman filtering which is explained in more detail in 2.10.6.1. The equations were solved with linear programming mathematics. The sequence of events in Figure 15 below is a good overview about the computing steps of this algorithm. [11]-(p.32)

![Figure 15 Maryland Algorithm Operational Flow Chart](image-url)
It is mentioned that there shall be some improvements for a faster and more robust work, like the exchange of the Kalman filtration with the Godunov scheme which would reduce the calculation time. In addition to that, the occupancy-demand flow is not detected directly. It is more determined by the time-varying occupancy-demand data on exit ramps.

Even though this algorithm is ranked as very good, there is no further information available about any implementations in a real system. [4]-{p.16}

### 3.93.4 Coordinated metering using ANN

This ramp metering algorithm from at least 1996 is a V/C based algorithm with the ability to evolve its metering rate results by using Artificial Neural Networks (ANN). At first this algorithm computes a basis metering plan which is going to improve over the time depending on the reaction of the environment. Therefore volume-capacity ratios have to be measured on the mainline upstream and downstream of the ramp and the ramp queue length has to be determined. The following **Figure 16** shows the individual steps of this algorithm. [11]-(p.30f)

![Figure 16 Taiwan Algorithm Operational Flow Chart](image)

This information is matched together on the local level to determine a metering rate based on the pre-defined pattern. This metering rate is deployed by the local ramp and is a further input data via the hidden layer for the other ramps. Thus, the local ramps are connected on a system wide level in an integral way. The next step would be to receive the new measured data and combine them with the previous solution to evolve the me-
tering rate to keep the V/C ratio beneath one. For a better understanding, the Figure 17 below presents this process in a simple visualized way.

![Figure 17 ANN Conceptual Operation](image)

Coordinated metering using ANN is not implemented in any real system, yet.

### 3.93.5 Fuzzy

This adaptive algorithm initialized and first deployed in the Netherlands in 1989 was in 1995 and 1999 in Seattle. Fuzzy is a sophisticated algorithm which depends on human abilities to react in an appropriate way on the upcoming traffic.

The algorithm can be divided into 3 blocks which edit the input data step by step. The first block, named fuzzyfication, takes the input data and transfers them into a pre-defined textual description of the actual condition to a certain degree, e.g. 30% small, 70% medium and 0% high for a description of the measured occupancy on the mainline. This fuzzy data is forwarded to the next block, called the inference, where plausible {IF}-{THEN}-{ELSE} rules processing the data. These rules should be as little as possible, to keep the syntax simple and the calculation time low. But the manual operator has a lot of opportunities to influence the depth of complexity in this system. The last step is the defuzzyfication, which transfers the result of the used rules into a real metering rate. This block-system is presented in Figure 18 below to clarify the single steps. [11]-(p.13f)
The Fuzzy logic algorithm has a great potential because of its plausible structure and the realistic evaluation of input data, i.e. that a certain value is not every time a hard fact, but can be interpreted as multiple states. The transitions are more smoothened and the behavior of the algorithm is more logical and more robust. But the problem of this algorithm is especially these declared rules, which demand a high insight of the operator at the time he programs them, because the robustness of the algorithm depends on the logical structure which has to be implemented manually. In addition to that, the rules have to be adjusted to the real conditions at the freeway at the time of implementation and also later, if the conditions are changing. [4]-(p.13) To defuse this drawback of this algorithm, there were efforts to create a real adaptive algorithm based on the Fuzzy Logic which shall be explained in more detail.

3.93.5.1 ACCEZZ

The adaptive and coordinated control of entrance ramps with Fuzzy Logic (ACCEZZ) was published in 2002 and extents the possibilities of the original Fuzzy controller in a way that the pre-set rules adjust themselves to the conditions on the mainline. It uses the mainline upstream occupancy and the flow-capacity ratio to compute its metering rates. The main improvement is the self-adjusting feature of the algorithm, which allows it to define the blocks of fuzzification and defuzzification dynamically. For this learning behavior is an approach of neural networks in use which defuses the main drawbacks of the Fuzzy logic that an operator has to tune the algorithm after implementing it and the manual adjusting when traffic patterns are changed. [39]-(p.1)

The algorithm is constructed in two layers. The first is the original Fuzzy Logic at the local ramp as described above. The second layer is the system-wide controller which
includes the genetic part to evolve the Fuzzy algorithm. This coordinated portion uses a macroscopic model to compute a minimum travel time within the system. For that it uses the local solutions and develops a best matching area wide result. This forwarded optimization repeats a pre-fixed number of steps or until the evolved parameters approximates a certain value. In the end, the algorithm chooses the best solution out of all iterations. [39]- (p.2)

![ACCEZZ Process](image)

**Figure 19 ACCEZZ Process [39]**

This extension of the original Fuzzy logic already has five modifications which are characterized by the type of algorithm they use to evolve the solutions and by the availability of its service, i.e. if it is activated once a day for estimation or is it a real-time forecasting model, which reacts every 15 minutes to the traffic demand. In general, the algorithm to evolve the system is either an artificial neural network or based on a genetic theory. There is also an idea to implement a reinforcement learning technique which is dissolved from the supervised training of a neural network theory. [40]- (p.2f) Tests with that technique show that this algorithm has very good results in unknown demand situations because of its real adaptive behavior. [39]- (p.3)
3.93.6 Dynamic metering control

This algorithm developed in 1997 consists of four following layers: [11](p.32)

1) State estimation
2) O-D prediction
3) Local metering algorithm
4) System-wide metering algorithm

Below is a figure about the general structure of this algorithm to visualize the implementation of the listed layers. Following to Figure 20, the strategy of this algorithm shall be briefly explained.

![Figure 20 Dynamic Metering Control Structure](image)

The system-wide metering algorithm computes metering rates on predictive assumptions about demand and its goal is to minimize the travel time of the whole area. That includes the mainline travel time as well as the delay on the ramps. Thus, the local ramp metering algorithm maintains the estimated metering rates of the system-wide algorithm and improves this rate for the actual situation on the local level. [11](p.32)

The state estimation and the O-D prediction layer were used to generate the estimated forecast model on which the system-wide algorithm calculates the metering rates. The combination of the local and the system-wide level is established by following equation:

\[ r_t = \bar{r} - K(o_t - \bar{o}_k) \]

- \( r_t \) = local ramp metering rate at time \( t \)
- \( \bar{r} \) = system-wide ramp metering rate
- \( o_t \) = local occupancy at time \( t \)
- \( \bar{o}_k \) = system-wide occupancy

This is a sophisticated algorithm might create good metering rates but it depends hardly on the provided data. Even though this algorithm is ranked as very good, there is no information about an implementation of this algorithm in reality. [4](p.17)
3.93.7 RMS 2000

This algorithm is a result of a project of the Federal Highway Administration (FHWA) which started in 1997 and was finished in 1999. The Ramp Metering System 2000 (RMS 2000) is better known through former summaries as Ball Aerospace/FHWA [11]- (p.26) [4]-(p.15) and is a mixed pre-timed and adaptive, coordinated strategy. The coordination is guaranteed through an offline simulation which considers the whole corridor and creates metering plans on this foundation. [11]-(p.27) The exact contents shall be explained in the following subchapter.

The general structure of RMS 2000 is a chain of three consecutive steps, which convert the simplified algorithm to a more sophisticated one, if it is needed. It starts first with a Time-of-Day Plan Generator, which uses archived data about the environmental conditions, e.g. storage capacity of the several ramps, and historic traffic data to create metering rates. There is a certain number of connected traffic demand with an associated metering rate deposited in the archive of RMS 2000. This also includes information about the expected traffic behavior after implementing the associated cycle time. [21]- (p.6f) These expected changes are the foundation for the second part, the Local or Segment Regulator, which gets activated, when the measured traffic behavior differs from the pre-defined assumptions. It replaces the old fixed rate with another which might better fit the current situation and it adjusts this new rate based on pre-defined parameters. [21]-(p.7) The third step is the Ramp Queue Management, which controls the implemented metering rates with the on-ramp demand and calculates based on this information the probability of a spillback on to the arterial network. [21]-(p.7) To summarize this general structure, Figure 21 below illustrates these three major steps.
These explained major steps are broken down into five modules which are realizing the described features and procedures of RMS 2000. These functions are:

1) Roadway Modeling
2) Traffic Modeling
3) Generation of Model-Based Metering Plans
4) Evaluation of Current Traffic Conditions
5) Generation of Real-Time Metering Plans

The first three modules are the foundation for future metering rates which are determined through the best matching plan to a measured pattern. The last two modules guarantee an adaptive behavior which reacts on incidents. To clarify the task of every single module, the explanation of the general structure above is itemized and combined to the executive module.

**Roadway Modeling:** it contains the general boundaries, e.g. the number of lanes or the situation of the detection devices. [21]-(p.8f)

**Traffic Modeling:** this module generates traffic demand estimations based on historical data. This step can be done from fully manually operated to fully automated. [21]-(p.9)

**Generation of Model-Based Metering Plans:** creates time of day metering plans for every on-ramp meter with expected traffic conditions for each plan. Also there are adjustments possible to improve the plan based cycle times through a comparison of the expected traffic conditions with the occurred conditions. [21]-(p.9f)
**Evaluation of Current Traffic Conditions:** this module uses the surveillance devices to compare the current traffic situation with the pre-defined patterns and it searches for inconsistencies. [21]-(p.10f)

**Generation of Real-Time Metering Rates:** the final step computes the cycle time based on the measured traffic conditions. It chooses the best matching pattern from the model based plan and looks for any incidents on the roadway. If there are deviations, the pre-choosen plan gets replaced by another better matching plan. The taken plan is adjusted to the real conditions via pre-defined parameters and the resulting metering rates are forwarded to the host traffic control center. [21]-(p.11f)

The interactions of the described modules are presented in **Figure 22** below.

![Figure 22 Overview of the Interaction of the Modules of RMS 2000](image)

The explained traffic pattern estimations are based on OD-estimation and uses DYMIN, a dynamic network equilibrium traffic model of macroscopic flow, to create these patterns. [21]-(p.19f) DYMIN is also able to work with HOV lanes and bus bypasses because of multiple vehicle type recognition. The step, which detects the best model based metering plan, uses the pattern of DYMIN and non-linear programming to minimize the travel time. This combination is called OPDYMIN. [21]-(p.49) The referring cycle times are computed by an improved ALINEA algorithm with a shortened iteration time.
and with the explained queue management. [21]-(p.80) In the case of detector loops failures, the input data is set to the previous information or historic data is used to keep the metering rate consistent. [21]-(p.86) In general, RMS 2000 has the capability to implement the arterial road network with surveillances of the choice of alternative routes. [21]-(p.7f) But in the end, RMS 2000 is not implemented in any real system, yet. [41]

3.93.8 HERO

The HEuristic Ramp metering coOrdination algorithm is a new method to calculate metering rates and was first tested in 2006 in Paris, France (in a restricted version with the name Coordinated Heuristic Control (CORDIN) [36]-(p.23)) and Amsterdam, Netherlands (with the RWS algorithm on the local level [24]-(p.19)), and is now implemented in Australia. Concerning to previous coordinated ramp metering algorithms and their disadvantages, this algorithm was simplified and optimized to use real-time measurements, but without doing real-time calculations. This way decreases the used capacities substantially.

This algorithm consists of a local algorithm, which is originally ALINEA but it would be possible to implement any other local algorithm as happened at the Rijkwaterstaat test, and the coordinated algorithm, which is called HERO. [24]-(p.2) This supplement reacts if a critical queue length threshold is reached at one ramp and activates this critical ramp as a “master-ramp” and recruits other ramps upstream as “slaves”. This procedure is similar to other coordinated algorithms to use the ramp storage capacity of the whole section to relieve the critical ramp. HERO uses gradually up to six upstream ramps to disperse the burden, which is measured and maintained by the control of the queue length with following equation: [23]-(p.6f)

\[
\text{queue}_{\text{min}}(k) = \frac{\text{queue}_{\text{max}}(k) \times \sum_{i=1}^{n} \text{queue}_i}{\sum_{i=1}^{n} \text{queue}_{i,\text{max}}}
\]

\[\text{queue}_{\text{min}}(k)\] = the minimum queue length, which has to be reached at slave ramp \(k\)

\[\text{queue}_{\text{max}}(k)\] = the maximum queue length at the slave ramp \(k\)

\[\text{queue}_i\] = the actual queue length at each ramp (master + slave) in the coordinated control

\[\text{queue}_{i,\text{max}}\] = the maximum queue length at each ramp (\(m + s\)) in the coordinated control
This information about the desired minimum queue length is transferred to the local level. This local algorithm will decrease the cycle time at slave-ramps as long as the desired queue length is not reached. The local algorithm at the master-ramp will act normally as so as there is no coordinated control. One example for an implementation of the mentioned recalculation of the cycle time is the test at Rijkswaterstaat with the following procedures:

\[
C_{\text{cycle time rest, capacity}} = \frac{n_{\text{lane}} \cdot n_{\text{veh}} \cdot 3600}{\text{Capacity}_{\text{mainline}} - \text{Flow}_{\text{mainline}}}
\]

\(C_{\text{cycle time rest, capacity}}\) 3.98 = generated cycle time to use the rest capacity on the mainline

\(n_{\text{lane}}\) 3.99 = number of lane on the on-ramp

\(n_{\text{veh}}\) 3.100 = number of vehicle per green per lane

\(\text{Capacity}_{\text{mainline}}\) 3.101 = pre-defined mainline capacity

\(\text{Flow}_{\text{mainline}}\) 3.102 = measured mainline flow upstream the on-ramp

If the computed \(C_{\text{cycle time rest, capacity}}\) is larger than the pre-used cycle time at the local level, then the algorithm proves the following boundaries:

\[
C_{\text{cycle time min, queue}} = \frac{n_{\text{lane}} \cdot n_{\text{veh}} \cdot 3600}{(\text{queue}_{\text{curr}} - \text{queue}_{\text{min, desired}}) \cdot 3600 \cdot \text{Control Interval}}
\]

\{IF\} \text{queue}_{\text{curr}} < \text{queue}_{\text{min, desired}}

\{THEN\}

\(C_{\text{cycle time}} = \max\{C_{\text{cycle time rest, capacity}}; C_{\text{cycle time min, queue}}\}\)

\(C_{\text{cycle time min, queue}}\) = generated cycle time to reach the minimal queue

\(\text{queue}_{\text{curr}}\) = the current queue on the on-ramp

\(\text{queue}_{\text{min, desired}}\) = the minimum queue which is desired by the coordinated algorithm

\(\text{Control Interval}\) = the time between the checks of the current situation
Finally, there is the possibility that the computed cycle time of the maximum queue length \((Cycletime_{\text{max,queue}})\) is less than the \(Cycletime_{\text{rest,capacity}}\). The following equations will explain how the \(Cycletime_{\text{max,queue}}\) will be calculated and solve the last boundary. [24]-(p.18f)

\[
Cycletime_{\text{max,queue}} = \frac{n_{\text{lane}} \times n_{\text{veh}} \times 3600}{(queue_{\text{curr}} - queue_{\text{max,admissible}}) \times \frac{3600}{Control\_Interval} + Flow_{\text{ramp}}}
\]

\[
\{IF\} \quad queue_{\text{curr}} > queue_{\text{max,admissible}} \\
\{THEN\} \\
Cycletime = \min\{Cycletime_{\text{rest,capacity}}; Cycletime_{\text{max,queue}}\}
\]

\(Cycletime_{\text{max,queue}}\) 3.103 = generated cycle time to stay below the maximum queue on the on-ramp

\(Queue_{\text{max,admissible}}\) 3.104 = maximum admissible queue length on the on-ramp

\(Flow_{\text{ramp}}\) 3.105 = incoming flow on the on-ramp

The coordinated control of HERO disengages the slave ramps when the queue length at the master ramp falls below a deactivation threshold. This threshold should be lower than the activation threshold to produce unambiguous conditions.

3.105.1 SRMS

The Sydney Coordinated Adaptive Traffic System (SCATS) Ramp Metering System (SRMS) from Australia is a strategy to compute cycle times at intersections in urban areas, in general. It was developed in 2005 to get an adaptive system for traffic signals, which reacts automatically on the actual traffic demand. The SRMS algorithm is a part of the SCAT System and shall be explained in more detail below. [31]-(p.2)

The strategy of SRMS consists of several parts which are listed and explained below. These features are the foundation of the algorithm to compute an optimized and integrated solution. [31]-(p.8f)

1. Dynamic bottleneck location identification: this feature allows algorithms to localize the critical bottlenecks automatically and is thereby less dependent on the manual operator and fixed traffic pattern assumptions.
2. Simultaneous coordinated response: is the ability to react on a bottleneck with several coordinated ramps at the same time.
3. Data-fusion of multiple mainline fundamental traffic measures: the equation of the algorithm calculates solutions based on speed and occupancy to guarantee reliable mainline capacity estimations.
4. Real-time integration with arterial traffic signals: this is an approach to connect the calculations for the on-ramp metering with data from the mainline and the arterial network.

The first two features are provided several ramp metering strategies, e.g. SZM or Bottleneck. But the last two features are an unique approach of the SRMS even though MI-LOS tried to connect the arterial network with the mainline, but not with real time measurements as SRMS is doing.

The following two equations describe the foundation of SRMS to compute cycle times: [31]-(p.9)

\[ \varepsilon_j(k) = \sigma_j^{\text{crit}} - \sigma_j^{\text{meas}}(k) \]
\[ \alpha_j(k) = \alpha_j(k - 1) + \Delta \alpha \]

- \( \varepsilon_j(k) \): calculated error at detector station j at time step k
- \( \sigma_j^{\text{crit}} \): defined critical occupancy at detector station j
- \( \sigma_j^{\text{meas}} \): measured current occupancy at detector station j
- \( \alpha \): accumulated conversion of \( \varepsilon \) through a pre-defined dependency
- \( \Delta \alpha \): direct dependent summand from conversion of \( \varepsilon \)

The dependency of \( \alpha \) and \( \varepsilon \) is given by the alpha increment function, which is pre-defined by the operator and visualized below.

![Figure 23 Alpha increment function][31]-(p.10)
This system is called the overlapped occupancy control strategy (OOCS) and is realized by controlling the situation at detector loops with several on-ramps. The regulation after an exceeded threshold at any detector station reacts the limitation at the associated ramps. This is more reactive than comparable algorithms because of the use of several ramps simultaneously and not a slowly increased regulation by adding ramps step by step if the goal is not reachable with less regulated ramps. The local control at the on-ramps is a modified ALINEA, depending on the trend of the alpha increment function, where a straight line through the origin would reflect the original ALINEA. [31]-(p.10)

The OOCS is a feedback controller with the general advantages and disadvantages described in 2.10.6.5, thus it is expanded by a Feedforward Disturbance Compensation (FDC). This unique implementation introduces a feedback-feedforward scheme first to a ramp metering algorithm and is a new approach of the SRMS. Including the FDC, the cycle time is computed by the following equation: [31]-(p.12)

\[ q(k) = \frac{n}{z} \times \left[ 1 - \max_j(\alpha_j(k)) \right] \]

\( q(k) \) 3.111 = computed cycle time at time step \( k \)

\( n \) 3.112 = describes how many vehicles are allowed to join the zone (see M+F at 3.2.3)

\( z \) 3.113 = number of ramps in the zone

Finally, there is an idea to expand the possibilities of SRMS by adding the opportunity for the manual operator to define IF-THEN-ELSE rules. This allows the user to react to queue spillback and other arterial network related problems and increases the complexity of the algorithm. This approach may help to control the global system with a ramp metering algorithm and can be a new classification of integrated algorithms. [31]-(p.13)

This algorithm is still in enhancement, e.g. is one goal to implement data from arterial network detector to estimate the on-ramp demand and possible queue spillbacks more precisely. Nevertheless, SRMS was tested in Auckland, New Zealand on several freeways in comparison to former data on these roads and has shown good results.

### 3.113.1 TIME

The Traffic Introduction Metering (TIME) is a rarely-described adaptive algorithm which was developed by MIZAR Automazione and is implemented on three ramps in Stockholm, Sweden and on the Mestre Ring Road near Venice, Italy. [7]-(p.7) The general idea is to keep the mainline flow stable but it tries to avoid queue spillbacks at the
on-ramp on to the arterial network. [42] This ramp metering strategy is able to interact with other sources, e.g. external traffic prediction, VMS or CCTV. [7]-(p.7)

This algorithm is divided into a central part, called Omnivue, which can be overviewed by manual operators and the algorithm itself, which computes cycle times based on all traffic input data at all ramps. This optimized calculation is sent to the local controllers, called SPOT, which try to implement the optimized solution based on the local condition. [7]-(p.4) The local controllers do not influence each other but they exchange information, e.g. the downstream flow information from one corridor is sent to the following and is used there as upstream flow input data. [7]-(p.7) The Omnivue component is more restrictive in every case. It is able to change single output information as well as it can switch the system off or let the system run based on a pre-timed data set. [7]-(p.6)

Unfortunately, there is no further information about the working method of the algorithm itself available.

3.114 Conclusion of the Algorithm Overview

The listed algorithms are a summary of all known strategies to compute metering rates, which were available at the time of research. Because of the diversity and the local peculiarities, this list cannot fulfill a complete overview of all algorithms and their varieties, thus it is possible that there are some algorithms or small local modifications are left out. Also, this overview only contains strategies which are implemented or ready for an implementation, including these, which are not even used anymore, for a complete overview of the state of technology. Efforts, to invent a new algorithm, are only known for the area of Switzerland. Other researchers mostly improve existing strategies and create adjustments for an improved local implementation, e.g. for the HERO algorithm in different countries.

All in all, this summary shows that ramp metering algorithms are not bound to a strict direction of developments. Next improvements and possible developments are only estimated in a rough overview, e.g. that the ramp metering algorithms will be connected with other controlling sources like VLS or VMS or a combined global work between freeway and arterial network. But the syntax to fulfil this goal depends on the creativity of certain researchers on this field. Some new ideas could lead the development in another direction, e.g. it was a goal in the middle of the 90’s to complicate and sophisticate the algorithms to increase their options to react on the mainline demand, but some new approaches try to simplify the calculations for a more stable system. It seems that there is no general optimized method, reflected by the variety of implemented algorithms all over the world with different ramp metering strategies, ranging from local,
pre-timed to adaptive, dynamic implementations. To clarify the world-wide situation, the next chapter presents an overview about the various approaches of different countries and shows how the use of ramp metering algorithms has grown.
4 Use of Ramp Metering World-Wide

In countries around the world there has been a growing demand to improve the effectiveness of existing freeways without consuming more space. Ramp metering is a well-known method used in a wide range of countries with varying congestion problems and driver behaviors. To illustrate the increasing use of ramp metering, this chapter gives an overview about the formation of ramp metering and its dispersion around the world. The most accurate account of the latest state of ramp metering strategies is compared to former publications. Following, an additional chapter highlights the outstanding situation of the USA in development, deployment and research efforts in ramp metering. The chapter also summarizes the current use of ramp metering in the USA and demonstrates the diversity of algorithms used throughout the country.

4.1 Brief Overview of the History of Ramp Metering

Ramp metering is an American invention developed as a reaction to the accumulation of traffic incidents following the deployment of highways and freeways in the mid-1950s. As the use of transportation increased, so did the occurrences of congestion and crashes. Given right-of-way constraints, it is usually not possible to respond to the demand by increasing the size of the roadway. The first attempt to mitigate this growing congestion local ramp control by police officers was implemented along the Eisenhower Expressway in Chicago, 1963. The improved situations led to a dissemination of ramp metering strategies to other states and to improvements and tests on the system itself. For example, a total ramp closure instated in Los Angeles, USA in 1967 and in the implementation of prioritized bypass lanes in Minneapolis, USA in 1972. These are states that are still leading in the research on ramp metering systems in the USA. [1]-(p.5f)

The deployment and development of ramp metering systems in Europe started in England in 1986 and continued in the Netherlands in 1989. The total amount of metered ramps does not reach the number of installed systems in the USA. Nevertheless, there were many invented algorithms; such as the ALINEA developed in France in 1990, which is even today a commonly used local ramp metering algorithm. The world-wide uses of such systems lead to the deployment of many algorithms that consider the local conditions throughout the continents. [2]-(p.4f)

The following time line (Figure 24) is an illustration of invented ramp metering algorithms and their deployments in various cities. Due to the sharp increase in the exchange of knowledge in the beginning of the 1990’s, the segmented time line ends and an era of
algorithm information and knowledge exchange overlaps. It is not possible to determine an exact date of an invention of an algorithm anymore because there are pre-tests, deployments of unfinished algorithms which were improved over the time and numerous publications where it is not clear if it is ready to deploy or is the research still in progress. Some dates are given based on a publishing date, a first simulation or a first field implementation.

Figure 24 Overview of Invented Algorithms

In addition to the improvement of the algorithms themselves, there has been progress in the use of collected data: from static time schedules for the metering rates to traffic responsive up to predictive systems, where the trend of traffic demand is analyzed and results in a short term forecast. This demonstrates that ramp metering itself is an adaptive system which is improvable over the time as the hardware and software of detection, computing and communication advanced. At the moment, sophisticated algorithms are being deployed which are coordinating several ramps under system wide circumstances using short term traffic forecasts. The limit of these systems is the provision of accurate real time data. [1]-(p.6), [9]-(p.79)

There are two main approaches available to manage the data. The first is to implement procedures into the algorithm to evaluate the measured input information and if they are feasible or not. This process excludes the infeasible data from next calculations, such as invalid overdriven or broken detector loop. The disadvantage of this method is that there might be a sizable loss of data. [9]-(p.42) Another approach is to change the strategy of collecting these data and to find a method that removes the least amount of inva-
lid data as possible. One alternative way might be a wireless data transmission. Another advantage of wireless transmission is it avoids the problem of wire theft. [6]-(p.4) An additional technique is the measurement of traffic with radar systems or probe vehicles. It is not certain if there are notable improvements with these alternative data collecting strategies. However, these approaches reflect that the quality of the data is an important factor. [5]-(p.27)

In addition to the research on data restriction algorithms, research on ramp metering algorithms used to tests the connectivity of on-ramp metering with other sources on the mainline, e.g. variable message signs (VMS) or variable speed limits (VSL), using one calculation are being developed to increase the potential to influence traffic. [43] This more sophisticated approach is in contrast to another strategy which tries to reduce the complexity of the algorithm and the required data. A typical example of the first method is the MILOS algorithm, and for the reduced strategy is HERO a good example.

4.2 Explanation World Map

When ramp metering was first implemented in Chicago, USA (as described in section 4.1), it spread internationally due to its success to expand the capacity and increases the mainline flow; decreasing congestion of freeway systems without additional lanes. Today, there are various approaches to implement the algorithms and to adapt these to the local situation to improve their results. The map in Figure 25 illustrates the latest numbers of metered ramps in these regions. It was not possible to get information from the last two years from every traffic control center from every country and there is huge diversity within each region. Thus, the following explanation describes the merely number at known sites with additional information about its date and a precise spatial alignment.
Argentina (2013): It was assumed that Argentina has ramp metering systems but the most recent source denied this and added that there is no attempt to implement such a system in the near future. [44]-(p.6)

Australia (2014): There are 77 metered ramps in the region of Melbourne under the organization of VicRoads, where 63 of them are situated on the M1 and 14 are installed on the M80. In the area of Queensland are 8 metered on-ramps. All are using the HERO algorithm. There is a project in development in Western Australia to install a ramp metering system which will use HERO. However, no funding is currently available for the project. [45], [46], [47]

Canada (2014): Eleven metered ramps are situated in the area of Mississauga, Ontario and are an additional feature of the operating COMPASS system. In 2012, the original ramp metering algorithm, also named Compass, was replaced by ALINEA as a more robust solution. [34] There are no ramp metering systems in Toronto, Burlington or Ottawa. [48] There was no further information about other states available.

France (2014): France has made some minor efforts to implement ramp metering. Two ramp meters are located on a trial in Bordeaux. There is also unconfirmed evidence about such a trial in Marseille. Ramps have been installed in Paris: Six installations on
the A6 and there is also a planned program for Grenoble, which may be implemented at the end of 2015. [49]

**Germany (2014):** Germany has 104 ramp metering systems unevenly dispersed over the country. The following itemization will give a better overview of their locations. Both states listed with a zero are in this summary, Lower Saxony and Hesse, is a way to distinguish between which assumed ramp meters are actually implemented and which not.

- Lower Saxony: 0
- Hesse: 0
- Baden-Wuerttemberg: 3
- Bavaria: 4
- North Rhine-Westphalia: 97

Bavaria and North Rhine-Westphalia are using an ALINEA algorithm to meter their ramps. Baden-Wuerttemberg is using PRO. North Rhine-Westphalia will implement an additional 15 metered ramps in the next few years. They will also be the PRO-algorithm in their area to replace ALINEA. There are upcoming efforts to implement three more ramp metering systems in the Bavaria region. [50], [51], [52], [53], [54]

**Great Britain:** There is some evidence that there are 100 ramp meters in the UK. [47] However, there is no source available to confirm this assumption and there is no itemized where these metered ramps are situated.

**Italy (2014):** An unknown number of metered ramps are installed on the Mestre Ring Road north of Venice. The system is called MARCO and the implemented algorithm is TIME. It appears to be the only place in Italy where ramp metering is used but there is no further information about the details of the system. [55]

**Japan:** Formerly, metered ramps were known to exist on the Hanshin Expressway. [11]-(p.1) There is no source available to confirm this information and no known number of metered ramps.

**Netherlands (2014):** The Netherlands conducts a lot of research in the field of ramp metering algorithms, e.g. tests with new algorithms like Fuzzy, V-ALINEA or HERO. The number of deployed ramp meter has grown from 20 installed systems in 2000 to 120 metered on-ramps by 2014. At the moment, there are tests with the ALINEA algorithm in combination with type of HERO algorithm on the coordinated level. In the field, most of the metered ramps were calculated by the Rijkswaterstaat algorithm, which is a feed forward control algorithm based on flow and capacity. [56]

**New Zealand (2014):** An installed ramp metering system is only used in the area of Auckland and is computed by the SCATS (SRMS) algorithm. [57]
**Russia:** There is some evidence that there are metered ramps situated in Moscow, based on some clues dispersed over out-of-print publications. Unfortunately there is no reliable source available which confirms this assumption.

**South Africa:** (2014): Some ramp metering trials were conducted in Durban as part of a comprehensive upgrade of the freeway system of Pretoria/Johannesburg in 2005. Today, there are ramp metering capabilities situated on this corridor. However the ramp meters were never turned on because of the existing toll system on the corridor and the uncertainty of these two strategies running simultaneously. [58]

**South Korea:** The extant of information on the number of metered ramps situated in South Korea is that they are located in three sections in the area of Seoul. There is no further explanation available about how many ramps one section includes. South Korea is probably using a fuzzy self-adaptive PID controller algorithm. [59]

**Spain:** It is unlikely that ramp metering in Spain will be implemented due to the fact that the major routes are privatized and are imposed with a toll. It would be counterproductive for the owner of the highway to hinder the traffic demand onto their road. [60] Trials were conducted in Barcelona and Murcia and a former system in Madrid, which was shut down because of political will. There may be a system installed in Zaragoza, but the scope of the project nor implementation has not been. [61]

**Sweden (2014):** There are three metered ramps located in the area of Stockholm. They are computed by the TIME algorithm with a switch-on algorithm based on ALINEA. There are additional ramp metering systems in Gothenburg, which will be reactivated soon, probably with ALINEA as computing algorithm. [62]

**Switzerland (2014):** There is research exploring the possibility of implementing ramp metering system in Switzerland. At the moment are there simulations to develop an algorithm which can handle the local situation of short, urban-near ramps by connecting it with other road control mechanisms (integrated solution with VMS and VSL). The simulation will last until 2014 and could be expanded to a field testing. A paper about the solutions is in progress. [43], [63]

**USA:** the number of total metered ramps in the USA is itemized and explained in the 4.3.

### 4.3 Explanation USA Map

The USA is the leading country in the deployment of ramp metering on their highways and freeways. This is reasoned historically as the ramp metering system was first invented and deployed in Chicago in 1963. It may also have to do with the geometry of
the freeways. Freeways in the US lack the same type of acceleration ramps found in other countries; introducing vehicle platoons that have a greater impact on the mainline flow than in countries which normally have these lanes. But even within the USA there is a huge diversity of implemented metered ramps which represents the local aspirations on the field of ramp metering in different states. This plurality has to be itemized and explained more detailed to get a true overview about the situation of ramp metering in the USA.

The number of ramps is extracted out of a general survey of the Federal Highway Administration which will be published within the end of the year of 2014. The survey itemized several state DOTs and assigned metered ramps to them, which is presented in Table 6. The number of ramps in each state is summed and assigned to the belonging state. This final conclusion is presented in Figure 26. Each of the summed number of ramp meters for each state is located at the center of gravity of the state. To compare the development of ramp metering, the data of published studies from 1999 and 2010 are also included as maps. The disadvantage of the surveys is that they ask for actual metered ramps in the time of the survey, which explains the alternating number of metered ramps in some states.
Figure 26 Detailed Summary of Ramp Metering in the USA
The following Table 6 contains, as mentioned before, the number of activated metered ramps at the individual locations. The table also displays data from previous years in order to get a better overview of where ramp metering capability exists or which states decided against this strategy for managing their traffic demand. The bold numbers represent the sum of each state ramp meters, which is presented in Figure 26. The others are, as far as it is known, the itemized number of ramp meters from each state DOT region. The first column of activated ramp meters from 2014 is considered the current situation. The next column contains the counts from 2010, which were provided through a survey of the Research and Innovative Technology Administration (RITA) in 2010. [64] Note that the far right column compares the rough data from 1999. Unfortunately, the number of metered ramps from 1999 is not itemized to the DOTs, except for Texas. [11]-(p.1)
Table 6 Itemized Overview: Number of Metered Ramps in the USA [11]-(p.1), [64]

<table>
<thead>
<tr>
<th>State, Referring City</th>
<th>Assigned DoT</th>
<th>2014</th>
<th>2010</th>
<th>1999</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ, Phoenix</td>
<td>Arizona DOT Statewide TOC</td>
<td>202</td>
<td>182</td>
<td>65</td>
</tr>
<tr>
<td>CA, Bakersfield</td>
<td>Caltrans District 6</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>CA, Los Angeles</td>
<td>Caltrans District 7 - Los Angeles TMC</td>
<td>1016</td>
<td>347</td>
<td></td>
</tr>
<tr>
<td>CA, Fresno</td>
<td>Caltrans District 6</td>
<td>64</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>CA, San Bernardino</td>
<td>Caltrans District 8</td>
<td>226</td>
<td>208</td>
<td></td>
</tr>
<tr>
<td>CA, San Diego</td>
<td>Caltrans District 11 TMC</td>
<td>0</td>
<td>288</td>
<td></td>
</tr>
<tr>
<td>CA, San Francisco</td>
<td>Caltrans District 4</td>
<td>425</td>
<td>298</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1732</td>
<td>1194</td>
<td>1782</td>
</tr>
<tr>
<td>CO, Denver-Aurora</td>
<td>Colorado Department of Transportation</td>
<td>70</td>
<td>95</td>
<td>30</td>
</tr>
<tr>
<td>DC-VA-MD-WV,</td>
<td>Virginia DOT - NRO Traffic Operations Center</td>
<td>24</td>
<td>24</td>
<td>26</td>
</tr>
<tr>
<td>Washington</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FL, Miami-Fort Lauderdale</td>
<td>Florida DOT-District 6 – Sun Guide TMC</td>
<td>22</td>
<td>22</td>
<td>0</td>
</tr>
<tr>
<td>GA, Atlanta Sandy Springs</td>
<td>Georgia Department of Transportation</td>
<td>170</td>
<td>154</td>
<td>5</td>
</tr>
<tr>
<td>IL-IN-WI, Chicago</td>
<td>Illinois Department of Transportation</td>
<td>0</td>
<td>113</td>
<td>110</td>
</tr>
<tr>
<td>LA, Baton Rogue</td>
<td>Louisiana Department of Transportation</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MA</td>
<td></td>
<td>0</td>
<td>0</td>
<td>75</td>
</tr>
<tr>
<td>MI</td>
<td></td>
<td>0</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>MN-WI, Minneapolis</td>
<td>Minnesota Department of Transportation</td>
<td>425</td>
<td>425</td>
<td>370</td>
</tr>
<tr>
<td>MO-IL, St. Louis</td>
<td>Illinois Department of Transportation</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MO-KS, Kansas City</td>
<td>Missouri Department of Transportation</td>
<td>28</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>28</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>NV, Las Vegas</td>
<td>Nevada Department of Transportation</td>
<td>70</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>NY-NJ-PA</td>
<td>New York State DOT - Long Island Region 10</td>
<td>0</td>
<td>82</td>
<td>0</td>
</tr>
<tr>
<td>OH, Columbus</td>
<td>Ohio Department of Transportation</td>
<td>24</td>
<td>29</td>
<td>0</td>
</tr>
<tr>
<td>OH-KY-IN, Cincinnati</td>
<td>TRW/ARTIMIS OCC for Ohio DoT</td>
<td>4</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>28</td>
<td>31</td>
<td>0</td>
</tr>
<tr>
<td>OR, Portland</td>
<td>Oregon Department of Transportation</td>
<td>142</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>OR, Eugene</td>
<td>Oregon Department of Transportation</td>
<td>4</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>146</td>
<td>140</td>
<td>60</td>
</tr>
<tr>
<td>PA-NJ-DE-MD, Philadelphia</td>
<td>Pennsylvania DoT District 6-0</td>
<td>15</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>PA-NJ</td>
<td>Pennsylvania DoT Allentown</td>
<td>0</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>29</td>
<td>12</td>
</tr>
<tr>
<td>TX, Dallas</td>
<td></td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>TX, Houston</td>
<td></td>
<td>0</td>
<td>0</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>0</td>
<td>24</td>
</tr>
<tr>
<td>UT, Provo-Orem</td>
<td>Utah DoT Region 3</td>
<td>24</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>UT, Salt Lake City</td>
<td>Utah DoT Region 1</td>
<td>0</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>UT, Salt Lake City</td>
<td>Utah DoT Region 2</td>
<td>19</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>43</td>
<td>51</td>
<td>8</td>
</tr>
<tr>
<td>WA, Seattle</td>
<td>Washington State DoT Northwest Region</td>
<td>222</td>
<td>205</td>
<td></td>
</tr>
</tbody>
</table>
## 4.4 Conclusion of the World-Wide Overview

This chapter is a demonstration of the implementation of the previous explained ramp metering algorithms. It presents the importance of this strategy to extend the use of freeways without greater constructional enlargements of the existing system. Countries, which implemented a ramp metering algorithm once, increase its efforts in this area over the time, because of visible effects which were discussed in chapter 3, before. The detailed explanations about the local implemented systems in the several countries give an overview about the still predominant diversity in used algorithms. It is strengthen the assumption that different strategies work better or worse on varying boundaries and thus it is necessary to improve the different strategies independently to keep extensive opportunities for the traffic control centers to react on their unique problems in their area of responsibility.

This overview, about the development and the deployment of ramp metering algorithms concludes the general summary of the latest situation in the world and shall be the basic knowledge for further researches and is the basic knowledge to understand development strategies in different regions and their varying approaches in their evaluation processes. These differences shall be given as a short summary in the next chapter to lead to a possible standard strategy in evaluating new implemented ramp metering algorithms.
5 Evaluation Concept

This chapter uses the information gathered in previous chapters about ramp metering, its advantages and disadvantages, and how the separate blocks work. This knowledge collected is the foundation of a more detailed interpretation of ramp metering algorithms and provides the needed data to further evaluate the use of these strategies, which will be the subject of this chapter. The task at hand is to analyze the evaluation processes that researched the effectiveness of individual algorithms in general and in certain local areas, and to summarize these evaluations into a recommended standardized procedure.

5.1 Evaluating Ramp Metering Algorithms in General

Every new ramp metering algorithm runs several simulations and/or field tests before it gets deployed, and even after its implementation, there are studies that compare the effectiveness of the new algorithm with the former strategy. This evaluation process is important in maintaining an objective overview about the benefits of newly invented or simply newly implemented algorithms, and helps to decide if the latest approach might be an improvement, or if this development leads to a worse situation on the freeway. There are two approaches to evaluate such a system that will be explained in more detail in the following subchapters.

5.1.1 Micro-Simulations

These computer-based simulations are a good way to evaluate and compare ramp metering algorithms, and examples would include PARAMICS, CORSIM or VISSIM. The manual operator defines the test corridor through boundaries like the shape of the road, the number of lanes, and the OD matrix. The program runs a given number of tests and analyses the traffic flow based on internally sophisticated parameters that describe the behavior of every single car. This contains acceleration or merging actions, and even computes risk probabilities that are an indicator for possible crashes, something that such tools do not create. The obvious advantages are that the preconditions are equal for every algorithm, and the environment is static over the whole test phase, leading to a good basis for further comparisons. The main disadvantage of this method is that the real driver behavior is only simulated. It is barely possible to simulate soft factors, such as the quality of the merging area or the influence of single drivers, which are called inter-driver variations for the interaction between individual cars, and intra-driver variations, which describe the changing quality of the driving behavior of the individual
driver. These set limits to the simulation that lead to a typical inaccuracy of 20%. [15]-(p.313) Such a simulation can provide an overview of the general aspects and the robustness of algorithms. Also, its independence of freeway construction sites or weather changes does not affect these simulations, and thus these models are good pre-evaluation tools for new ramp metering algorithms.

5.1.2 Field Tests

The other possibility in testing the effectiveness of an algorithm is to implement it in the real system and collect the data over a specific period of time. In that case, it is completely certain how much impact this new algorithm has, especially in comparison to the previously used strategy of using historical data. Such a test covers all of the local boundaries that are not completely implementable in a computer simulation, as described in the previous paragraph. But this local view is also the disadvantage if the task is to evaluate the effectiveness of an algorithm in general. The transfer to other regions would result in varying results, depending on the local freeway system and its technical equipment. For example, SWARM might be a really successful ramp metering strategy for Orange County that has not performed as well as it was intended in Portland, OR. One problem could have been that the data collection infrastructure in Portland was not able to provide the high data volume the algorithm needed. In addition to these static differences, other impacts like weather, construction sites, or special events can vary the input data and the results. Data that is not comparable cannot be fully included in the research because of its unique nature, and as a result it has to be excluded from further analysis. It is important to compare the different systems on comparable data bases, which leads to an extension of the testing period in order to have enough information for an appropriate evaluation. This expanded timeframe influences the environmental boundaries, e.g. the change of seasons or the general increase of traffic demand, and thus produces multi-objective dependencies that degrade sophisticated field tests with a large database and leads to great efforts in a semi-interpretive evaluation of implemented ramp metering algorithms.

Table 7 below provides an overview of the described advantages and disadvantages for better clarity in a direct comparison.
Table 7 Comparison of Evaluation Methods

<table>
<thead>
<tr>
<th></th>
<th>Micro-Simulation</th>
<th>Field Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages</td>
<td>- Completely independent of time and space</td>
<td>- Precise working conditions at test area</td>
</tr>
<tr>
<td></td>
<td>- Easily repeatable trials</td>
<td>- Includes soft parameters, e.g. local driver behavior or value of installed equipment</td>
</tr>
<tr>
<td></td>
<td>- Flexible trials with manually implementable boundaries</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Easy to present</td>
<td></td>
</tr>
<tr>
<td>Disadvantages</td>
<td>- Cannot cover all important boundaries</td>
<td>- Requires a lot of resources (time, operator, analysis, etc.)</td>
</tr>
<tr>
<td></td>
<td>- Soft parameters are difficult to implement</td>
<td>- Includes a lot of useless data due to special events</td>
</tr>
<tr>
<td></td>
<td>- Difficult to recognize false assumptions</td>
<td></td>
</tr>
<tr>
<td>Usage</td>
<td>Pre-Evaluations/Comparisons</td>
<td>Re-Evaluations</td>
</tr>
</tbody>
</table>

5.2 Previous Evaluations

This subchapter is a brief description of selected previous evaluations that will be an overview of different techniques, workloads and environmental boundaries to clarify the difficulties of field evaluations based on real projects. The results and thoughts are the foundation for the construction of a standardized strategy for implementing ramp metering algorithms, and for that reason it is important to analyze their advantages and disadvantages.

5.2.1 Minnesota’s Shutdown

The best known example of a ramp metering strategy field test was the Minnesota highway shutdown in 2000. Based on public demand because there was no longer any trust in the ability of ramp metering to improve the traffic situation, the Minnesota Department of Transportation (MnDoT) began a field test to evaluate the true benefits of ramp metering on its freeway system. The project involved data collection between
9/11/00 until 12/8/00, and was divided into a period of time when ramp metering was turned on, and a period when the system was shut down. [65]-(p.ES-3) The project cost $651,600 and yielded important results which are often cited even today. [65]-(p.ES-1)

5.2.1.1 General Structure and Preparation

To begin with, the general structure of this field test with its preparations and the multiple parts it consisted of should be clarified. As a good overview, Figure 27 shows the workload of the main components: preparation, data collecting with, data collecting without, cost-benefit analysis and presentation. To carry out these tasks, the project was split into two committees. The first was the technical committee, which oversaw the engineering tasks and was comprised of scientific and technical representatives. The second was the advisory committee, which consisted of government representatives and stakeholders. [65]-(p.2-1f)

<table>
<thead>
<tr>
<th>Task</th>
<th>Year 2001</th>
<th>Year 2001</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aug</td>
<td>Sept</td>
</tr>
<tr>
<td>1. Develop Evaluation Plan for Test Corridors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Meet With Steering Committee</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1 Collect “With” Data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2 Collect “Without” Data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Benefit-Cost Analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Conduct Primary Research</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.1 Collect “With” Data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.2 Collect “Without” Data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Conduct Secondary Research</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Prepare Reports and Presentations</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Deliverable

Figure 27 Minnesota’s Shutdown Schedule [65]-(p.1-2)

The whole evaluation process was divided into three main goals, which were broken down into smaller indicators. These indicators were broken down further into measurable parameters that formed the foundations for the research. An example for such a proceeding can be seen in Figure 28. To reduce the workload in an appropriate way, these
goals were not analyzed at the whole freeway system level, but at the level of representative corridors that meet pre-determined characteristics. This process is broken down further from the general idea to the real situation.

**Figure 28 Breakdown of a Measurable Goal** [65]-(p.3-2f)

At first, the types of characteristics Minnesota roads have were defined, followed by a determination of possible corridors that match these criteria. The last step was to pick the best freeway sections that matched the criteria and had the best conditions for an evaluation process. [65]-(p.4-3) The concrete classification was given as an example in **Table 8** below, where it can be said that the top four general criteria were the most important in choosing a freeway corridor.
Table 8 Minnesota's Field Test Freeway Classification [65]-(p.4-3f)

<table>
<thead>
<tr>
<th>Classification</th>
<th>Description</th>
<th>General Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A</td>
<td>Freeway beltline section, high percentage of commuter, heavy commercial and recreational traffic</td>
<td>- Availability of alternate routes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Level of congestion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Geographic representation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Construction activity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- HOV lanes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Transit service nearby</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Geometric constraints</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Traveler market segments</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Representative corridor length</td>
</tr>
<tr>
<td>Type B</td>
<td>Radial freeway outside beltline</td>
<td></td>
</tr>
<tr>
<td>Type C</td>
<td>Intercity connector freeway, connects major business and commercial centers</td>
<td></td>
</tr>
<tr>
<td>Type D</td>
<td>Radial freeway inside the beltline, connects downtown and suburbs (commuting route)</td>
<td></td>
</tr>
</tbody>
</table>

5.2.1.2 The Examination

After setting up the constraints, the measurement of the with-case started and was switched after 5 weeks to the without-case, with a transition period of one week to allow the driver to react to the new situation and establish the probably of changes in the traffic pattern (e.g. a shift of driving times or routes) [65]-(p.4-2). The whole system was shut down to create equal conditions, but only the pre-evaluated representative corridors were measured and analyzed. Another restriction to save time and money was to measure only at peak time periods for between 3 and 4 hours during each weekday morning or afternoon peak [65]-(p.4-10). This data was grouped according to the day of the week, such as whether it was Monday, Tuesday to Thursday, or if it was a Friday. Other classifications were assigned to the incident that occurred (e.g. snow, rain or an accident on the main route), and it was compared with similar days. These additional variables were assigned to the day, time and freeway corridor to ensure a completely usable data set. [65]-(p.4-10)

Besides the typical field measurements, the study was enhanced by an accompanying survey about how the shutdown affected the driver personally. This addition was made because of the initial problem that we were quite unsure as to whether the ramp metering system was still beneficial for all users, or if there were unfair trends or unreasonable disadvantages for the user [65]-(p.4-15f). The investigation concerning these soft
facts was accomplished through a telephone survey based on random calls and a survey of specific individuals that were localized by their traffic patterns based on gathered license plate information. There were 1,520 calls made which were evenly dispersed over the time period in the four examined corridors with and without ramp metering [65]-(4-18). The percentage of responses was very high because of the Minnesotans’ initial interest in the topic, as explained in the beginning of this chapter.

In the end, all information gathered was evaluated using a cost-benefit analysis with a conservative approach, which means that every congestion management system (CMS) cost was assigned to ramp metering. This overestimation served the researchers as a safety zone to keep their results feasible, even though minor inaccuracies could have been detected (which was very conceivable in a public interest project such as this). The result was extrapolated to the whole system based on a categorization of the roads that were not considered using the ABCD model and the assigned costs it produced.

5.2.1.3 Summary

All in all, this study is a leading and comprehensive example of a ramp metering system evaluation, and contributes many possible examples for other studies with similar goals. The scope of the study covered most areas, but also included some necessary simplifications to keep the study reasonable and feasible. The fact that this study is still often cited and serves as the main example in papers and other reports of a successful study about the advantages of ramp metering shows that it should be used as the first approach for a foundation for a standardized concept.

5.2.2 Portland’s Evaluation

Another well-documented evaluation of a current ramp metering system was done in Portland, Oregon in 2008. The reason to describe it along with the Minnesota shutdown experiment is because of its fundamentally different approach. In Minnesota, the task was to evaluate the general ability of ramp metering based on measurements and surveys that included the publicity of comparing the case with and without ramp metering. The evaluation in Portland was more a comparison of the former algorithm used with the newly implemented algorithm based on slightly different databases, other approaches and different conditions. This included a different environment as well as a decreased workload. It was a great project in contrast to the Minnesota study that was described, and thus both create the basis for the further development of a standardized evaluation concept because they can be applied to cover many different cases.
5.2.2.1 General Structure and Preparations

The ramp metering system in Portland has been working with a pre-timed algorithm since 1981, and was updated to the coordinated and adaptive SWARM algorithm in 2005 as described in 3.66.1. [9]-(p.1) When the new system was fully implemented, it was tested and compared with the previous system to evaluate the benefits of SWARM, which was the main goal of this evaluation. The identification of possible corridors that may be representative for the whole system was bound by the following criteria: [9]-(p.15f)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level of Congestion (LOC)</td>
<td>intensity and scope to test the coordinated part of SWARM</td>
</tr>
<tr>
<td>Scope of queues</td>
<td>avoid interconnections with other freeways and situations</td>
</tr>
<tr>
<td>Detector infrastructure</td>
<td>small spacing for reality reflecting data sets</td>
</tr>
<tr>
<td>Data quality</td>
<td>determine corridors with effective loops and ramps</td>
</tr>
<tr>
<td>Construction sites</td>
<td>avoid upcoming construction sites that distort reality</td>
</tr>
<tr>
<td>Alternative routes</td>
<td>analyze detour side effects</td>
</tr>
</tbody>
</table>

For this study, none of the existing freeways met all criteria, and thus the next best compromise was selected. As a result, the examination of the influence of and on alternative routes was abandoned. The categorization of different LOCs is a completely new approach and shall be explained in more detail. Based on the fundamental diagrams of speed, flow and density, there is a turning point in each diagram that splits the graph into an uncongested, and a congested part as shown in Figure 29 below. [9]-(p.34)
The categorization of whether a station is congested or not is highlighted over the course of the day, and depending on how long it was congested, the station is classified as uncongested, lightly congested or congested. This definition is not consistent and had to be refined for the situation in the corridor. The refinement was made in the Portland evaluation that the number of congested stations was grouped according to a certain LoC. The concrete use of LoC in the study is presented in Table 9 below. [9]-(p.35) At the end of the study, all days evaluated were compared with each other and grouped by their LoC.

Figure 29 Fundamental Traffic Flow Diagrams [9]-(p.34)
Table 9 Criteria for levels of corridor congestion [9]-(p.35)

<table>
<thead>
<tr>
<th>Level of Congestion</th>
<th>I-205 NB</th>
<th>OR-217 NB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Least congested</td>
<td>&lt; 2 stations</td>
<td>Average 1 - 1.5 hours of speeds less than 40 mph at 3 - 4 stations</td>
</tr>
<tr>
<td>Moderately congested</td>
<td>2 - 3 stations</td>
<td>Average 2 - 2.5 hours of speeds less than 40 mph at 4 stations</td>
</tr>
<tr>
<td>Highly congested</td>
<td>4 - 7 stations</td>
<td>Average 3 hours of speeds less than 40 mph at 5 stations</td>
</tr>
<tr>
<td>Very highly congested</td>
<td>8 - 9 stations</td>
<td>Average 3.5 - 4 hours of speeds less than 40 mph at 5 stations</td>
</tr>
</tbody>
</table>

Because of a decreased in the planned study size, in comparison to the Minnesota study, the project was divided into two parts. [9]-(p.13) The first part was a pilot study to gather first information with minimized effort to improve the workload of the second part, which was a larger study hardly influenced by the experiences of the pilot project. In the following paragraph, the project’s boundaries and ideas are explained in general, and after that the two parts are analyzed to clarify which ideas had to be rejected, and which approaches improved efficiency.

5.2.2.2 The Examination

The foundation of Portland’s project was the Portland Oregon Regional Transportation Archive Listings (PORTAL), which is a SQL-based database with automatically stored freeway data, including important side notes like weather data in form of precipitation in inches, detector failures, and a connection to the Oregon Department of Transportation (ODOT) crash data. [9]-(p.17f) This solid foundation gave the project a more theoretically-based research approach to the data, and led to a comprehensive analysis of the former and current system. The stored data included the main measurements like main-line flow and speed, and these were derived with VMT and VHT, which replaced additional information measurements. [9]-(p.14) Because of the small estimated impact on general driver behavior produced using the new cycle time calculation software, some typical examinations were omitted, such as use of alternative routes, changed transit behavior, and changes in safety or pollution impact. [9]-(p.14) One measuring problem was on-ramp demand and queuing due to the lack of queue override detectors, and the sole implementation of use loop detectors behind the ramp metering traffic signal in
measuring when the car passed through the system. The solution and its outcomes will be described in the next paragraph, the detailed explanation of the pilot and the regular study.

The first trial of the 2006 pilot study took 10 days from 6/19 to 6/23 for the former pre-timed algorithm, and from 6/26 to 6/30 for the new SWARM algorithm. In it, a seven mile highway corridor in the southbound direction that is a typical commuting route for citizens of the suburban area travelling to downtown for business was examined. As the corridor was only examined in one direction, the affected critical time period was the AM peak, which was, depending on the real situation, measured flexibly between 6am and 9:30am. [9]-(p.17) The on-ramp waiting time, which was necessary to determine the global VHT, was analyzed using a simple approach comparing the number of vehicles entering and leaving the ramp. The previously described lack of loop detectors at the beginning of the ramp was solved by using existing CCTV cameras, and re-evaluating using a person who counted and archived them. At ramps without existing CCTV cameras, there were tubes installed that delivered the necessary data. [9]-(p.19)

The result of the pilot study led to a slightly modified study that was larger. This second study was given a two-week duration period for measuring the necessary data with each ramp metering strategy. [9]-(p.17) This extended period of time allowed a reaction to incidents, such as weather impacts, and provided the opportunity to categorize the days into several LOCs. Another change was the approach to estimating VHT. The use of the tubes and CCTVs delivered good results, but needed a substantial effort to gather the information, and thus the data was collected by a programmable logic controller (PLC). This device connected inflow and outflow and could estimate the delay on the on-ramp via simple queuing theory, which would have reduced the labor by a lot. [9]-(p.20) The disadvantage was that no single cars could be counted because of the retarded storage capacity of the device, but the results seem to be reasonable. In the end, this data was not accessible because of an undiscovered error, and assumptions were made based on the outflow volume that was delivered by PORTAL detector loop data. [9]-(p.49)

Days were excluded from the comparison when there were incidents. This included crashes, data loss gaps which were no longer interpolatable [9]-(p.42), or heavy weather impacts. Exclusions justified by the weather were only made if the associated traffic pattern changed too. Also, time was divided into AM and PM periods so that the full day could be used. [9]-(p.44)

5.2.2.3 Summary

This study is basically comparable to Minnesota’s shutdown experiment, but because the boundaries differ a lot, the methods and solutions were adjusted to the environment
and the main goals. Even though this evaluation had some minor downgrades and simplifications, the scope of the study is more consistent with reality than the efforts that were made in Minnesota. In addition, the comparison of a new algorithm with the former strategy used is more common than a basic examination about the general benefits of ramp metering. The study was actually comprised of two separate studies: a 1-week trial study done in a smaller, more limited area, and one year later a 2-week more comprehensive study was done that benefited from the experience and findings of the first study. The data from the first study formed the basis for the entire project. Because of these changes, the evaluation of Portland’s system provides a good example for the foundation of a standard concept that will be developed in the next chapter.

Standardized Evaluation Concept

The previously explained projects are only two examples of evaluations of ramp metering performance. A lot of effort was put into these studies to cover any eventualities and generate scientific results for further research and evaluation. As was briefly explained in section 2.11, ramp metering implementations are very diverse because of varying environmental contexts. This flexibility is a disadvantage for any standardized evaluation concept approach because it is not possible to design one evaluation concept that can address all of the site-specific nuances in a particular ramp metering implementation. This chapter summarizes the experiences of previous projects to develop a guide that demonstrates comprehensive opportunities to react to the specific situation of future projects. The guide can help future operators who have to evaluate a project in checking the general procedure based on the ideas and mistakes of former studies.

The ramp metering evaluation framework is presented in Figure 30 below. The procedure is based on the general structure of such an evaluation, starting with the preparation time, followed by the data collection (Implementation), and concluding with the formal evaluation and publication of the results. Often, the boundaries are blurred so the general structure of this overview can be seen through the major tasks. The scheme is discussed in more detail in the following sections.
There are several opportunities for implementing this evaluation process. One commonly used option is to commission a private company, but even with that decision, the DoT should know about the necessary preparations, steps and possibilities that are required for a successful study. Furthermore, if the study reaches a larger scope with public involvement, the government should give additional responsibilities to teams to support communication and simplify the preparation of some tasks, such as police support to gather telephone numbers based on license plate data as it was done in the Minnesota shutdown experiment. These representative teams may bring new perspectives to the evaluation concept and demonstrate the neutrality of the evaluation, which might be necessary if the public demands the topic. [66]
5.2.3 Task

Initially, the preparation of the whole evaluation process is important in order to increase the efficiency of the evaluation, and to guarantee that the collected data is appropriate in determining the results sought. The first step in the evaluation process is to define the scope of the project evaluation. There are two main possibilities as to how the task could be characterized. First, the section of the freeway that is in planning presents an opportunity. This leads to whether the evaluation process could determine how to best implement ramp metering in the new corridor. This scenario occurs very rarely, so advice as to how to address this situation is not covered in depth here. The second and more probable option is that the existing road network needs an evaluation for several different reasons. The next two discuss details of the initial situation. After that, the following subchapter defines more clearly which sorts of requests can occur on an existing network.

5.2.3.1 New Project with Ramp Metering

This scenario, where a new road is built with ramp metering capabilities, is comparable to the procedure described during a comparison of a period of time with ramp metering and without ramp metering in section 5.2.4.3. It is therefore similar to the situation of an existing road where an organization plans to implement a ramp metering strategy for the first time. This overview includes some hints about the structure of the road, including spacing and the positioning of vehicle measurement systems. It is just a brief description of that whole topic because the individual implementations such as the type of vehicle detector system would be a whole thesis by itself. The following list is a short overview of topics that have to be mentioned:

Detector Position: depending on the algorithm scheme, if it is using feedback or feed-forward control, if it has fixed distances (e.g. the PRO algorithm, see section 3.28.2) or if it is dependent on the queue measurements of the on-ramp, the locations for the detector devices have to be adjusted.

Detector Devices: the standard way to measure the needed input data for the ramp metering calculation is to use a detector loop. The reason is because of the low installation costs and high coverage rate of pre-existing loops. But this solution has been questioned more and more recently because of several factors. It has to be implemented on the road, which introduces lane closures during installation and maintenance, difficulties during road surface work, digging work if the detector is defective, and even wire thievery because of high copper prices. [6]-(p.4) Other possibilities are optical CCTV cam-
as, wireless magnetic sensors, radar or thermal scanners, just to mention the standard options. [5]-{p.27f}

**Technical Infrastructure:** depending on the space, estimated data volume, or other boundaries, the infrastructure needs to fulfill the demand of the ramp metering system. A large amount of valid data is needed for an accurate working system. Otherwise, fewer benefits than calculated during the pre-evaluation process will be measured. As mentioned, because of possible wire thievery or other local boundaries, the path of data transmission has to be analyzed.

In addition to the necessary technical infrastructure, topics like the existence of VMS, VSL, and maintenance crews need to be covered to see if any of these are necessary for the ramp metering algorithm, or if they might assist the strategy.

**Data Management:** depending on the installed algorithm, different amounts of data are needed to compute the cycle times. It is important to use accurate methods to determine the input data such as occupancy, volume or speed. In addition to the type of measurement, the scope needs to match the desired activation time (see, 2.10.4). Furthermore, information storage is an important topic because a unified system with historic data allows maintenance and adjustments without greater evaluation processes.

**Ramp Shaping:** the shape of the ramp has to fulfill the needs of ramp metering, or at least the metering strategy should match the existing infrastructure. This whole topic includes the existence of HOV lanes or bus bypasses and how to implement these lanes into the system. Also, it follows that the storage capacity has to match the strategy of the algorithm and vice versa, which leads to thoughts about one- or two-lane metering, or multiple car per green solutions (see 2.10.5).

**Arterial Network:** some algorithms use the information of the subordinated network, which leads to detector stations on the previous intersection, analyses of the severity of spillbacks, or the estimation of turning probabilities. Also, this topic includes thoughts about alternative route choices because of possible rat running, or on-ramp delays that do not merit the use of the freeway anymore for certain drivers.

These are only the main parts of the ramp metering topics that have to be covered before the implementation. Also, it is important to mention that many minor possibilities are included, such as the possibility of a stationary law-enforced ramp meter, which increases the accuracy of this strategy due to fewer ramp meter violations.

**5.2.3.2 Existing Road with Ramp Metering**

This thesis concentrates on the case that a ramp metering system has already been implemented and the task is to evaluate the benefits of the system in comparison to another
strategy, or to the case in general. Thus, this work does not explain how ramp metering should be best implemented, but in the following subchapters gives an overview of the execution of an evaluation process with the background that such a system has already been installed.

5.2.4 Request

This step categorizes what necessities may occur because of the background of why this upcoming evaluation process is initiated. It is important to analyze the different needs in doing the necessary research at the right locations and with the required depth. The next three subchapters will explain the difference in the general expectations that might require evaluation. The results are only general advice that is examined in greater detail in 5.2.7 when it comes to the real measurement.

5.2.4.1 Public Demand

As the trigger for the previously described Minnesota shutdown experiment, and in general, the transition to a modern society that wants to participate in and question governmental solutions, public demand is mentioned in this chapter. The main reason would be to justify the necessity of ramp metering in general, and to present the measurable benefits that remain, in contrast to the personal drawbacks of the individual drivers. The goal should be to research the fairness, the efficiency and the financial benefits of ramp metering, and to present and maybe to defend it against subjective, individual opinions. In such a case, it is important to work transparently and comprehensively, and to involve the public in this project to show that their requested project covers the questions and needs they have. To become more inclusive, the following paragraph gives recommendations about techniques. Hints to evaluate the features of ramp metering mentioned are summarized in 5.2.4.3 where a list of possible general inclusions is also provided that might be necessary due to the increased will of participation in society. The following suggestions to improve involvement are additional possibilities to widen the inclusiveness to fulfill special local expectations or project goals.

Improved Inclusion

The increased participation is only useful if the need for it is requested. There are no more major benefits to be considered that could be achieved with the later explained general inclusion. But to create a demanded further involvement, it would be possible to add some additional tasks to the overall project. The basic situation is that the public questions the benefits of ramp metering. Therefore, an increased effort is necessary to summarize the benefits. Typically, this is done via mail-in or telephone-based surveys. An online survey should be available, and it should be discussed an incentive format,
such as a raffle, because even minor public surveys from the private sector lure people with a chance for a prize. A disadvantage is that people who are only interested in the prize might provide invalid answers. Due to the possibility of this kind of behavior, this is a step that should be discussed in advance.

**Pre-evaluation:** to gather first impressions, public outreach could be performed to gather perceptions on the implications of the new system. Typical issues concern fairness, waiting time and overall benefits in comparison with the costs. However, it is possible that the view of the system differs within the city. To define the focus of the research, an initial representative survey should be carried out before the detailed planning of the study. In addition to the main focus, this survey will determine local particularities and may be used to disseminate information about upcoming participation events.

**Ongoing evaluation:** this step is not completely necessary, and depends on the duration of the overall project. The idea is to keep the public interested in the process and to gather driver experiences after the first half. Especially over longer studies, memories about the first half can be influenced over time and differ from the real experiences. Again, surveys are the best option to achieve this goal.

**Re-evaluation:** following the main examination of the ramp metering system and its two test periods, the public should be involved again to evaluate their experiences. This is a great opportunity to compare and extend the test results and hard facts with the subjective views of the drivers. The re-evaluation is also an opportunity to reveal the test results to the public and present the benefits of ramp metering. This should be done after the survey to exclude the influences of the results, and can be carried out through publications in papers or also in a direct presentation, depending on the general interest in the topic.

Such surveys, however, in which an extension was carried out provide an overview of driver perceptions and improve the ramp metering system used. [66] It is a foundation to predict driver behavior, and can lead to new approaches like maximum waiting times at the on-ramps, or to see where the ramp metering favors long distance commuters. [65]-(p.6-5f)

### 5.2.4.2 General Research

This task describes the goal of evaluating the benefits of ramp metering in general. This study would be really unlikely because of the major effort that was made in 2001 in the Minnesota shutdown experiment (see 5.2.1). If it would really be necessary to repeat such a project with different boundaries (other driver behavior patterns in another cul-
ture or in a varying roadway structure), this subchapter contains a general overview about the required data.

The basic situation for this evaluation can vary a lot from “no infrastructure implemented” to “existing road network with detector stations and data sets about the traffic”. The last situation would be covered through the efficiency evaluation explained in 5.2.4.3. Every situation requires all of the steps for a ramp metering implementation and evaluation process, which include: the preparation to define the goals, the installation of the ramp metering system, the detector stations to measure the needed input data, measuring the case “without ramp metering”, the activation and calibration of the ramp metering system, measuring the case “with ramp metering”, and finally, the comparison of both cases. Because of the very different situation for drivers, this evaluation process should be combined with a campaign about the general uses and benefits of ramp metering, which can be repeated after the evaluation to present the experiences and show the public their benefits. Also, because of the new situation, there should be longer transition phases planned to guarantee that the system is used correctly and possible traffic pattern changes made. Additionally, this behavior leads to a larger surveillance of alternative routes to estimate the impact of these transformations.

All in all, general research is the most comprehensive way to evaluate the ramp metering system for an individual city, but it also includes a lot of information about general driver behavior and ramp metering. Time schedules should be planned carefully and generously to guarantee the success of the evaluation.

5.2.4.3 Efficiency Evaluation

The most likely event is to compare the efficiency of an older strategy with a new implementation. This task is the most economical way to evaluate a system because it contains a lot of information and results. But in comparison to the other tasks, this one is less sophisticated. One reason for that is the less detailed approach, which is enough to get most of the data as a foundation for the comparison. If possible, a project should try to match these kinds of boundaries to spare resources like time and money.

The evaluation of the efficiency of the implemented ramp metering strategy in general includes a comparison of the new system, which is already implemented, with the system, which ran previously. If there was no system before, the task is covered through the explanations in the subchapter about the general research (see 5.2.4.2). The main difference is that there are often appropriate data about the efficiency of the former algorithm, which compresses the measuring process. This can be the foundation for a comparison with a larger data set that verifies the study itself. The task is to find appropriate data that is comparable to the new measurements with the latest algorithm. It is
important to calibrate the new system before measuring in order to have reliable data. Because of this minor approach, such a study would mainly consist of: calibrating and measuring the new algorithm, finding comparable data for the previous algorithm(s), and evaluation. Public involvement is normally not necessary, but this assumption is explained in more detail in the following paragraph.

**General Inclusion**

It is not necessary to include the inhabitants of a city in every case, but it can be helpful in justifying the use of ramp metering from time to time and ensuring that people recognize the benefits. Such unawareness led to the public demand in Minnesota in 2000 that the government had to prove the general benefits of ramp metering, which led to their expansive and comprehensive study. Depending on the scope and the intention of the study, there are some possibilities to include the public and receive additional information from that. In general, there are two major cases to cover. Case one belongs more to the general research and is described through a comparison of a period of time without ramp metering, and a period with ramp metering activated. The second case, which belongs more to the efficiency evaluation, is the comparison of two algorithms. Both cases create a different benefit from public involvement, but the borders between the benefits out of these are blurred, and the operator has to decide to what extent it would be beneficial to include the public in the project.

**Case 1) with and without comparison:**

Projects with that intention should be revealed and explained to the public, because there are quicker changes in personal adapted route, mode or travel time measurable and thus it shortens the study time. Also, it breaks with the normal habits of driver behavior, such as stopping on the on-ramp in the case that the ramp metering is turned off. This was possible in certain situations because of the old algorithm that was fixed at the time and it was unquestionable to stop at the on-ramp for the driver. To announce that the meters are shut down leads to adjusted driver behavior. Also, if surveys are planned, to overview traffic patterns, this pre-information explains to people what the surveys are used for. In general, the ramp metering evaluation project becomes visible and does not seem like a technical hazard, which would be a self-developed explanation of the driver, and underestimates the efforts made in traffic engineering.

**Case 2) comparison of algorithms:**

In this case, it is not really necessary to involve the public in the project because in general, they do not notice a huge difference. In fact, it is a common opinion that the cycle and activation time of a ramp metering system is fixed, and not nearly as sophisticated as it is in reality. Because of that, there are no major routes, modes, or travel time
changes to expect that would justify the inclusion. But it is highly recommended that positive results be revealed and explained to the public to show that there are changes, and to what extent the individual person benefits from it. It justifies ramp metering in general, and reacts to the increased general will of the people to participate in governmental issues.

5.2.5 Scope

In this chapter, the scope is defined by the real local spread that strives to analyze the situation in a decent way. This topic is highly influenced by the amount of financial and human resources, and because of that, the next two subchapters will explain the general scope of such an evaluation process and make recommendations as to how a minimal effort can result in an appropriate evaluation.

5.2.5.1 Whole System

This approach means that the whole area is covered by the research, which is very unlikely and is questionable in some points if the efforts in every detail would be rewarded by enough additional information. Such an approach contains:

- The local freeway and highway system
- The local arterial road network
- The regional freeway and highway connector system
- The regional arterial road network

The examination of the listed parts would lead to a comprehensive understanding of the local traffic patterns and influencing factors. In the way mentioned, it is not feasible because of financial and personnel resources, but it is also not worth it because of the complex relationships on the local level that would not reveal general irregularities. It is highly recommended to abstract the problem and to exclude or assume minor influences.

5.2.5.2 Selected Corridors

The more general approach is to reduce the system in an appropriate way in order to minimize the data collection efforts and the evaluation, while keeping the results consistent and generalizable. Such a strategy is economical and more easily explainable to the public. Especially for a shutdown experiment, it is necessary to turn off every metering system to avoid changed driving patterns based on routes with deactivated ramp metering. [65]- (p.ES-2) The following list contains major fields of exploration and tries to shrink the effort-result ratio in a feasible way.

- Representative local freeway and highway corridors
- Most likely local alternative routes

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Representative regional connector routes

The main idea is to compress the efforts in significant corridors that are most affected by congestion and that are representative enough to be an example for other facilities within a city. These should cover the most common types of freeways and highways categorized by the location or the user. Possible classes can be determined on the basis of shape:

- Beltlines
- Bottlenecks like river crossings or tunnels
- Connectors into suburban area or other regions

Other possible categorizations based on the type of usage might be:

- Commuter
- Recreational
- Freight

Each freeway and highway section should be assigned to these categories in a certain percentage because normally, a road consists of several classes, such as 20% freight, 10% recreational, and 70% commuter peak influence on congestion. Also, the task and local situation of a road can be mixed. The benefits measured have to be analyzed on their foundation, and can then be transferred to the whole system on the basis of the percentage of each classification to estimate the benefits for the whole system.

Another approach would be to categorize the corridors by their level of congestion, because in the comparison of the effects of ramp metering, it is noted that these effects differ based on the severity of the congestion. This inconsistent behavior of ramp metering makes an evaluation very complicated and questionable, but the above-mentioned classification is based on the traffic situation and not on the shape of the facility, contributing to that disadvantage. It shows how efficiently the single algorithms can handle an increased traffic load, and this information can be used to decide whether or not an implementation in a certain corridor would lead to an improvement.

The procedure described first with its representative corridors is only necessary when an evaluation for the whole city is desired, but it sometimes makes sense to focus on the corridors with the most grave congestion, or an implementation that is only situated along one route. In that case, an economic evaluation of the whole city is unnecessary. Also, minor adjustments regarding the probability of changes of any of the topics researched has to be questioned. For example, is a change of traffic patterns considered unlikely only if the cycle time calculation algorithm is modified, and therefore such efforts can be spared?
5.2.6 Duration

As with scope, the duration of a study is restricted by given resources. To accomplish good results that lead to a representative evaluation, this subchapter makes recommendations for minimum surveillance periods and ways to deal with overly restrictive boundaries. In general, such a project consists of three major parts: the preparation, the examination and the evaluation. The following paragraphs cover these different phases.

5.2.6.1 Preparation

This phase is very inconsistent in its duration, and therefore no specific times can be given. It hardly depends on the type of funding, e.g. if the money is available out of their own resources or if there might be any governmental support available. Also, if the inclusion of other departments is necessary, such as the police in receiving contact information based on license plate numbers, preparation time can vary a lot whether the general interest in this kind of study is really high or not. Also, depending on the country or state, there are different hindrances to these individual boundaries, and the available resources determine how much effort can be made with each case, including how many people can work on the project, whether it is announced to a private company, or a time restriction that might determine the price range.

As a general parameter, the preparation time for the MnDoT shutdown experiment began in May 2000 following legislative support for the project and the search for a consulting company. Three months later, in August 2000, the development of an evaluation plan began and took one and a half months. These time periods were very straightforward because of the high political and public will, but provide a first indication as to possible duration.

5.2.6.2 Examination

A typical timeframe for traffic studies is four weeks, which should also be the goal in a ramp metering evaluation process. [66] Depending on the severity of the change, there should be a transition phase to let driver’s pattern react to the different situation. This severity can be categorized in roughly two classes with a gradation because of an introduction to the study. At first, there is the case with and without activated ramp metering. The huge difference between these two states induces major traffic pattern changes, and therefore a longer transition phase is necessary. During the MnDoT shutdown experiment, the time was set to one week with massive public involvement. [65]-(p.4-2) The people involved estimate this time as sufficient, but there should be a longer transition period planned when the public interest is not as great. In general, two weeks are conceivable, and three weeks would cover most circumstances. The problem with this
comparison without larger public involvement is that because of the driver’s uncertainty, it is not sure whether they are willing to change their patterns.

The second case is the comparison of different algorithms, which does not induce larger driver behavior changes. Because of that, even without any public inclusion there is no transition time necessary. Of course, this is a general estimation. In cases where the algorithms differ a lot, such as the new strategy using VSL or having major deviations in the activation time, a transition time is conceivable. The explanation to the driver can reduce this time to zero if the new estimated activation times can be revealed, or if a week can be spent clarifying uncertainties.

5.2.6.3 Evaluation

The duration of the evaluation phase is comparable to the variety of influencing factors in the preparation phase. In general, it is to say that the scope of the whole project has the greatest influence on the time needed to analyze the data. A larger scope means more data, more individual aspects to research, and more dependencies between these aspects. Again, as an example, the MnDot shutdown experiment took three months to evaluate the results and prepare them for presentation. [65)-(p.1-2) This time was predetermined through the legislature period, but there were no major problems in meeting this deadline. [66] As an overview of which tasks have to be solved in this phase, the following list gives a brief idea of the fields that might be covered.

- Overall travel time delay
- Mainline travel time delay
- On-ramp delay
- Alternative route, mode or travel time choices
- Speed deviations
- Capacity examinations
- Weather impacts
- Activation times
- Red light violations
- Fuel consumption
- …

The listed indicators are single parameters that define the positive or negative impacts on a major goal. Depending on these goals and the way to examine them, the project’s scope and duration is influenced. However, these parameters are the foundation for evaluation methods, which are briefly explained in 5.2.8.1, and because of the variety in the scope of the research itself and in further related topics, it is not possible to give general advice for the duration of a good evaluation process.
5.2.7 Data

The body of this evaluation is all about the data, which includes evaluating which information would be of common interest, how to gather it, and how to keep the whole set consistent through discarding isolated measurements. The following provides some advice concerning these topics to improve the efficiency of the whole process.

5.2.7.1 Data Collection

The foundation of an appropriate evaluation is a set of data that needs to contain every measurement for the referring conclusion. The following list shows typical information that has to be gathered in preparation for the evaluation.

**Speed:** the speed in distance per increment of time is important to measure because it is a descriptive unit that is easy to understand and to interpret. Also, it is an important dimension in determining the delay. Depending on the gage, speed is directly measurable and a basic unit for further evaluations.

**Flow:** this describes the number of vehicles per unit of time, and helps to maintain and explain the understanding of capacity that describes the theoretical maximum of a specific number of vehicles per unit of time, depending on the road type. Flow is directly measurable, and like speed is an important basic measurement for further evaluations.

**Travel Time:** this unit is another basic measurement that can be detected through probe vehicles, Bluetooth detector stations that recognize individual cars by their Bluetooth mobile phone signature, or other ways to detect and recognize individual cars. Travel time is a basic unit for further evaluation, and it is recommended to measure it with a sensor spacing of every 0.4 mi., or a coverage rate of 4% of probe vehicles (either direct GPS-tracking or Bluetooth data) to receive appropriate travel time estimates. [67]- (p.74f)

**VHT:** the vehicle hours travelled is the computed product of the volume and the travel time in a section, which are summed over all sections. It is used for decision-making evaluations and cost-benefit analysis because of the assumption of a convertible time and money relationship.

**VMT:** the vehicle miles traveled is the “traffic volume integrated over the total link length of the network and over time” [15]- (p.380). It is a summary that is easily convertible into fuel consumption or other global indicators.

**Delay:** this dimension is not directly measurable, but it is important to visualize the benefits of a ramp metering system. To determine the delay, the optimum travel time during uncongested hours is subtracted from the actual travel time. But there are also approaches to minimize the optimum travel time through the consideration of a baseline
delay or more detailed approaches. In the end, all approaches need a uniform distance and can be taken for delay in the whole system, on the mainline, on the on-ramp, or in other areas of interest. [68]-(p.118)

**Weather/Incident:** for a later evaluation, special days should be marked with their anomalies to decide whether the day is truly comparable or not. This includes incidents like rain, snow, hail, fog, crashes, lane closures, or other events that may affect the driver’s behavior.

To gather all of the information in an appropriate way, it is recommended to have detector stations at every location where the situation may change. This includes mainline detectors on each lane with proper spacing, on-ramp detectors, and off-ramp detectors. The detector coverage ratio can be improved by using non-stationary systems, but it has to be pre-evaluated if they match the requirements. (Tubes are a frequently used measurement tool, but on freeways is the average speed too high, which would destroy the tubes, and at locations like the on- and off-ramps, radial forces may damage the tubes because of the geometry of the ramps [69]).

To measure the clean results, there should be a special effort to localize the best sites that meet the criteria for the possible representative corridors (see 5.2.5.2), but also exclude the following disruptive events:

**Weather impacts in general:** the study should not be planned for a time when severe and especially unpredictable weather conditions are expected, which is winter for most of the world, as well as the transition phases into or out of it. Especially with snow, there are multiple side effects like changed merging quality, decreased average speed, or different driver behavior.

**Corridor infrastructure:** this topic emphasizes that the chosen sections should contain well-maintained detector stations with minor priority, and that they should not influence each other (e.g. congestion on a crossing section spilling back on to the chosen corridor).

**Construction sites:** to avoid an additional factor that increases the variety of the information and minimizes the set of comparable data, it is recommended to examine possible corridors as to whether there is construction planned. In addition, even construction on the arterial network or on different sections may influence the data because of shift effects.

**Major events:** At the construction sites, major events can influence the consistency of data as well. It is necessary to check the scope and the impact of such events to estimate their possible effects on the evaluation study. Even if the event is at a different time or place than the study is, there can be side effects like a different traffic pattern due to
people leaving work early or taking different routes because they estimate a higher impact.

**Holidays:** as weekends, holiday seasons imply an increased recreational traffic demand compared to normal weekdays. Depending on the corridor considered, the effects should be forecast and can vary from less congestion over no impact to more congestion depending on local variation.

5.2.7.2 Data Discarding Criteria

Because of unpredictable incidents, there will be some data that are not comparable. This subchapter will present an overview of possible boundaries that may lead to an exclusion of certain information, and describes the extent that some incidents influence the results of the study.

At first, it is presumed that the possible disruptive events that are explained in 5.2.7.1 have already been excluded from the evaluation study. In addition to these predictable impacts, there might be other effects that influence the data. These are listed below and contain the major influences that cannot be planned.

**Weather impacts:** besides the normal weather patterns based on the season, even slight differences can influence a driver’s behavior (e.g. rain, hail or fog, which may occur in every season and is only slightly predictable).

**Incidents:** this point covers everything that leads to high deviations from the normal traffic pattern, such as crashes or lane closures for any reason. Such incidents have a huge impact on the system due to decreased capacity and changed driver behavior.

**Detector failures:** these failures may lead to data gaps or inconsistent results, and can be detected during the study or in the evaluation process. Depending on the detection device and the severity of missing data, a spontaneous repair is not possible or necessary in every case.

These three topics, in the following paragraph summarized as incidents, contain the majority of things that influence the data and are not predictable at all. If one of them occurs, it does not imply that the entire day’s data has to be discarded; there are still other possibilities for using the data.

**Firstly,** measured data is only interesting for the times that are evaluated in the end, which is mostly during the morning and the evening peak of a weekday. An incident on the morning peak may lead to incomparable data, but the information measured during the PM peak can be still used for comparisons. **Secondly,** incidents do not automatically lead to incomparable data sets because there might be a chance that they do not have an effect on a driver’s behavior. For example, there were precipitation measurements in the
Portland evaluation project that showed that some days lead to changed driver behavior, but that these days had less precipitation than other days with more rain, but less effect. [9]-[p.44] This may be a problem of accumulated incidents and lead to the recommendation that the information about an incident should be stored, which provides an explanation about changed driver behavior in the end. But it should not lead to discarding the data per se. Instead, this decision should be made based on the general comparability of the data set in terms of the other days considered. Thirdly, referring to the previously mentioned point, the data set should be considered a whole set, which implies that even irregular days may have comparable counterparts. Especially in projects with a smaller scope, this approach may save the foundation of the evaluation. Fourthly, regarding detector failures, special missing information may be interpolated based on the overall measured average or other experiences. Broken detectors may be fixed during the time of the study or be assumed as average, depending on adjacent detector stations.

5.2.8 Evaluation

The last third of such an evaluation process is characterized by the evaluation and the final presentation of the results. There are different approaches in analyzing the collected data, and thus there will be an overview given about the most common techniques to evaluate the advantages and disadvantages of an implemented strategy. This is followed by minor advice concerning the interpretation of the results and the probable publishing.

5.2.8.1 Concepts

There are many approaches to measuring the benefit or efficiency of a system. The most common concepts are described in this subchapter, and recommendations are given that can help future evaluations in defining the best matching method.

Cost Benefit Analysis (CBA)

The CBA is the typical method to measure the overall outcome of a project. It compares the real costs, which occur during the implementation and the running of the new system, with the benefits. These benefits are calculated into a comparable financial value, and include pecuniary and non-pecuniary effects, e.g. the pricing of decreased delay or noise emission.

This method is very common because its results are easy to present and seem to be logical. The disadvantage is the possible manipulation of the indicators with their values, and that these values are often based on assumptions and virtual benefits. For example, the benefit of decreasing a delay by 2 minutes for each driver does not change anything for the single person, but multiplied with all users, the price of an average working hour becomes significant indicator. [70]
**Cost Utility Analysis (CUA)**

The CUA, or Scoring-Model, is a technique used to compare alternative projects on the basis of financially measurable indicators, as well as those that are not valuable, with a certain price. To achieve that, the main goal, e.g. the decision to implement a new ramp metering algorithm, is itemized to several minor goals that are each weighted. After that, the alternative options are examined as to how far they achieve the individual sub-goals, e.g. on a scale from 1 to 10, each algorithm gets points for being better or worse in satisfying one minor goal. In the end, all scores of an option are summed, and this utility factor can be compared with the result of the other alternatives.

This method does a great job with indicators that are difficult to measure in terms of financial value, but it necessitates a greater effort to find a consensus as to how important an individual goal is. Also, the premise is that the sub-goals are independent from each other, and thus the evaluation of a single goal does not influence the utility factor in the end. [71] An example of dependent sub-goals for ramp metering would be the measuring of delay on the whole system, delay on the mainline, and delay on the on-ramp. These indicators are interesting in comparing the fairness and the benefit, but they would increase the importance of delay in the utility factor in comparison to the costs for electricity, for example.

**Cost Effectiveness Studies (CES)**

As an improved version of the CBA, the general methodology of the CES is comparable. In fact, the CES combines the contemplation of non-financial indicators aggregated to a utility factor with the financial factors that are represented through the cost factor. These two factors are kept separated, leading to an evaluation in the end that chooses this alternative and reaches the pre-determined utility factor with the lowest cost or that has the highest utility with a pre-defined cost. [72]

This method is fair and comprehensive, but through the different factors and the larger scope, it is more sophisticated than the other approaches.

**Analytic Hierarchy Process (AHP)**

The AHP is an advanced CUA. In contrast to the general utility factor, this method forces the operator to compare the alternative options on the sub-goal level directly. Also, the basic arithmetic of the CUA is replaced by matrix multiplication, which increases the complexity of this method. Nevertheless, it has an internal logic controller, which verifies the manual relationships and logical assumptions. This is not possible at the CUA, where such inconsistencies are not visible in the result. [73]

**Conclusion**
Depending on the scope, the budget, and the time frame of the evaluation process, it is possible to choose between several method options to measure the efficiency of the system. In the case of ramp metering, there are only a few pecuniary effects and parameters that are not financially assessable. Thus, the typical CBA would be good enough. Also, when the task is only to compare a former algorithm with a newly implemented one, often the measured parameters are solid enough to compare them directly, and decide the overall value of each strategy. In cases of presentations of the evaluation made, an official method helps to keep the process transparent and comprehensible.

5.2.8.2 Advice

To conclude this rough scheme of a typical evaluation process, there are some hints in the way to interpret and present the results, which exceed the previously mentioned advice and were experienced through the study of many earlier projects.

Data analysis: besides the normal evaluations of increased speed, travel time or general delay, it has been shown that many research projects only consider restricted parameters. The best example of that is the travel time. It is not easy to measure, and thus most projects only consider either mainline, ramp or the overall travel time behavior. It is necessary to itemize this indicator because of different interpretations for these results. Slightly increased overall travel time could mean that the mainline is preferred by the algorithms, and depending on the on-ramp demand, the delay there accumulates more or, in a worse case scenario, less drivers on the on-ramps of the corridor are punished disproportionally in comparison to the minor effects on the mainline. But it can also be the other way around. For a good evaluation, these different travel time influences have to be considered in combination, and in their isolated development. This refers to the topic of fairness, which might be a huge problem in justifying the ramp metering system. In general, fairness is characterized by travel time changes, depending on the origin and destination, and on the delay on the single parts of the freeway. A public survey may research the tolerable waiting time on the on-ramp, which can be verified through the evaluation. [66] Another point is the data quality that should also be considered.

Presentation: depending on the public interest, the presentation of the results can be held in a different way. But in general, there should be a presentation of the larger benefits of ramp metering, because through discussions with people it turns out that the greater value of this strategy is often not understood. The sophisticated cycle time calculation is not visible, and it seems that the delay is simply moved from the mainline to the on-ramps, penalizing the inhabitants close to the city and preferring those living in the suburbs. To avoid a smoldering conflict that may turn into fundamental questioning,
such as in Minnesota in 2000, research should be presented through a media campaign [66] or an open meeting. The way to present differs a lot from region to region, but it should be held in a public way (at least the focus) in order to reach as many people as possible.

5.3 Conclusion of Evaluation Concepts

The chapter about evaluation concepts begins with an overview of which possibilities are conceivable to evaluate a ramp metering system. In general, there is the micro-simulation and the field test. The simulation is great for pre-evaluations and comparing many different algorithms on the same test corridor. It is easy to conduct a lot of studies, but it is hard to estimate whether the defined boundaries match the real situation that is only simulated. There are many opportunities to vary the input data, and because of the large amount of micro simulation tools with different approaches, this evaluation method is only briefly explained. The field test is a good tool to evaluate new algorithms on real constraints that have been pre-evaluated in simulations. But the more common use is the comparison of a new implementation with a previous strategy that might have become inefficient. The complexity of such large projects is shown in a summary of two different projects that evaluates the benefits of ramp metering. One of these projects is the well-known Minnesota shutdown experiment, and the other, the evaluation project of the city of Portland, Oregon, which compares their original static strategy with their new dynamic one. These two different approaches cover a lot of possibilities and boundaries that can be handled in such a project, and therefore they are a good foundation for the given standardized concept in this chapter.

The concept itself is more a compendium about advice and suggestions for future research and evaluation projects than a universal scheme that a person only has to follow. It summarizes the most important steps in a comprehensive process, and lists the associated parameters and indices and gives short explanations about them. This overview starts with a rough scheme of the major tasks that are explained in more detail in the followed subchapters. At first, the general task is explained by showing the difference between a new system that is to be implemented and an existing system that is being re-evaluated. The second step is to clarify additional perspectives, depending on the circumstances demanded by the evaluation process. In general, such a project can be demanded for the public, for basic research, or for the concrete efficiency evaluation. These different foundations lead to a different scope and objectives to discuss. Thirdly, the scope of such a process is estimated, which mainly includes an explanation of how to develop a comparable study for the whole road network without monitoring every single corridor, because such an effort would overextend the resources of such a project.
There are examples of important corridors and how to substitute the complete local network with these main sections. After the scope, the fourth part followed is to determine the typical duration of a ramp metering evaluation process. This subchapter itemizes the three main tasks that influence the needed amount of time to evaluate the ramp metering system in a city. Often, these parts are the preparation, the examination and the evaluation phases, and it turns out that, depending on the task and local diversity, there is only a rough opportunity to give such advice. Because of that, this subchapter tries to summarize the required minor tasks that determine the length of the whole study and thus give an appropriate overview for future projects to estimate, based on this summary and on the local boundaries the duration of the study. Step five explains the whole process around data, which includes the measuring process and hints about discarding invalid information. The data collection process contains a list of needed parameters and explains possible impacts that influence them. The influencing factors are categorized through the possibility that they might be excluded before the study begins (which technically belongs more to the preparation, but because of the sophisticated relationships between all parameters, this part is categorized in this subchapter). Other factors that modify measured data but which may occur spontaneously are handled in the followed paragraph about data discarding criteria. This includes the mentioned possible factors and to the extent they change the results of the study. The sixth and last point is the evaluation of the whole study. To clarify in general how to evaluate a system, typical evaluation methodologies are explained. After that, there is some final advice regarding possible data interpretation, as well as a presentation of them.
6 Conclusion

This thesis examines ramp metering algorithms and the strategy for implementing them. Therefore, the literature review gives a general overview of the basics of ramp metering. It explains how using a ramp metering approach to handle freeway free flow in comparison with arterial demand works, and which goals it seeks to achieve. In preparation for the following chapters, the different approaches and ideas as to how ramp metering algorithms work are explained. Additionally, some major background information is given which is used in later chapters, but does not necessarily solely concern ramp metering, such as the Kalman filtration, which is used in many other fields too.

After this general overview, the thesis is divided into two main parts. The first is mostly a summary of all known ramp metering algorithms that existed at the time this study took place. The different algorithms are sorted by their operating mode, which is either on a local level, or on the coordinated level. The algorithms of the last mode are divided again into their relationship at the local level, which is either cooperative, competitive or integral. All algorithms are explained as to how they work, or where they are or have been implemented. If available, a short description of their performance is provided. Then, an overview of implemented ramp metering strategies all over the world is provided, along with an historic explanation of the development of ramp metering algorithms. After this, a map of the world and of the USA is shown, which contains the number of implemented ramp metering systems in the different states and countries.

The second main part deals with a standardized evaluation concept for implemented ramp metering algorithms. The two main strategies for evaluating these algorithms, which are micro simulation and field tests, are explained and compared. Then, two larger projects are explained as far as their structure to deliver driver knowledge about prior projects. These two projects are the Minnesota’s shutdown experiment of 2001, and the evaluation of the system of Portland, Oregon in 2008. Both are extensive in their research, but very different in their goals, and thus provide a good foundation for the following standardized concept. This concept explains through a general scheme the basics of an evaluation process, and gives recommendations for major tasks. These mostly contain lists of important parameters of studies, and give advice about the project’s operations and how measurements are conducted. The goal was to construct a standardized evaluation scheme, which was not achievable in the scope of the thesis, and thus the recommendations are only a rough overview to introduce operators to that topic. Future recommendations are described in the following chapter to discuss how this intended work could be completed and improved upon.
6.1 Future Research Recommendations

This thesis is a summary of the basic knowledge of ramp metering. It contains general applications of the algorithms and briefly describes mathematical procedures that are often implemented. To extend the general overview about ramp metering, all known algorithms were gathered and their syntax briefly described, including how they used to work.

Currently, there is only one hint about an algorithm that is in development at the moment, but nevertheless, this summary should be maintained from time to time, since its scope doubled in comparison to the last great compendiums from Bogenberger and May in 1999, or from Zhang in 2001. The research revealed that many recent implementations work with either general well-known algorithms, or regional project specific algorithms. This may be a sign of an information gap about all possibilities of ramp metering algorithms, and can be dissolved through a current and updated summary of the different strategies. A global review, including states, countries, or DOT’s would be useful. These experienced departments can be the basis for other possible research. It seems that newly implemented strategies are based on personal recommendations rather than on a standardized manual. It would be necessary to explain in a universal way how such a ramp metering system should be installed to achieve the highest possible efficiency. Especially in places where the old strategy is replaced by a new one, the DOT tries to handle the situation with the existing infrastructure. It would be necessary to explain the possible different locations of detector stations and comparison of detector devices, which vary a lot with many different advantages and possible implementations, and give standardized recommendations for a completely new ramp metering solution. In fact, there are guidelines to implement ramp metering systems, but they are not a universal tool that helps the organization to handle even the necessary details because they are mostly general explanations of how ramp metering works.

In addition to the latest overview of ramp metering that reveals the increasing use of ramp metering in the world, how efficient ramp metering performs under different environmental boundaries should be researched. Most of the evaluations were made in the US with a generally different form of acceleration lane then in other countries. The validity of the reported 20% reduction in travel time that results from ramp metering is questionable because the driver’s behavior also tends to change when there is a longer acceleration lane on test sites, which in itself causes improvement in the merging area.

The fourth block is the standardized evaluation concept. The intention was to create a scheme that helps future operators implement ramp metering on their corridors and to provide a guideline about an efficient analysis of existing systems. The intended goal has only been partially achieved because the recommendations for the individual steps
are too general and cannot cover it all. One reason for that is the underestimated scope of covered fields, or rather the whole ramp metering process, urban planning, street modeling, surveys, or economical rating methods. Each field could be researched and adjusted in its performance for the special needs of a ramp metering evaluation process. To develop such a universal tool in form of a guideline with recommendations and evaluations of all possibilities, this thesis can contribute the needed basic knowledge of ramp metering and possibly provide a brief structure for such a guide. The individual steps should be explained more in detail and be researched as to their real efficiency impact on such an evaluation.

To summarize the recommended future research the four major blocks are:

- Updated algorithm and implementation summary
- Evaluation of the ramp geometry influence
- Standardized implementation of ramp metering
- Improved standardized evaluation concept

They are based on the experience gained in compiling this thesis. There is a lack of proven and standardized recommendations that lead to inefficiently implemented and analyzed systems. The overviews provided in this thesis are a great foundation for the recommended research and can help to start this standardization process.
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