Advanced Coordinated Traffic Responsive Ramp Metering Strategies

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EXECUTIVE SUMMARY

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This report introduces different coordinated traffic responsive ramp control algorithms, implemented or not-implemented. A total of 17 different ramp metering approaches is described. For the implemented algorithms, the historical background, the network, the algorithm and the main references are described. The proposed, but not-implemented ramp control approaches are briefly described and the literature references are included. These were included in this report to provide an understanding of what is available in advanced 21st-century systems, the 'next step', currently under development in different parts of the world. Information on each algorithm and their operational history, performance, etc. was obtained through literature reviews as well as phone interviews with key persons involved in the deployment and operation of the algorithms.

Two possible directions of ramp metering for the future are qualitatively described. Based on the literature review, online simulation and fuzzy logic seem to be two very powerful approaches to control on-ramps to be considered in the future.

A freeway control system based on on-line simulation is proposed and described, <u>hierarchic</u> and <u>dynamic</u> characteristics being its unique features.

The <u>hierarchic</u> characteristics of the proposed system permit stages of development which allow each earlier stage to become an integral part of later stages. The implemented stages of development would depend upon the local situation but might include pre-timed fixed-time control, fixed-time demand-responsive control, fixed-time demand-capacity responsive control, and dynamic freeway control. Thus, it is possible for an operating agency to use the proposed freeway control system in stages of development and in accordance with local constraints.

The <u>dynamic</u> characteristics of the proposed freeway control system provide adjustments for short- and long-term changes in freeway demands, capacities, and operational conditions. Adjustments procedures range from manual adjustment for the long-term changes to automatic adjustment for both short- and long-term changes. In the automatic adjustment procedure, current and historical data are processed, and demands and capacities for the next time period are predicted. A system-wide optimization process selects the control strategy; the strategy is then

implemented. Demands, capacities, and operational conditions are continuously monitored, and if changes are detected, new control strategies are determined and implemented.

Fuzzy logic seems to be well-suited for ramp metering for several reasons. The rule base, defined as the set of rules in the fuzzy logic algorithm, incorporates human expertise. Since rules are easy to define, alter or eliminate fuzzy logic allows simple development and modification. Fuzzy logic control is especially suitable when an accurate system model is unavailable. Without question, the freeway's complexity, nonlinear nature, and non-stationary behavior makes obtaining a model extremely difficult. Most traditional controllers are only as good as the system model and usually force nonlinear systems into a linear context. Because a fuzzy controller can handle nonlinear systems with unknown models, it has a distinct advantage over traditional controllers for the ramp metering problem.

To develop a ramp metering algorithm various input data from different sources or locations could be used. It is important to gain detailed knowledge from the current traffic conditions of the controlled area. Therefore occupancy or speed/flow from different mainline detector stations could be integrated as input data. By using the bottleneck capacity-reserve downstream the possibility to create a coordinated ramp metering system and to distribute the necessary metering rate over several on-ramps exists. Also additional input data like queue length on the on-ramps, predicted traffic data or public transport information could easily be integrated into the control scheme. The output of the fuzzy control algorithm could be the specific metering rate or the cycle time for an on-ramp.

A general fuzzy logic controller for ramp metering is introduced and the three main parts, fuzzification, inference, and defuzzyfication are briefly described. After the theoretical description of the three parts of a fuzzy logic ramp metering controller a simple example is described. To overcome the conventional problems of the calibration process of fuzzy controllers an adaptive component, like a neural network or an evolutionary algorithm, could be added. Two different approaches, neuro-fuzzy control (ANFIS) and evolutionary fuzzy systems, to construct and calibrate a general fuzzy controller automatically (adaptive components) are mentioned. The result is the initial design of an adaptive fuzzy ramp metering control algorithm

The appendix includes a list of cities in the United States and abroad that have implemented ramp meters and provides estimates of the number of ramp meters currently in operation.

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Berkeley, October 1999

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ABSTRACT

This report introduces different coordinated traffic responsive ramp control algorithms, implemented or not-implemented, but based on promising new mathematical techniques. A total of 17 different ramp metering approaches is described. For the already implemented algorithms, the historical background, the network, the algorithm and the main references are described. The proposed ramp control approaches are briefly described and the literature references are included.

Two possible directions of ramp metering for the future are qualitatively described. Based on the literature review, online simulation and fuzzy logic seem to be two very powerful approaches to be considered in the future. The <u>hierarchic</u> and <u>dynamic</u> characteristics of the online simulation ramp control system are its unique features. The on-line simulation approach is designed to handle both recurring and non-recurring congestion situations. The adaptive fuzzy logic control approach allows a fast and reliable calibration of the existing parameters and the controller adapts itself to a new environment or to changes of the traffic patterns. Two different adaptive components, neuro-fuzzy systems (ANFIS) and evolutionary strategies are introduced.

KEYWORDS: Ramp Metering, Fuzzy Logic, On-line Simulation, FREQ

1.   INTRODUCTION

Ramp metering, considered in the context of traffic management systems, offers several operational features for improving freeway flow, traffic safety and air quality by the regulation of input flow to a freeway. Ramp meters are traffic signals placed on freeway entrances in an objective manner. In the "metering" mode, ramp meters operate to discharge traffic at a measured rate based on real-time conditions; thereby protecting the sensitive demand-capacity balance at the ramp merge or at a downstream bottleneck. As long as mainline traffic demand does not exceed capacity, throughput is maximized, speeds remain more uniform, and congestion related accidents are reduced.

Ramp meters also regulate the ramp traffic in order to break up platoons of vehicles that have been released from nearby signalized intersections. The mainline, even when traffic flow nears capacity, can usually accommodate merging vehicles one or two at a time. On the other hand, when platoons of vehicles attempt to force their way into the freeway traffic, this action creates turbulence that can cause the mainline flow to break down. Reduced turbulence in the merge zones also leads to reduced sideswipe and rear-end accidents that are associated with unrestricted ramp access during high volume conditions.

Ramp metering is not a very new traffic management concept. Various forms of ramp metering were used experimentally in Detroit, New York, and St. Louis in the early 1960's. In Chicago, traffic responsive ramp meters have been in operation on the Eisenhower Expressway since 1963. Eight ramp meters were installed on the Gulf Freeway in Houston in 1965 and operated successfully until freeway reconstruction caused their removal in 1975. Over 30 ramp meters were operated successfully on the North Central Expressway in Dallas from 1971 until major freeway reconstruction forced most of them to be removed in 1990. In Los Angeles, ramp metering began 1968. The system has been expanded continually until there are now about 1300 meters in operation in metropolitan Los Angeles, making it the largest system in the world. Ramp meters are currently operating in 21 metropolitan areas in the United States and also in many other parts of the world. A list of ramp metering projects in the United States and abroad is provided in the Appendix.

Metering Deployments Outside The U.S[1].:

- Britain
- Canada
- Denmark
- France
- Germany
- Japan
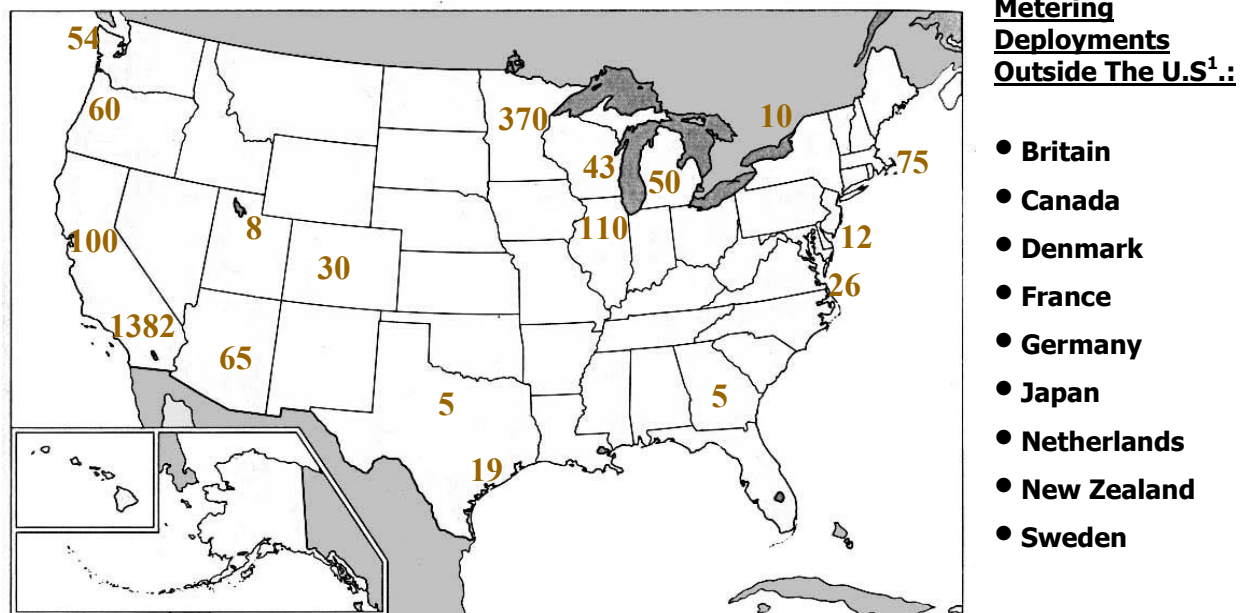- Netherlands
- New Zealand
- Sweden

Figure 1: Ramp Meter Deployments - USA

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[1] The numbers on the map indicate the number of ramp meters in operation

Historically, there have been three control approaches in developing ramp metering strategies: pretimed, local traffic responsive, and coordinated traffic responsive. Each of these three control approaches are briefly described in the following three paragraphs.

Pretimed ramp metering control was first implemented in the 1960's and continues in several locations today. A local or system-wide pretimed ramp metering plan is developed based on historical traffic information and established on a time-of-day basis. The advantage of this approach is its simplicity and the ability to develop a control plan considering a system-wide view. The disadvantage of this approach is its lack of response to current traffic conditions, either changes in demands or capacities.

Local traffic responsive control was also first implemented in the 1960's and continues in many locations today. A local traffic responsive ramp metering plan is developed based on current traffic information obtained on-line in the vicinity of the individual ramp. The advantage of this approach is its relative simplicity and the ability to develop a local control plan based on current traffic information. The disadvantage of this approach is its lack of coordination between ramps in order to work toward optimization of the freeway facility.

Coordinated traffic responsive control was first implemented in the 1970's and is gradually spreading to many freeway control systems both in the United States and abroad. A coordinated traffic responsive ramp metering plan is developed based on current traffic information but with individual ramps being metered in such a manner to work toward optimization of the freeway facility. Pretimed and/or local traffic responsive control approaches are often imbedded in the coordinated traffic responsive control approach in the event of communication and/or traffic detectors failure. An interesting new development is to enhance this form of control by adding prediction capabilities. The advantage of this approach is that it is traffic responsive and can work toward freeway facility optimization. The disadvantage is that it can become very complex and expensive to implement and maintain.

A number of coordinated traffic responsive control approaches have been proposed and implemented, and there seems to be a consensus that this is the most promising control approach for the future. However the approaches vary considerable, are limited in number, and with little implementation experience and evaluation.

This report has three objectives. The first objective is to identify and describe all coordinated traffic responsive ramp metering approaches which have been implemented (Chapter 2). The second objective is to identify and describe selected coordinated traffic responsive ramp metering approaches which have been proposed but not implemented (Chapter 3). The final objective is to propose and present two advanced-types of coordinated traffic responsive ramp metering approaches dealing with on-line simulation and adaptive fuzzy control (Chapter 4).

2. IMPLEMENTED RAMP METERING ALGORITHMS

The analysis began by examining all the algorithms that have been used worldwide, then categorizing them as coordinated local traffic responsive, locally traffic responsive or fixed-time in operation. Metering operations are currently in place in over thirty cities around the world, with a total of about 2500 individual ramps being metered on a daily basis (see Appendix).

Information on each of these algorithms and their operational history, performance, etc. was obtained through literature reviews as well as phone interviews with key persons involved in the deployment and operation of the algorithms. It should be noted that the information contained in this report is current as of August 1999. Ramp metering deployments and algorithm developments are continually being updated and changed, and it should be expected that while functional descriptions of the algorithms contained herein will remain valid, deployment and operational information regarding specific locations will require periodic updates.

The next step of the analysis was to identify those implemented metering algorithms that have or are utilizing some form of coordinated traffic responsive control. This narrowed the list of candidate algorithms to the ten presented in this section of the report.

2.1. ZONE ALGORITHM

Minneapolis/St. Paul, Minnesota

2.1.1. Background and Experience

Ramp metering was introduced in the Minneapolis/St. Paul area along I-35 East in 1970. These first meters were initially controlled with time-of-day metering programming, then converted soon thereafter to local traffic responsive control. The metering system has been periodically evaluated and continues to show improvements in freeway traffic operations.

By 1974, a second ramp metering system was installed along a 27 kilometer section of I-35 West, including 39 ramp meters, 16 closed circuit television cameras (CCTV), 380 roadway detectors, and a computer control monitor at the MnDOT traffic management center. After ten years of operation, comprehensive evaluations showed increased freeway speeds and reduced freeway accidents and air pollution.

Over 300 additional ramp meters have been deployed between 1988 to 1995, bringing the current total to almost 400 meters in the Minneapolis/St. Paul area. Over the next five years, plans are to install meters along the remainder of the Twin Cities freeway network.

Keys to the success of the Twin Cities metering system are its staged implementation on a segment-by-segment and freeway-by-freeway basis over time, strict attention to bus priority and priority entry control and freeway-to-freeway connector metering.
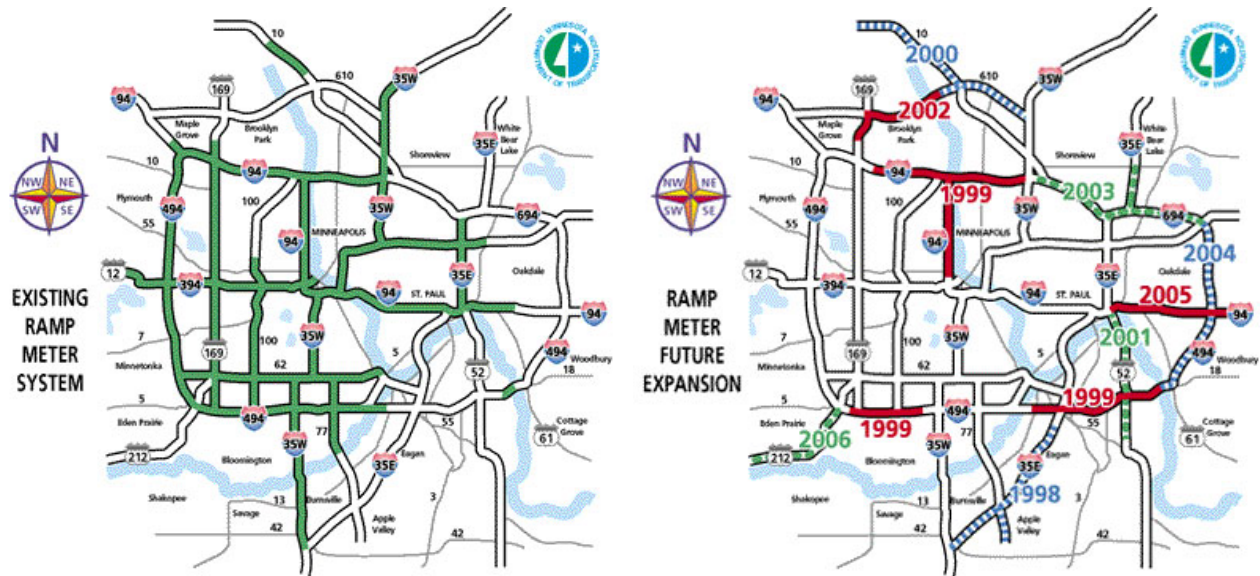
Figure 2: Metering Deployment In The Twin Cities Region

Source: http://www.dot.state.mn.us/tmc/program/ramp.fhtml

2.1.2. Algorithm Description

This algorithm defines directional freeway facility 'metering zones' with zones having variable lengths of three to six miles. The upstream end of a zone is usually a free-flow area not subject to high incident rates. The downstream end of a zone is usually a critical bottleneck, where the demand-to-capacity ratio is highest, such as lane drops, high-volume entrance ramps and high-volume weaving sections. A zone may contain several metered entrance ramps, exit ramps, and possibly one or more unmetered entrance ramps.

The basic concept of the algorithm is to balance the volume of traffic entering and leaving each zone. All entering and exiting traffic volumes on both the mainline and the ramps are measured in 30-second increments, and balancing these total volumes is used to keep the density of traffic within the zone constant. Based on the density of traffic in the zone, the space available for entering traffic is calculated. The metering zone equation can be expressed as:

$$[A + U + M + F = X + B + S]$$

A =   Upstream mainline volume (measured)
U =   Sum of unmetered entrance ramp volumes (measured)
M =   Sum of metered ramp volumes (controlled)
F =   Sum of metered freeway to freeway ramp volumes (controlled)
X =   Sum of exit ramp volumes (measured)
B =   Downstream bottleneck capacity (constant – usually 2220 vehicles per hour per lane)
S =   Space available within the zone (computed volume based on measured variables

Setting (S) equal to zero and rearranging the equation, the maximum volume that can enter the system within the zone at local and freeway-to-freeway ramps becomes:

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

Stored historical volumes are available to the system to account for detector failures in determining (X, A, or U). The metering rate for each metered local and freeway-to-freeway ramp is determined from the (M + F) value and the individual ramp factors. These ramp factors are pre-defined by the system users for each metered location, defining ramp priority at each site to control the split of available metered volume. Every

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meter has six distinct metering rates, varying from no metering to a cycle length of 24 seconds. All green times are fixed at 1.3 seconds and all yellow times are fixed at 0.7 seconds.

The algorithm also incorporates occupancy detection along the roadway within each zone to account for localized congestion and queuing due to incidents, weather, construction, etc. Based on the measured occupancy at each detector site, metering rates within the zone are adjusted to account for localized traffic conditions.

References

1. "Trunk Highway 169 Dynamic Ramp Metering Evaluation", Research Report 1998-14, Minnesota Department of Transportation, 1998.

2. "Ramp up the Volume: Sophisticated Ramp Metering Techniques Promise to Alleviate Highway Congestion in Minnesota", ITS International, Issue No. 13, November-December 1997.

3. "Ramp Metering by Zone - The Minnesota Algorithm", Richard Lau, Minnesota Department of Transportation, Revised in June 1997.

4. "Ramp Metering for the 21st Century: Minnesota's Experience", Nick Thompson, Selvin Greene, ITS America 7th Annual Meeting, April 1997.

5. "Implementation of on-line Zone Control Strategies for optimal Ramp Metering in the Minneapolis Ring Road", Yorgos Stephanedes, 7th International Conference on Road Traffic Monitoring and Control, 1994.

6. WWW Resource; http://www.dot.state.mn.us/tmc/program/index.fhtml

2.2.   HELPER RAMP ALGORITHM

Denver, Colorado

2.2.1.   Background And Experience

Ramp metering was introduced in the Denver area along the I-25 freeway in March 1981. The initial deployment consisted of five local traffic responsive metered ramps. This pilot project was considered successful and additional ramp meters were installed along several freeways in the Denver area in 1984. As part of this secondary deployment, a computer control system was built to allow centralized monitoring and override control for all the metering locations.

A comprehensive evaluation of this coordinated traffic responsive system was conducted in 1988 and 1989. The results showed that if the local traffic responsive algorithm could maintain a mainline speed of 90 km/hr or more, centralized control had little or no benefit. However, when speeds were less than 90 km/hr, centralized control was found to be very effective in reducing congestion. There have been some minor adjustments, but no major changes, in the ramp metering system and its control algorithm during the past ten years.
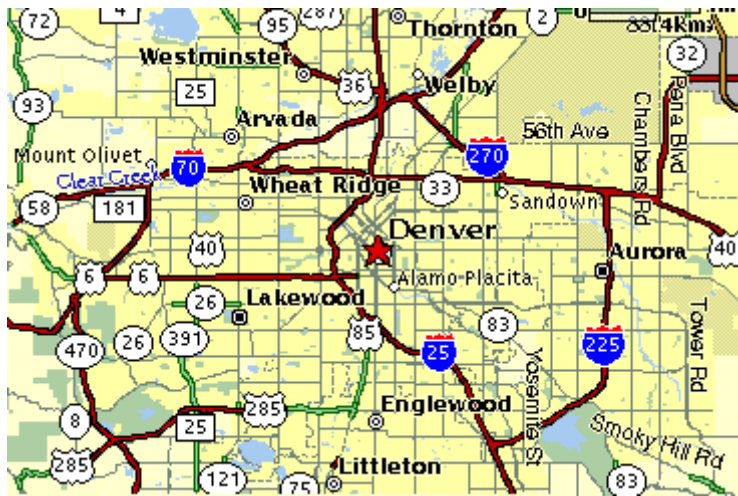
Figure 3: Map of the Denver Metropolitan Area

Source: http://www.mapquest.com

Thirty-one ramp meters were in operation by 1998, when it was announced that an expanded traffic operations center was being planned which included upgrading the computer control system and communications used for metering support. However, there are no current plans to significantly modify the existing metering algorithm.

2.2.2. Algorithm Description

The Denver algorithm consists of a local traffic responsive metering algorithm combined with a centralized coordinated operational override feature. The ramps being controlled are divided into six location groups (or zones), with one to seven ramp meters assigned to each group. Metering is permitted only during the weekday peak periods with freeway traffic conditions monitored by the central computer to adjust the starting and ending of metering operation as needed.

Within the local responsive algorithm, each meter selects one of six available metering rates based on localized upstream mainline occupancy. Ramp presence and passage detectors are used to detect vehicles waiting and clearing the ramp signals. Ramp queue detection is also used, increasing the metering rate one level per time interval (as required) to clear excessive ramp queues. The algorithm also incorporates an exponential smoothing function to prevent wide swings in metering rates during concurrent time intervals.

At the coordinated control level, the central computer monitors and collects detector and metering data from each ramp controller every 20 seconds (metering time interval). So long as a meter is not operating at its most restrictive metering rate and the ramp queue detector is not exceeding its threshold occupancy value, the ramp is classified as not critical. If a meter is operating at its most restrictive metering rate and/or the ramp queue detector is exceeding its threshold occupancy value, the ramp is classified as critical.

When a ramp is classified as critical, the centralized algorithm immediately begins to override upstream ramp control. If a ramp remains critical for three consecutive time intervals, the central computer reduces the metering rate at the next upstream ramp by one metering rate level. If the ramp remains critical, the process moves upstream at a rate of one ramp per time interval until the problem is either remedied or all upstream ramps within the location group have been overridden. If more restrictive ramp control is still required once all ramps in the group are overridden, the metering rates at ramps in the next upstream location group(s) are then reduced. This coordinated control state continues until all ramps return to the not critical state, when the ramps revert to local control in the opposite order in which they were overridden, one ramp per time interval.

References

1. "Benefits of Central Computer Control for the Denver Ramp Metering System", Louis Lipp, Lawrence Corcoran, and Gordon Hickman, Transportation Research Board Record 1320, January 1991.

2. "Freeway Ramp Metering Effects in Denver", Corcoran, Lawrence and Gordon Hickman, 59th Annual Meeting of the Institute of Transportation Engineers, San Diego, Compendium of Technical Papers, 1989.

3. "I-25 Ramp Metering: Final Evaluation Report", Colorado Department of Transportation, District VI, November 1983.

4. "Ramp Metering Computer Control System: Software Functional Description", JHK and Associates, 1982.

5. "Bay Area Traffic Operations System – Ramp Metering Algorithm Report"; JHK and Associates, 1989.

2.3.   BOTTLENECK ALGORITHM

Seattle, Washington

2.3.1.   Background and Experience

Beginning in 1981, the Washington Department of Transportation (WDOT) implemented metering with the bottleneck algorithm on I-5, north of the Seattle central business district. A six-year evaluation study was then undertaken, consisting of seventeen southbound ramps during the AM peak and five northbound during the PM peak along a 6.9-mile test corridor.

Over the study period, travel time dropped from 22 minutes before metering to 11.5 minutes after, despite higher volumes (mainline volumes increased over 86% northbound and 62% southbound). The accident rate dropped about 39%, and average metering delays at each ramp remained at or below three minutes.
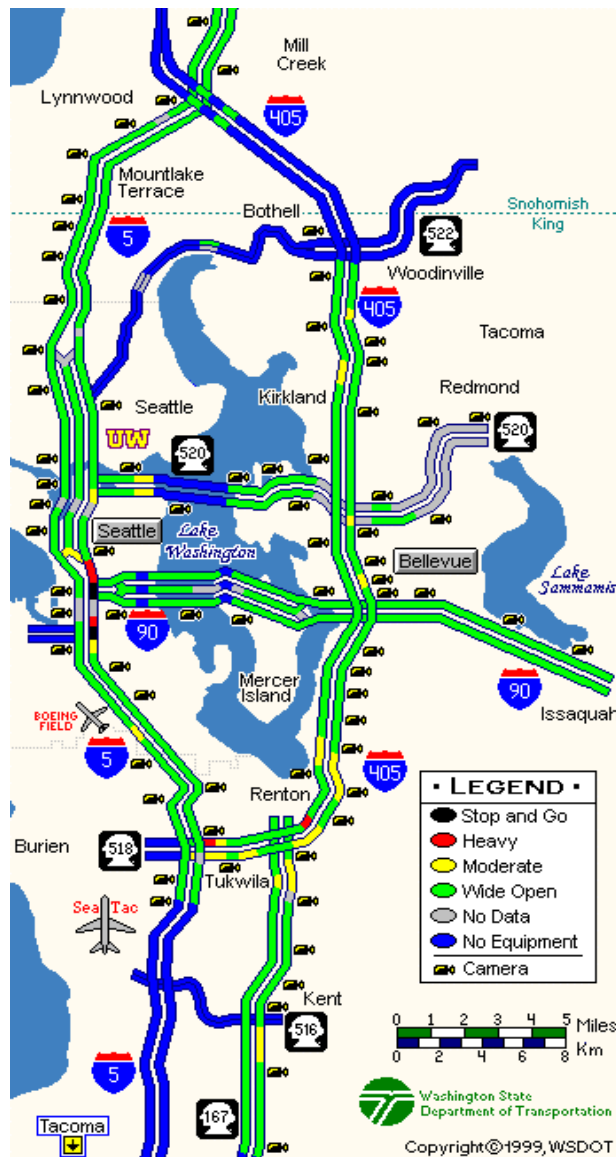
Figure 4: Map of the Seattle Freeway Network

Source: *http://www.wsdot.wa.gov/PugetSoundTraffic/cameras/*

2.3.2. Algorithm Description

The Seattle Bottleneck metering algorithm is described as one of the most sophisticated in the country due to the presence of several internal adjustments, including a volume reduction based on downstream bottlenecks and localized adjustments such as queue override. The system currently uses local responsive detector data (upstream occupancy) at each ramp, as well as bottleneck data, to determine both a local metering rate and a bottleneck metering rate. The more restrictive of the two rates is then implemented at each ramp.
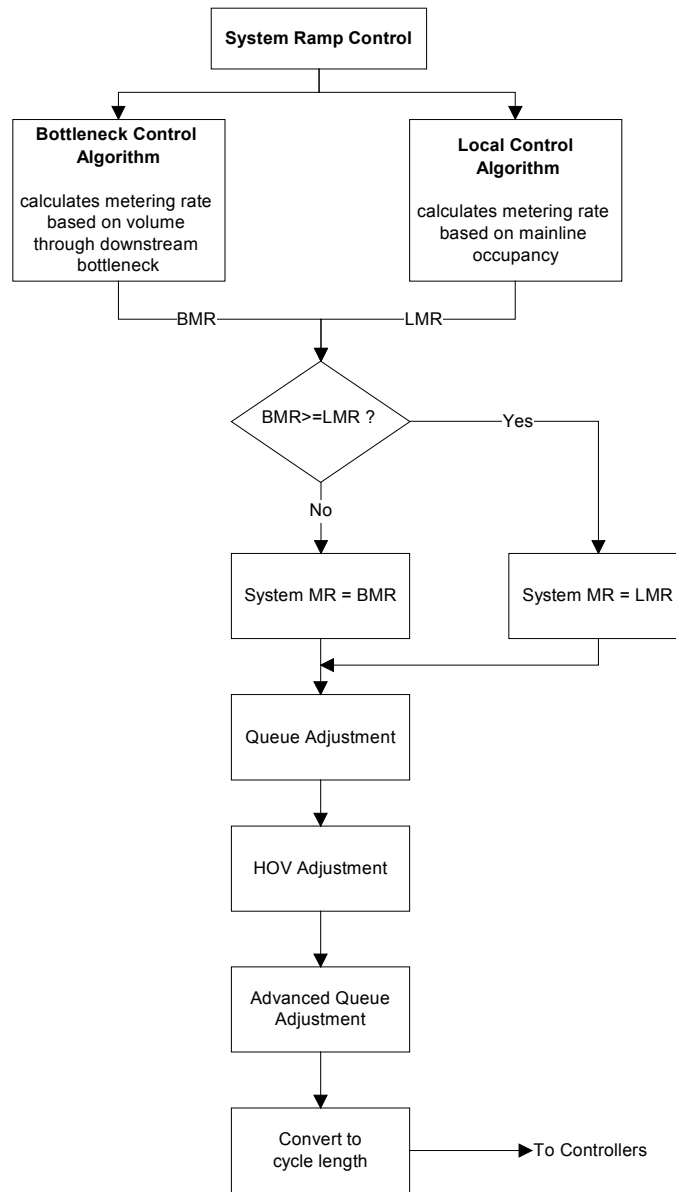
Figure 5: Bottleneck Algorithm Operational Flow Chart

At the local level, historical data is used to determine approximate volume-occupancy relationships near capacity for each ramp location. Local metering rates are then calculated to allow ramp volumes to equal the difference between the estimated capacity and the real-time upstream volume.

The coordinated Bottleneck algorithm is activated when the following two criteria are met: 1) A downstream bottleneck-prone section surpasses a pre-determined occupancy threshold, and 2) The 'zone' or area of influence upstream of the bottleneck is storing vehicles. The algorithm then uses centrally assigned metering rate reductions applied to meters in the zone to reduce the number of vehicles entering the mainline by the number of vehicles stored in the bottleneck area of influence.

After selecting the more restrictive of the local and bottleneck metering rates, the algorithm further adjusts the rate based on detected and physical conditions at each site. Each ramp has both queue and advanced queue detection to prevent spillback onto the arterial street network. Metering rates are increased when the occupancy on a ramp exceeds a predetermined threshold for a specified duration, with the increase based on whether occupancy or duration is exceeded. High occupancy vehicle (HOV) adjustment accounts for the

difference between the number of cars targeted for freeway entry and the actual number of cars that enter, as HOV lanes are typically not metered. The same adjustment takes place to account for violators as well.

References

1. "Real-Time Metering Algorithm for Centralized Control", Leslie Jacobsen, Kim Henry, Omar Mahyar, Transportation Research Record 1232, TRB, 1989.

2. WWW Resource, http://www.wsdot.wa.gov/

2.4. SPERRY RAMP METERING ALGORITHM

Arlington, Virginia

2.4.1. Background and Experience

The Virginia Department of Transportation installed 26 ramp meters along I-395 and I-66 in northern Virginia during 1985. No future expansion of this system is currently planned, though some meter foundations and conduits are being replaced as part of a major freeway reconstruction project in the area.
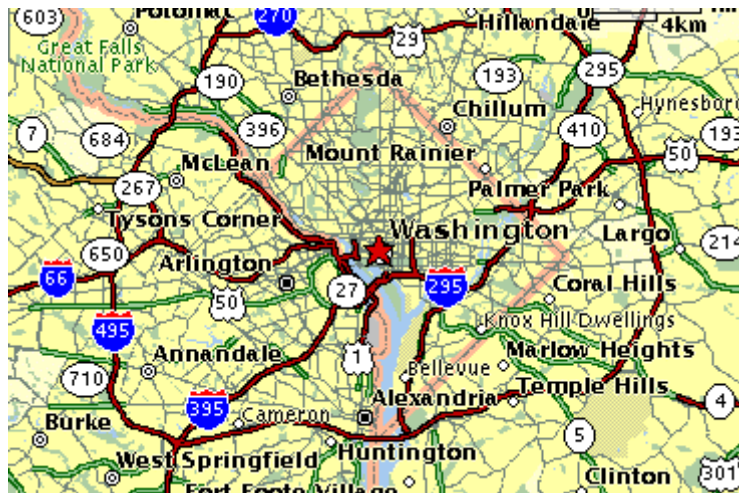
Figure 6: Map of the Northern Virginia / D.C. Freeway Network

Source: http://www.mapquest.com

2.4.2. Algorithm Description

The Sperry algorithm defines two basic modes of entrance ramp control: 1) non-restrictive metering and 2) restrictive metering. Non-restrictive metering is when the ramp queue detector indicates a spillback into the arterial network, causing the metering rate to be increased until the spillback is contained. Restrictive metering is the default state which occurs whenever freeway traffic conditions warrant and a ramp spillback does not occur. The restrictive mode utilizes an automatic coordinated traffic responsive metering scheme with system operator override available. This algorithm is essentially a demand-capacity equation, attempting to keep centralized demand below capacity at each detector station. The objective is to maximize freeway vehicle-miles of travel with some adjustments for 'fair-play' between ramps.

The system divides the directional freeway facilities into control sections, comprised of several contiguous entrance and exit ramps where at least some of these ramps are metered. Each section contains up to ten individual ramp meters.

The system uses traffic counts at each entrance and exit to a ramp metering control section as input data, as well as pre-defined mainline capacities for each mainline detector station. The traffic counts are adjusted to attempt to represent traffic demands in the next time interval, while the capacity values are adjusted for weather conditions.

Algorithm implementation begins with the entrance ramp furthest downstream in the section, where a metering rate is obtained either by subtracting its associated mainline capacity from its expected mainline demand or by using the minimum metering rate for that site, whichever is larger. This process then continues upstream, one ramp at a time.

The algorithm also contains several specialized features.

- If a ramp is manually overridden, the automatic algorithm will adjust the upstream ramp rates within the section appropriately.

- Whenever possible, ramp metering rates are set slightly lower than required to provide a higher level of service (LOS) on the mainline.

- The algorithm can adjust the expected freeway demand factor at various ramps to reflect expected vehicle-count changes due to variable message sign messages.

- A concept referred to as 'continuous staging' has been introduced for more accurate implementation of metering rates based on predicted flows at downstream ramp locations. This prevents pre-mature implementation of restrictive metering rates prior to the arrival of predicted flow volumes.

One negative aspect of the algorithm is that it uses only volumes and capacities in its calculations. No mention is made of introducing occupancy, density, or speed as measured or calculated algorithm variables.

References

1. "Guidelines for Entrance Ramp Metering", Virginia Department of Transportation, undated.

2. "Ramp Metering Algorithm Description", Virginia Department of Transportation, undated.

3. "Ramp Metering: A Review of the Literature", E. D. Arnold, Virginia Transportation Research Council, 1998.

2.5. COMPASS ALGORITHM

Toronto, Canada

2.5.1. Background and Experience

Ramp metering was introduced in the Toronto area in 1975. There are currently ten ramp meters in operation along the inbound Queen Elizabeth Way (QEW). The ramp meters can be operated as an automatic coordinated traffic responsive ramp metering system or can be controlled manually from the traffic control center. This current system includes 50 detector stations and 18 cameras over 19 kilometers. Detector stations have been upgraded from 170 controllers to Ontario's ATC controllers.

Feasibility plans are currently underway for expanding the current QEW system to 43 ramps. Feasibility studies for 54 meters along Highway 401 are also expected to begin soon.

Figure 7: Map of the Toronto Area Freeway Network

Source: http://www.mapquest.com

2.5.2. Algorithm Description

The manual control feature of the system allows the selection of up to seventeen different metering rates for each ramp, with cycle lengths ranging from 0 to 15 seconds. The system also allows for automated coordinated traffic responsive metering control. In this mode, the control algorithm selects a metering rate for each ramp based on both the overall traffic flow along the freeway and the local freeway traffic condition at the individual ramps. The four major elements of the automatic metering algorithm are control section, control period, control algorithm and queue override.

Control sections correspond to segments of directional freeway that maintain a common influence at a point downstream. The purpose of the control section is to define the location of decision variables for each entrance ramp control strategy, as well as grouping individual ramps which are to be coordinated.

Control periods tell the system when to activate and deactivate automatic metering control. There are five distinct control periods that may be assigned to meter controllers:

- In period zero, all ramp signals should be resting on green;
- In period one, a ramp meter will be turned on only if real-time mainline detector data exceeds the lowest volume or occupancy threshold value;
- In period two, all entrance ramps should be available for coordinated ramp metered control;
- In period three, a ramp will be turned off as mainline traffic flow drops off;
- In period four, all ramps can be metered by the time of day schedule.

The actual metering rate calculations are run every 30 seconds. Three decision variables are measured to select the appropriate rate: 1) local mainline occupancy, 2) downstream mainline occupancy, and 3) upstream mainline volume. These values are used for determining the local ramp metering rate from a look-up table, which contains thresholds for occupancies (local and downstream) and volume (upstream), as well as the associated offline optimized rate. If multiple metering rates are determined from this table based on the different measured variables, the most restrictive one is implemented.

This algorithm also incorporates queue spillback detection. If the occupancy at a ramp queue detector exceeds its threshold value, the metering rate for that location is increased by one rate level and is maintained until the detected occupancy is back below the threshold level.

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References

1. "Mississauga FTMS System - Ramp Metering Algorithm", Ontario Ministry of Transportation, undated.

2. WWW Resource: http://www.mto.gov.on.ca/english/index.html

2.6. FUZZY LOGIC ALGORITHM

Seattle, Washington / Zoetermeer, Netherlands

2.6.1. Background and Experience

Seattle, Washington

A ramp metering algorithm incorporating 'fuzzy logic' decision support has been under development at the University of Washington for a number of years. This algorithm was installed in early 1999 by WsDOT, controlling 15 metered ramps along I-405. Early evaluation results have shown such improved operation in comparison with the more traditional Seattle Bottleneck algorithm that the entire I-405 network has recently been converted to fuzzy logic control (55 meters).
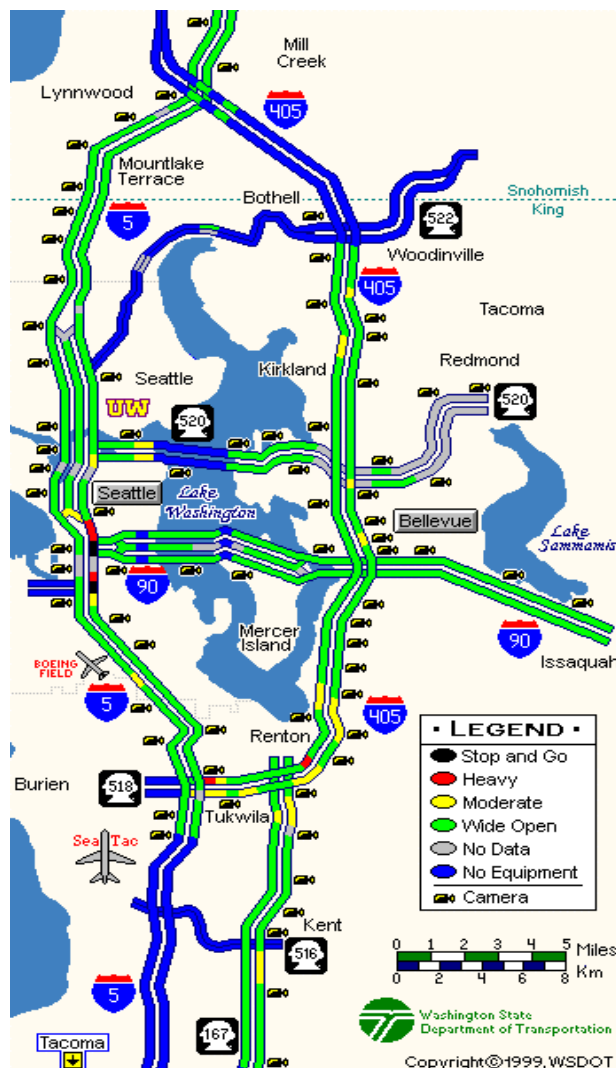
Zoetermeer, Netherlands

Fuzzy logic metering was first initiated in 1989, with nine operating meter locations by 1995. Evaluation of the system focused on the A12 freeway between Utrecht and Hague, and showed a 3% increase in bottleneck within the 11 km study area. Other results included higher speeds during congested periods and shorter travel times. Although ramp delay increased, system wide effects were positive.

On one ramp along the A12 near Zoetermeer, Netherlands, three different local metering algorithms (RWS strategy [Dutch version of US demand-capacity strategy], ALINEA and Fuzzy-Logic) were implemented and evaluated. The results of the assessment showed that fuzzy logic out-performed the other two.

2.6.2. Algorithm Description

The algorithm, based on fuzzy set theory, is designed to overcome some of the limitations of existing conventional ramp metering systems. In a simulation based evaluation using FRESIM and a model of the Seattle I-5 corridor, the fuzzy controller demonstrated improved robustness, prevented heavy congestion, intelligently balanced conflicting needs, and tuned easily. The objective was to maximize total distance traveled, minimize total travel time and vehicle delay, and still maintain acceptable ramp queues. This algorithm functions on two levels, as with many of the metering algorithms available, providing both local and downstream bottleneck metering rate selection.
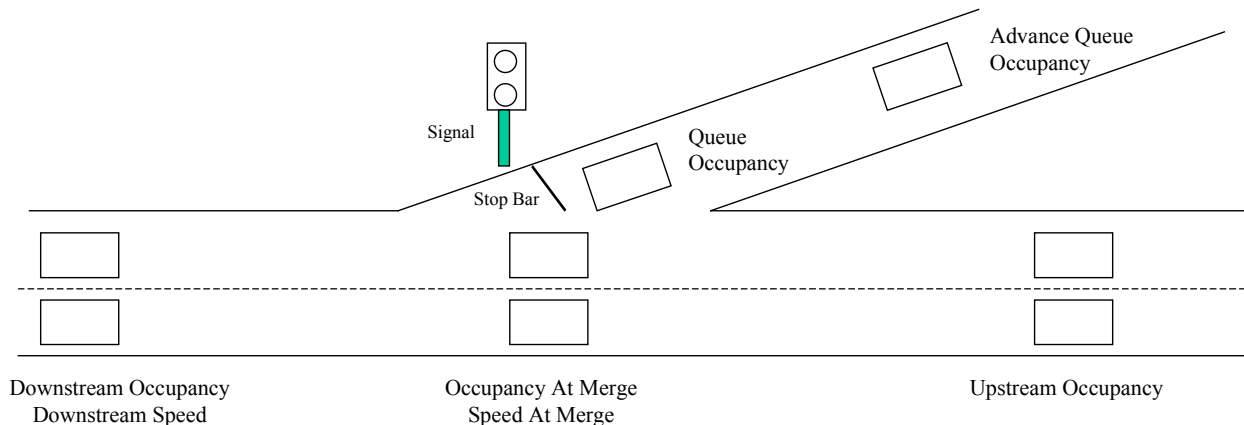
Figure 9: Fuzzy Logic Algorithm - Detector Layout and Data Requirements

The algorithm uses seven inputs measured at 20-second intervals (except for ramp occupancy) as shown in Figure 9 above. The fuzzy logic process takes these 'crisp' measured (detected) values and bins them into one of 5 different textual classes (fuzzification) based on their value – *very small, small, medium, big, and very big* – and assigns them a degree of membership within the class. These 'fuzzified' inputs are then run through a rule-base (IF – THEN rules), or set of textual rules that determine control actions. For example, the following could be a rule for a given metering deployment:

[IF *very small* AND *bottleneck* THEN *high metering rate*]

The textual control actions determined to apply from these rules are then subjected to 'Defuzzyfication' to produce real-number metering rates. The fuzzy-logic process is graphically represented in Figure 10.
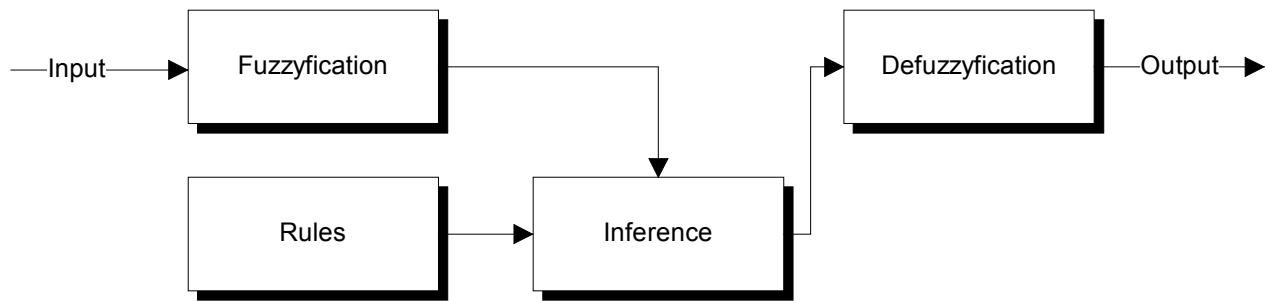
Figure 10: Fuzzy Logic Operation

References

Seattle, Washington

1.   "Fuzzy Ramp Metering - Design Overview and Simulation Results", Cynthia Taylor, Diedre Meldrum, Les Jacobson, Transportation Research Record 1634, Washington 1998

2.   "Freeway Traffic Data Prediction using Artificial Neural Networks and Development of a Fuzzy Logic Ramp Metering Algorithm", Diedre Meldrum, Cynthia Taylor; Final Technical Report, Washington State Department of Transportation Report No. WA-RD 365.1, Washington 1995

3.   WWW Resource: http://isdl.ee.washington.edu/GNL/Cyndi/blurb.html

Zoetermeer, Netherlands

1.   "The Assessment of Ramp Metering Based on Fuzzy Logic", Hank Taale, Jan Slager, Jeroen Rosloot, 3rd ITS World Congress in Orlando, 1996.

2.7.   LINEAR PROGRAMMING ALGORITHM

Kobe, Japan

2.7.1.   Background and Experience

A freeway traffic control system has been in place on the Hanshin Expressway near Kobe, Japan since 1970. Evaluations of the system show continued improvement in performance since that time. One of the primary features of this system is the ramp metering algorithm is supported by detector stations every 500 meters along the mainline and at all exit and entrance ramps within the system.

Figure 11: The Hanshin Expressway Between Kobe and Osaka, Japan

Source: http://www.mapquest.com

2.7.2. Algorithm Description

The Hanshin algorithm is based on Linear Programming formulation, identifying an objective function to maximize/minimize and a series of constraints to work within while optimizing this function. The algorithm requires a very comprehensive data collection system with detectors closely spaced on the mainline and multi-point detection on all exit/entrance ramps.

To solve for metering rates, the algorithm uses both real-time and pre-defined system variables as well a number of tuneable parameters and weighting factors for a series of ramps. These variables and parameter values populate the objective and constraint equations which are then solved simultaneously to find an optimal metered flow value for all ramp locations. While mathematically complex, the process is easily supported by any number of off-the-shelf and even shareware software programs capable of solving thousands of constraint equations simultaneously. This means that segments of roadway to be optimized may be as long or short and contain as many metered and unmetered ramps as desired by the controlling agency.

The operation of the algorithm is based on the following steps:

1. The roadway is divided into segments (h) between ramps (i).

2. Detection of speed (Y_h) for each section is used to calculate the real-time capacity reduction due to congestion, and thus to find the real-time capacity (C_h) for each roadway section.

3. Ramp detection determines queue length (N_i), while advance queue detection or historical O&D information is used to measure or pre-define ramp demand (D_i). These values are expressed as volume, as with the capacity terms above.

4. Maximum allowable queue lengths for each ramp (L_i) are pre-defined for all ramp locations based on the storage capacity of the ramp.

5. Using historical O&D information, a tuneable influence factor (Q_{hi}) is pre-defined for each unique combination of ramp inflow and downstream segment. This factor is a weight that scales the amount of traffic from ramp (i) remaining on the mainline at a downstream segment (h). This is equivalent to producing a downstream flow profile for the area of influence at each ramp.

6. A tuneable weighting factor (A) is pre-defined for each ramp as part of the objective function to allow for weighting ramp inflows. This weighting factor is used to give preference to or discourage the use of specific ramps in the system.

7. The objective function is then maximized for ramp flow at each ramp (Ui) and becomes:

$$[Z = (A1*U1) + (A2*U2) + ... + (Ai*Ui)]$$

This function is subject to the following operational constraints:

[(Qmain*Ui) + (Q1h*U1) + (Q2h*U2) + ... + (Qih*Ui) <= Ch] for all segments (h).

[0 <= Ui <= Ni + Di] or, ramp demand plus ramp queue must be less than or equal to the ramp flow rate.

[Ni + Di - Ui <= Li] or, ramp queue plus ramp demand minus ramp flow must be less than or equal to the maximum queue length.

[Umin <= Ui <= Umax] or, the metering rate must be between the maximum and minimum values.

The LP equations are solved simultaneously for all meter locations within an area of influence, maximizing the metering rates for all meters as defined above. This interaction at the variable level is the defining coordination characteristic of the algorithm - no other direct communication between ramps occurs. In operation, this linear programming model functions identically to the FREQ internal optimization model.

References

1. "The Traffic Control System on the Hanshin Expressway"; Tsuyoshi Yoshino, Tsuna Sasaki, Toshiharu Hasegawa; Interfaces Magazine, Jan/Feb. 1995.

2. "Dynamic Traffic Control System for Urban Expressway with Constraint of Off-Ramp Queue Length"; Xiao-Guag Yang, Yasanori Iida, Nobuhiro Uno, Pi-Yun Yang; ITS World Conference Proceedings, Seoul 1996.

2.8.   LINKED-RAMP ALGORITHM

San Diego, California

2.8.1.   Background and Experience

Ramp metering in the San Diego area began in 1968. Currently, the California Department of Transportation (Caltrans) District 11 operates approximately 240 ramp meters in San Diego County along some 200 miles of both interstate and state highways. Before 1994, this system was partially coordinated, with communication between meter locations upstream of known bottlenecks. Though this system was deemed an operational success, it was de-centralized in 1994 as part of the Caltrans statewide ATMS computer upgrade project. Since that time, all meters have been operating as local traffic responsive controllers.
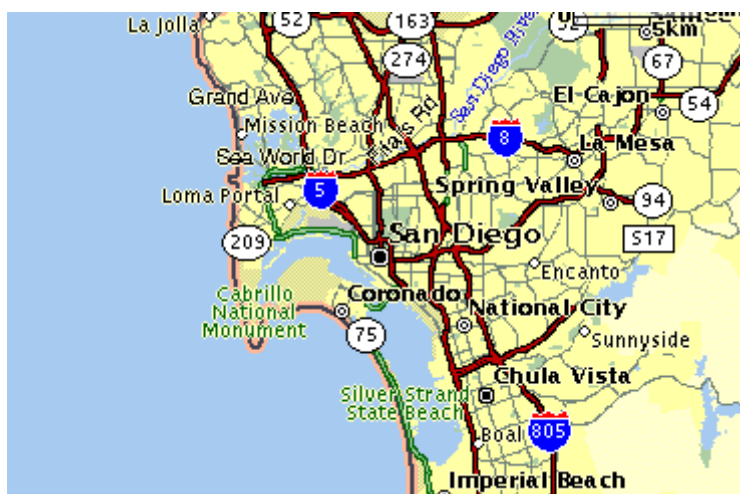
Figure 12: The Caltrans District 11 (San Diego Area) Freeway Network

Source: http://www.mapquest.com

2.8.2. Algorithm Description

The operation of the San Diego Ramp Metering System (SDRMS) is based on demand-capacity theory. To configure the SDRMS, the capacity of each segment of roadway is assigned to all influencing upstream ramps and the mainline itself, using O&D and historical ramp flow information. This capacity distribution becomes the maximum possible metered flow allowed from each ramp. The distribution may not be equally divided at all ramps, as usage/demand, ramp storage and queue spillback impacts must be taken into consideration.

Using the same physical constraints (ramp storage, demand, etc.), a minimum allowable metered flow is also developed for each ramp. A flow profile is then constructed for each segment of the mainline using historical peak period mainline flows and minimum ramp metering rate flows. This flow profile creates a target flow rate for each segment.

The SDRMS uses a 16-level metering rate system, where meter rates are linearly distributed between the maximum and minimum rates identified above. The highest rate (Rate 0), one level up from the maximum metered rate, is a green-rest (free-flow) for the meter. Determination of which of the discharge rates to use for a given ramp is local responsive, based on measurement of the flow upstream of each location. The rate which most closely matches the required meter flow is then implemented. The Demand Capacity theory represents this relationship as the following:

[Metering Rate = Target Flow Rate – Upstream Flow Rate]

If the upstream flow is greater than the target flow, the controller defaults to the minimum metering rate. This should not happen frequently however, as the target flow is to represent the maximum peak-period flow on the mainline. The SDRMS also incorporates an upstream occupancy measurement into meter rate determination for each ramp. Using Occupancy allows the algorithm to correct for measured low flows occurring in heavy congestion. The most restrictive of the two calculations is then implemented.

The multi-ramp coordination element of this algorithm is functionally similar to the 'Helper' system seen in the Denver metering algorithm, where a link between meters exists for each bottleneck area of influence. Whenever a ramp drops into one of its lowest three metering rates, the system signals the next upstream ramp and requires it to begin metering at the same rate or less. Each time interval thereafter (or after some other pre-programmed time delay) the situation is re-evaluated and if necessary the metering rate restriction/override is propagated upstream to the next ramp, and the next, etc. – even moving into the

next metering area of influence if necessary. These ramps remain constrained until either all linked meters are operating at or below the initial metering rate, or the problem is cleared.

References

1.   Notes on San Diego Ramp Metering System operations, From Don Day, Caltrans District 11.

2.   "Effect of Response Limitations on Traffic-Responsive Ramp Metering", James Banks, TRB Record 1394, 1993.

3.   "Evaluation of The Two-Capacity Phenomenon As A Basis For Ramp Metering", James Banks, December 1990.

4.   "The History of Ramp Metering In California", S.H. Harvey, Caltrans District 11, July 1990.

2.9.   METALINE ALGORITHM

Paris, France / Milwaukee, Wisconsin / Amsterdam, Netherlands

2.9.1. Background and Experience

Paris, France

In 1990 and early 1991, METALINE and ALINEA (local traffic responsive algorithm upon which METALINE is based) were both applied on three on-ramps of the internal (westbound) Boulevard Périphérique. The study area was 6 km of freeway, including the three metered ramps and two non-metered ramps. The morning peak-period was studied for 10 days using each algorithm, with results showing mainline speeds increasing for both. This 10-day study remains the only field implementation of METALINE in the Paris area.
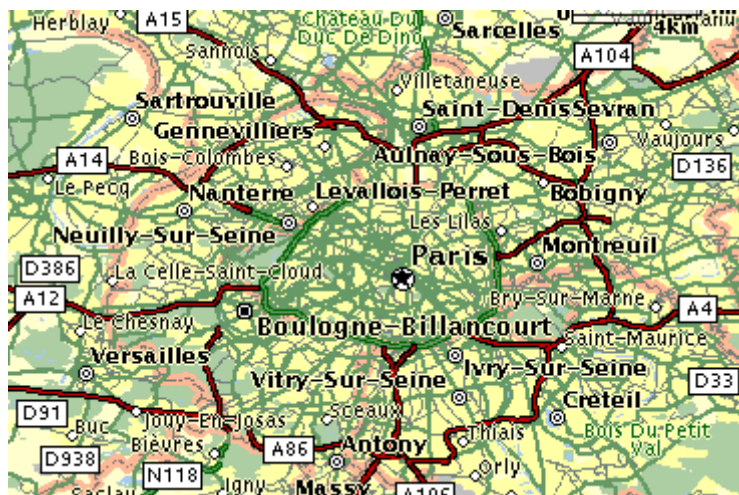
Figure 13: Map of the Paris Freeway Network

Source: http://www.mapquest.com

Milwaukee, Wisconsin

The first three ramp meters in Milwaukee were installed in 1969. In 1994 and 1995, an additional 34 meters were installed. Seven ramps have HOV-bypass lanes and all are operating under centralized control. In 1997 METALINE was implemented, and while field evaluations showed it to be successful, it was discontinued shortly after its deployment. Current operations in the Milwaukee area include 43 local traffic responsive ramp

meters installed on five different freeways (I-94, I-43, I-894, I-794 and US 45). Plans exist to expand this system as it currently operates to a total of 60 metered ramps.

Figure 14: Map of the Milwaukee Freeway Network

Source: http://www.mapquest.com

Netherlands, Amsterdam

In 1989 the first ramp metering system in the Netherlands was installed near the Coentunnel of the A-10 West ringroad around Amsterdam. Due to the good performance of this system, two other deployments were implemented (Delft, Zoetermeer). In June 1994 three other local responsive metering systems also become operational on A-10. A field comparison of METALINE with the Dutch RWS-Strategy (European demand-capacity theory) and ALINEA has been planned, and while METALINE was tested by simulation for this purpose, its field implementation and assessment have been delayed for organizational reasons.

Figure 15: Map of Freeway Network Around Amsterdam, Netherlands

Source: http://www.mapquest.com

2.9.2. Algorithm Description

METALINE is a coordinated generalization (using lists of multiple values, or columnar vectors, in place of single values) of ALINEA whereby ramp metering rates are calculated from the following equation:

20

$$[\ r(k) = r(k-1) - K_1\{ \ o(k) - o(k-1) \ \} - K_2\{ \ O(k) - O^c \ \} \ ]$$

where:

r $\quad = [r_1 \ ... \ r_m]^T$ is the vector of m controllable on-ramps metering rate values [at time k or k-1]

k $\quad$ = Current time interval

o $\quad = [o_1 \ ... \ o_n]^T$ is the vector of n measured occupancies within the directional freeway segment [all occupancies desired within the defined coordination segment]

O $\quad = [O_1 \ ... \ O_m]^T$ is the vector of m measured occupancies downstream of the desired ramps (note: O is a subset of o) [occupancies at any locations within the segment desired for use in calculating meter rates, such as bottlenecks]

O^c $\quad = [O^c_1 \ ... \ O^c_m]$is the vector of m corresponding capacity values [occupancies at capacity for all locations defined in the O vector]

$K_1 \in R^{\ mxn}, K_2 \in R^{\ nxn}$ $\quad$ = Two gain matrices [tunable weighting factors for each ramp location defined by r vectors]

With this approach, the metering rate for a particular on-ramp may be calculated using mainline data from a variety of locations. The K_1 matrix factors are used to tune the sensitivity of each ramp location to the various detector occupancies reported in the (o) vector. The K_2 matrix factors are used to tune the contribution of the critical detectors to the ramp meter rates at each meter. As (n) and (m) values are required in these vectors to make the equation mathematically correct, zeros may be used whenever detector occupancies are used which have little or no impact of specific ramp locations. As not all detectors impact all meters, and as the number of critical detectors is often small, the two matrices will generally be small.

This algorithm incorporates a smoothing feature from the ALINEA algorithm, preventing wide swings in metering rates between concurrent time intervals by incorporating the previous metering rate into the equation for calculating the next time interval metering rate. The sensitivity of this algorithm is also quite high, as it responds to the change in occupancy between time intervals, rather than the overall occupancy of the system, allowing more responsive operation for smaller changes in traffic flow.

The algorithm performance can be adjusted via the weights in the matrices, though tuning these weights to optimal values can be a difficult process. As a whole, the algorithm responds quickly to any change in traffic flow within the system.

References

Paris

1. "ALINEA Local Ramp Metering: Summary of Field Results", M. Papageorgiou, H. Hag-Salem, F. Middelham, Transportation Research Board 76th Annual Meeting Paper No. 970032, Washington, 1997.

2. "Modeling and Real time control of Traffic Flow on the southern part of the Boulevard Peripherique in Paris: Part I: Modeling", M. Papageorgiou, Habib Haj-Salem, Jean-Marc Bloseville, Transportation Research - A, Vol. 24A, No. 5, 1990.

3. "Modeling and Real time control of Traffic Flow on the southern part of the Boulevard Peripherique in Paris: Part II: Coordinated On-Ramp Metering", M. Papageorgiou, Habib Haj-Salem, Jean-Marc Bloseville, Transportation Research, Vol. 24 A, No. 5, 1990. .

4. WWW Resource; http://www.sytadin.tm.fr/

Milwaukee

1. "Milwaukee Monitor FTMS Software Design Report", JHK & Associates, 1998.

2. WWW Resource; http://www.dot.state.wi.us

Amsterdam

1. "ALINEA Local Ramp Metering: Summary of Field Results", M. Papageorgiou, H. Haj-Salem, F. Middelham, Transportation Research Board 76th Annual Meeting Paper No. 970032, Washington, 1997.

2. "Design of a coordinated Ramp Metering System Near Amsterdam", H. Taale, W.J.J.P. Schouten, 7th International Conference on Road Traffic Monitoring and Control, 1994.

3. "The Assessment of multiple Ramp-Metering on the Ringroad of Amsterdam", H. Taale, G.A. Van Velzen, 8th International Conference on Road Traffic Monitoring and Control, 1996.

2.10. SYSTEM WIDE ADAPTIVE RAMP METERING (SWARM)

Orange County, California

2.10.1. Background and Experience

The SWARM algorithm is currently under development by NET as part of a contract with Caltrans. Scheduled for initial field tests in Orange County, California, the algorithm (under development since 1996) will be deployed next within the Los Angeles transportation network. This network contains over 1,200 ramp meters, and testing is expected to begin by 2000. While no performance or evaluation data is yet available, SWARM is already drawing interest from DOT's around the country, including Illinois DOT and Oregon DOT, which have both considered using the new algorithm.

Figure 16: Map of the Los Angeles Freeway Network

Source: http://www.mapquest.com

2.10.2. Algorithm Description

The SWARM algorithm actually consists of two individual algorithms operating independently from one another, with the more restrictive of the two being implemented each time interval. SWARM1 is a forecasting and system-wide apportioning algorithm, while SWARM2 is a more traditional local traffic responsive system.

Figure 17: SWARM Forecast Operation

The operation of SWARM1 is based on traffic density, with the goal of maintaining real-time density below a pre-determined saturation density for each segment of roadway. It uses linear regression and a Kalman filtering process applied to prior-interval detector data (NOT historical data) to forecast a density trend at each detector location for each time interval. The time into the future to forecast is a tuneable parameter (Tcrit). From the forecast, an 'excess density', or density above the saturation density, is determined (see Figure 16). This value is used by SWARM to determine how much to reduce traffic density at that location to pre-empt congestion. SWARM uses a standard 30-second interval when iterating this metering rate calculation.

Once the excess density for each detector is determined, the target density (called 'Required Density' by system designers - it has been re-labeled here to aid in conceptual understanding of the algorithm) for the detector sites is found as follows:

$$[\text{Target Density} = (\text{Current Density}) - (1 / \text{Tcrit}) * (\text{Excess Density})]$$

Once this target density is known, the corresponding volume reduction required at each detector to achieve it may be calculated as follows:

$$[\text{Volume Reduction} = (\text{Local Density} - \text{Target Density}) * (\text{\# of Lanes}) * (\text{Distance to next Station})]$$

The algorithm thus produces either volume reduction or volume excess values (when the local density is less than the target density) for each detector site. These reduction or excess values are then distributed to upstream ramps within the defined area of influence for each site using unique, pre-defined weighting factors at each ramp based on ramp demand, queue storage capacity, etc. The most restrictive volume reduction/excess is then utilized at each ramp location, subject to pre-defined constraints (spillback impacts, storage, demand, etc.), to calculate a metering rate for each location.

```
                    ┌─────────────────────────┐
                    │   Forecast Density Using │
                    │ Previous Interval Detector Data │
                    └─────────────────────────┘
                                │
                                ▼
                    ┌─────────────────────────┐
                    │  Measure Excess Density  │
                    └─────────────────────────┘
                                │
                                ▼
                    ┌─────────────────────────┐
                    │  Calculate Target Density│
                    │    At Each Detector Site │
                    └─────────────────────────┘
                                │
                                ▼
                    ┌─────────────────────────┐
                    │ Calculate Required Volume│
                    │ Reduction At Each Detector Site │
                    └─────────────────────────┘
                                │
                                ▼
                    ┌─────────────────────────┐
                    │ Assign Volume Reductions/Excess │
                    │    To Upstream Meters    │
                    └─────────────────────────┘
                                │
                                ▼
                    ┌─────────────────────────┐
                    │ Calculate Locally Responsive Metering │
                    │      Rate (Headway)      │
                    └─────────────────────────┘
                                │
                                ▼
          NO        ┌─────────────────────────┐     YES
      ◄─────────────│ Is Locally Responsive Rate │─────────────►
                    │     More Restrictive?    │
                    └─────────────────────────┘
      │                                               │
      ▼                                               ▼
┌──────────────┐                            ┌──────────────┐
│  Implement   │                            │  Implement   │
│ SWARM1 Rate  │                            │ SWARM2 Rate  │
└──────────────┘                            └──────────────┘
```
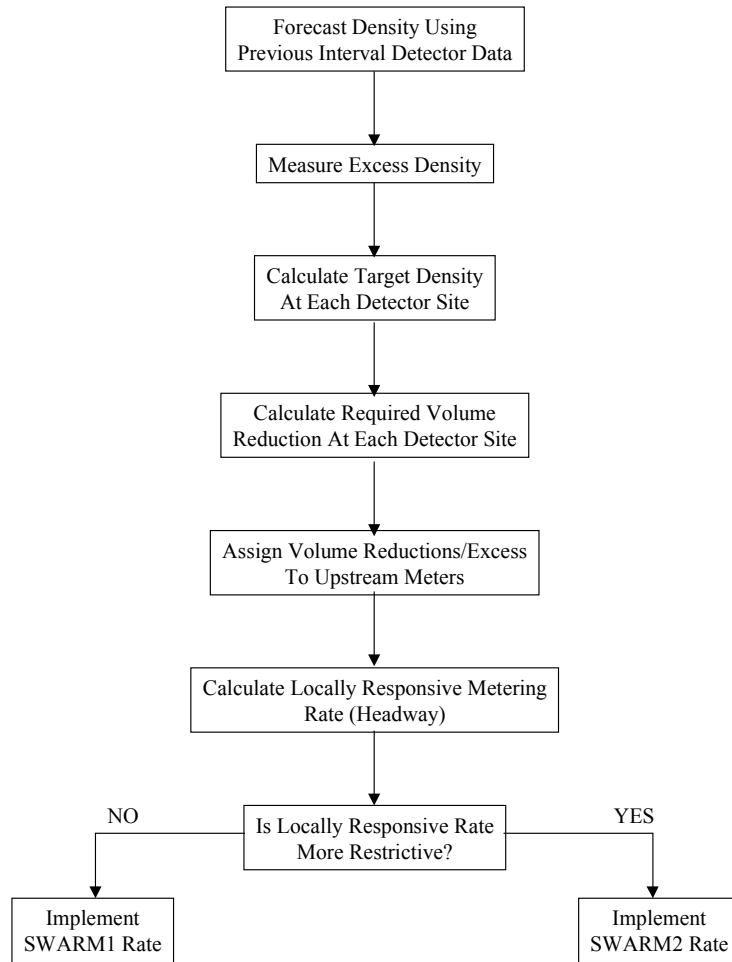
Figure 18: SWARM1 Operational Concept

SWARM2 is simply a local traffic responsive algorithm, assigning metering rates based on distance headway measurements (converted to density) at the detector site just upstream from each metered ramp. This algorithm uses a linear conversion from the calculated local density to find metering flow rates, with the goal of preserving headway and thus maintaining flow. It runs concurrently with SWARM1 at all times and the most restrictive of the two for each time interval is implemented. Maximum and minimum metering rates are pre-defined to prevent excessive metering operations under SWARM1 or SWARM2.

In addition to the operation of the metering algorithms themselves, SWARM also incorporates a failure management and data enhancement system for checking detectors against historical trends to identify failures and eliminate data 'noise', should they occur.
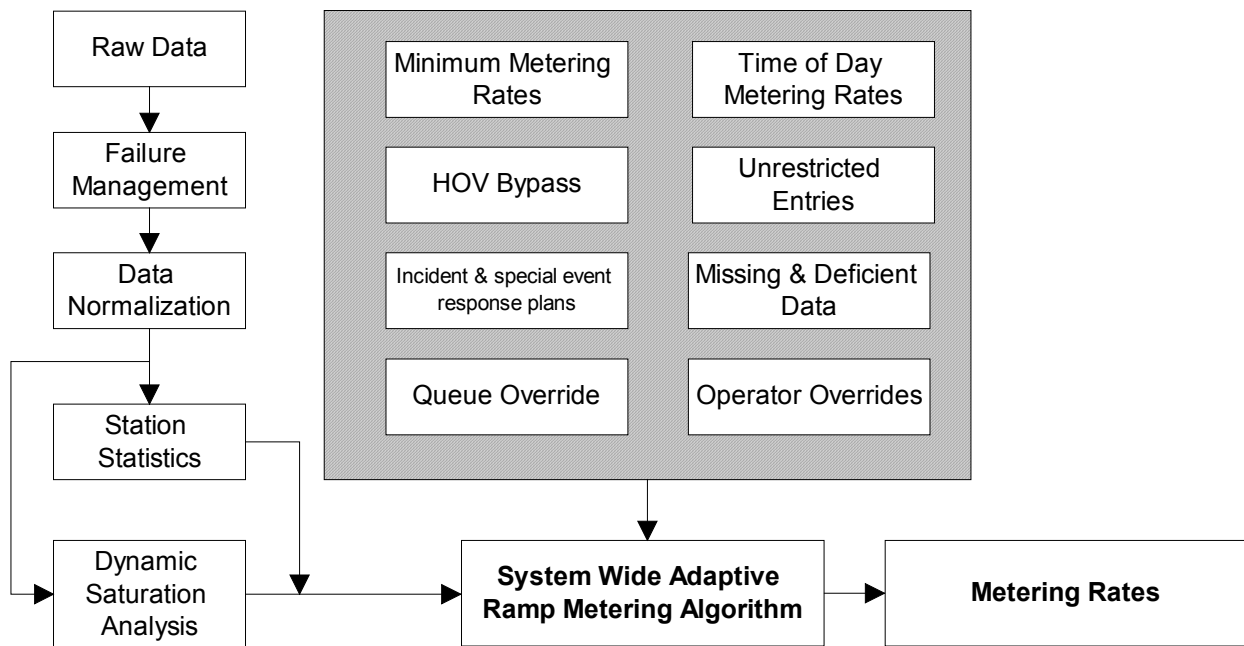
24

Figure 19: SWARM - General Concept

References

1. "System Wide Adaptive Ramp Metering In Southern California", Gordon Paesani, James Kerr, Pat Perovich, Edward Khosravi, ITS America 7th Annual Meeting, June 1997.

2. "System Wide Adaptive Ramp Metering Algorithm - High Level Design" Final Report, Prepared by NET for Caltrans and FHWA, March 1996.

3. PROPOSED RAMP METERING ALGORITHMS

In the course of this study, several additional coordinated traffic responsive algorithms were identified which have not yet been implemented within a metering system. These were included in this report to provide an understanding of what is available in advanced 21st-century systems, the 'next step', currently under development in different parts of the world.

3.1. BALL AEROSPACE / FHWA ALGORITHM

The BALL Aerospace/FHWA corridor control algorithm is currently under development. The project began in 1997, with the first field-test of the system planned for the Orange County, California transportation network in Caltrans District 12 in 2000.

The BALL algorithm is unique to the transportation field, as it is a corridor coordination system, of which the ramp metering algorithm is only one portion. At this time, no specific algorithm formulation is available, though conceptual diagrams and user requirements are available to an extent that allows understanding of the system functionality at a high level. The conceptual operation of the metering algorithm within the corridor algorithm is outlined in the flowchart shown below.

The conceptual operation outlined above accomplishes the following physical steps:

Step 1: Roadway Modeling. This step takes as input the physical characteristics of the corridor, including lanes, ramp configurations, distances, control capabilities, etc. This creates a simulated physical model of the corridor to be used in metering plan generation.

Step 2: Traffic Modeling. Historical data, supported by up-to-date surveillance data, is used in conjunction with O&D tables and the internal roadway model (Step 1) to generate a model of traffic demands at various points along the corridor.

Step 3: Model-Based Metering Plan Generation. This step uses the demand model and the internal roadway model to simulate the corridor and create metering plan sets along the corridor for various traffic conditions and time-of-day operation. These plan sets are then archived for use by the system as warranted.

Step 4: Current Condition Assessment. Based on the real-time conditions as detected by the system, these archived metering sets (Step 3) are called up for implementation each time interval according to which of the sets most closely fits the condition of the corridor traffic patterns at the time.

Step 5: Generation of Real-Time Metering Rates. The archived set that is called up for implementation1 is modified at this point to match the constraints in place at the time, such as faulty detection, unusual traffic patterns in some areas, etc. Once these adjustments are made, the modified metering plan is then sent out to the individual controllers. This entire process is iterated over 1-minute intervals.
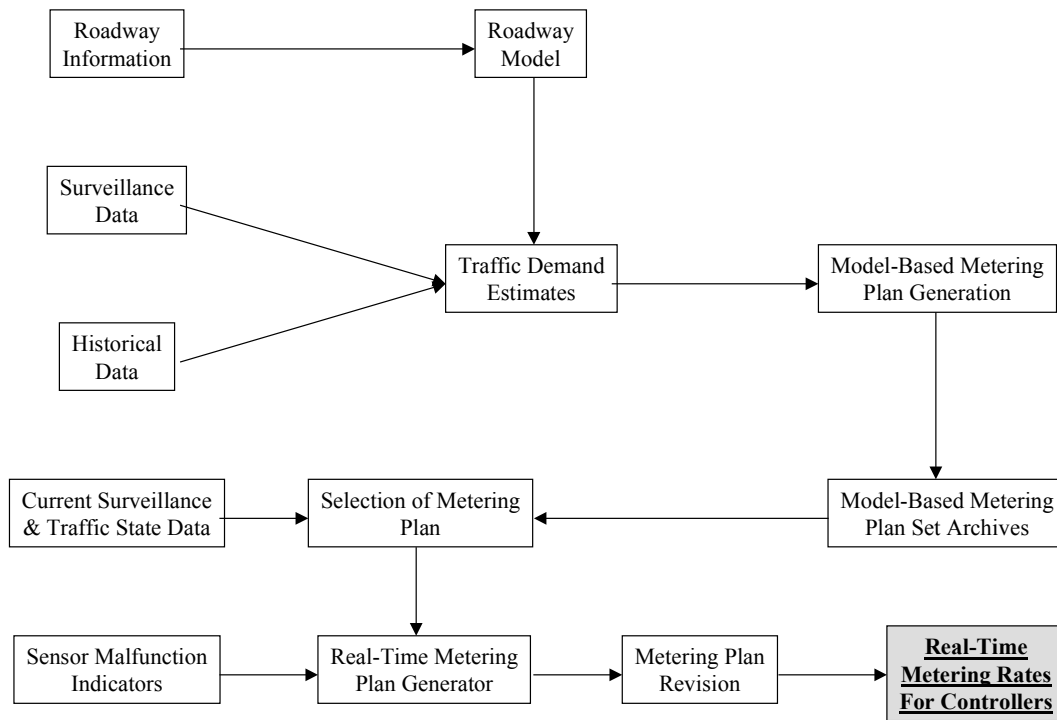
Figure 20: Ball Aerospace Algorithm Operational Flow Chart

The BALL system operates on two different levels, 1) the operational environment and 2) the simulation environment. This enables offline processing and modeling of data to develop roadway and traffic models and archived metering plan sets, yet maintains a direct link to the real-time, real-world system operations to respond to non-recurrent events. The simulation environment has been developed to function with the CORSIM modeling package.

While the system is presented as being a regional coordination algorithm, linking surface street and ramp meters operations, this connection exists only at the modeling level within the simulation environment. The BALL algorithm maintains no control over surface street operations, relying instead on the coordination achieved within the simulation environment to properly configure ramp metering plans.

In the simulation environment, the full algorithm will utilize a non-linear programming method to develop time of day plans for database storage. The real-time adjustments to the stored time-of-day plans will be accomplished using one of two generalized metering algorithms; FLOW (Seattle Bottleneck Algorithm) or ALINEA/METALINE. The Bottleneck algorithm is documented independently in the body of this report. ALINEA is discussed independently later in this appendix in support of the Ball algorithm. The METALINE algorithm extends ALINEA to a series of ramps, and is discussed independently in the body of this report.

References

1. "Ramp Metering Project - System Functional Requirements Specification", BALL Systems Engineering Operation, Prepared for FHWA, November 1998.

2. "Ramp Metering Project - Algorithm Development", BALL Systems Engineering Operation, Prepared for FHWA, November 1998.

3.2.   ALINEA

Asservissement Linéaire d'Entrée Auotroutière (ALINEA), a <u>local</u> responsive feedback ramp metering strategy, has had multiple successful field applications (Paris, Amsterdam, Glasgow, Munich), with additional deployments currently planned in several countries (e.g. A40 in Germany on 28 ramps). This algorithm considers traffic flow as the process being controlled and the metering rate as the control variable. Based on feedback control theory, the algorithm attempts to set the metering rate such that traffic flow will not exceed system capacity. For each time interval, the algorithm solves the following equation for metering rates at each ramp:

$$[\; r(k) = r(k-1) + K_R\{o_c - o_{out}(k)\} \;]$$

where:

$r(k)$ = meter rate (volume) in time interval k

K_R = tunable parameter (weighting factor) greater than zero

o_{out} = local occupancy at ramp (measured by one mainline detector)

o_c = Pre-defined occupancy value at capacity (or a desired occupancy maximum value) for the location (Paris: 29%; Amsterdam: 18%; Glasgow: 26%)

The algorithm uses this difference in occupancy values (desired or capacity versus measured), measured at a point 40 meters downstream of the ramp gore, to calculate a metering rate. One of the most desirable features of this algorithm is the integration of the previous time interval metering rate within the equation. This allows integrated smoothing of the metering rates to avoid wide swings between concurrent time intervals.

References

1. "ALINEA Local Ramp Metering – Summary of Field Results", M. Papageorgiou, H. Hadj-Salem, F. Middelham, Transportation Research Record 1603, TRB, 1997.

2. "Eurocor and A10-West Coordinated Ramp Metering Near Amsterdam", F. Middelham, W.J. Schouten, J. Chrisoulakis, M. Papageorgiou, H. Haj-Salem, Proceedings of the 1st World Congress on Applications of Transport Telematics and IVHS, ERTICO, 1994.

3.3.   ARMS

ARMS (Advanced Real-time Metering System) consists of three operational control levels within a single algorithm: free-flow control; congestion prediction and congestion resolution.
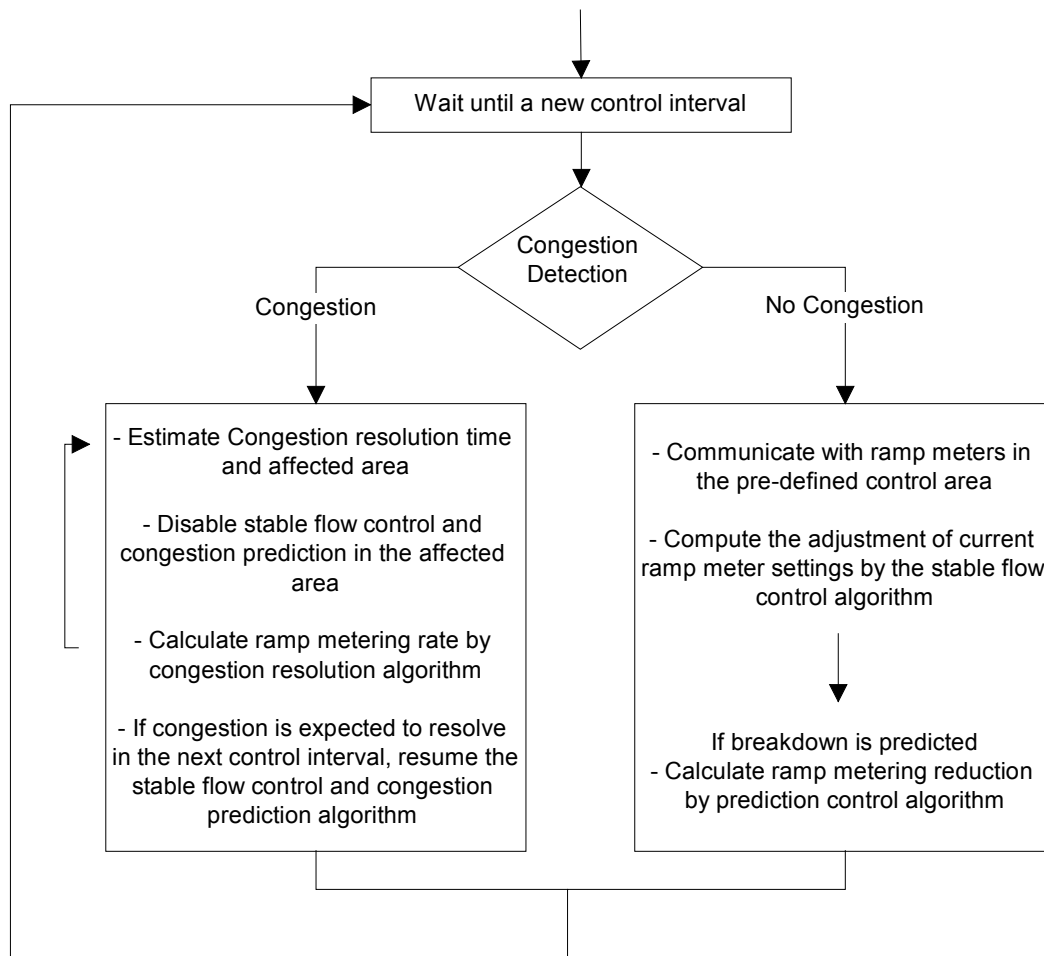
Figure 21: ARMS Operational Flow Chart

Free-flow control works to smooth peak demands to reduce the possibility of recurrent congestion. Traffic flow is treated as a semi-static process in which traffic flow varies slowly with time, where the control decisions are based on a free flow model.

Congestion prediction works to predict (and thus pre-empt) traffic flow breakdowns caused by dynamic traffic fluctuations. Traffic flow is modeled as a rapidly changing dynamic process. This model portion of the algorithm has a learning capability: it starts iterating congestion prediction with an arbitrary set of traffic patterns, improving the accuracy of the modeled results as actual field measurements are obtained from online operation. Integration of this control module with the free-flow control module provides for an environment in which the probability of congestion occurring is reduced.

Congestion reduction is a dynamic algorithm that balances congestion resolution time and metering rates by integrating both freeway and surface street operations.

This algorithm has been successfully tested in simulation models.

References

1. "A Successful Return To Ramp Metering - The Houston Experience", John M. Gaynor, Darrell Borchardt, ITS America 7th Annual Meeting, 1997.

2. "An Advanced Real Time Metering System (ARMS): The System Concept", Jyh-Charn Liu, Junguk Kim, Yiloeng Chen, Ying Hao, Sojung Lee, Taeyoung Kim, Michael Thomadakis, Texas Department of Transportation Report Number 1232-24, 1993.

3. "Advanced Freeway System Ramp Metering Strategies for Texas", Carroll Messer; Texas Department of Transportation Report Number 1232-23, 1993.

4. WWW-Resource: http://traffic.tamu.edu/

3.4. COORDINATED METERING USING ARTIFICIAL NEURAL NETWORKS

This algorithm is based on an Artificial Neural Network (ANN) with 'learning' capability. The FREQ10PC model is used in an offline capacity to generate an initial, preliminary metering plan, which is used within a back-propagation algorithm to 'train' the neural network. The roadway system is divided into control zones, and input data for the algorithm is collected at each ramp in a zone; V/C ratios upstream and downstream of the ramp and the ramp queue length on each ramp.
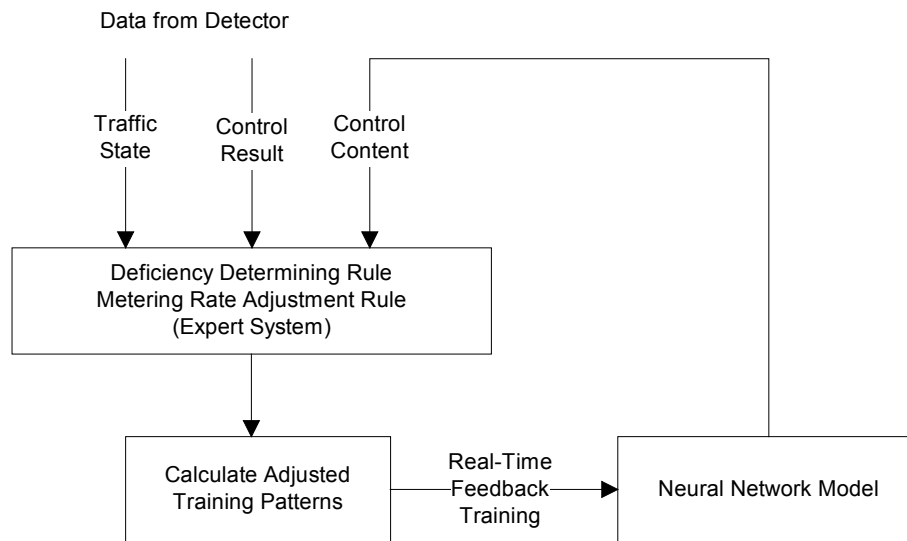
Figure 22: Taiwan Algorithm Operational Flow Chart
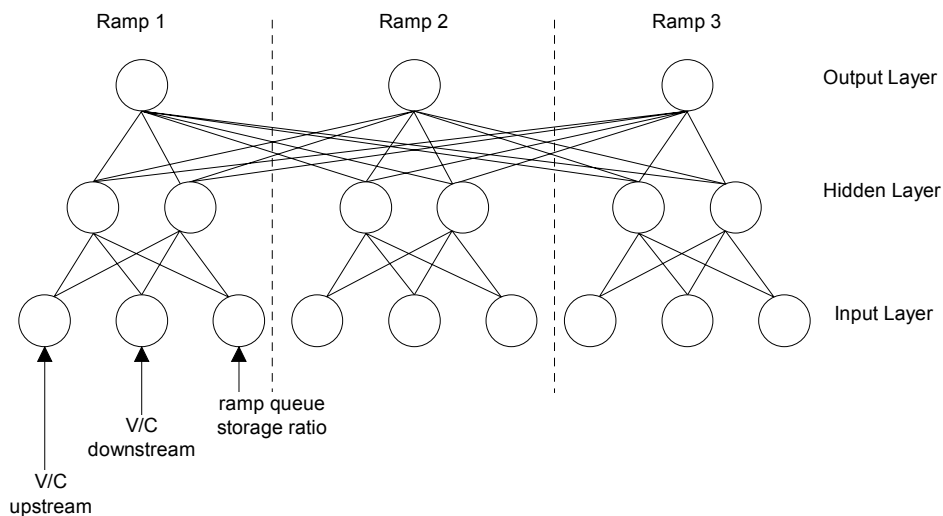
Figure 23: ANN Conceptual Operation

As the metering rate for each on-ramp is affected primarily by the mainline V/C measurements near the ramp and only partially by the traffic conditions elsewhere in the zone, a partially connected neural network is used. The network consists of different subsystems, one for each controlled on-ramp, where each subsystems connected via the 'hidden layer' (see Figure 22) to all other subsystems. This interconnection represents the coordination element of this algorithm.

The internal FREQ model tracks the actual traffic conditions, the implemented control strategies, and the results. This information is evaluated (expert system) and if necessary, additional self-adjustment training data is provided for the ANN system until the desired traffic condition is reached.

This algorithm has only been tested via simulation, where good results were obtained.

Reference

1. "Applying an Artificial Neural Network Model To Freeway Ramp Metering Control", Chien-Hung Wei, Kun-Yu Wu, Transportation Planning Journal, Vol. 25 No. 3; 1996.

3.5. LOCAL METERING USING NEURAL NETWORKS

This algorithm is a local traffic-responsive ramp metering algorithm which integrates an Artificial Neural Network (ANN) to support metering calculations. This algorithm treats mainline traffic at each ramp location as a nonlinear feedback control problem, where the model is based on the hydrodynamic model developed by Lighthill, Whitham and Richards. The fundamental diagram of this model (flow-density relationship) is nonlinear, with the feedback controllers composed of one or more feed-forward neural networks.
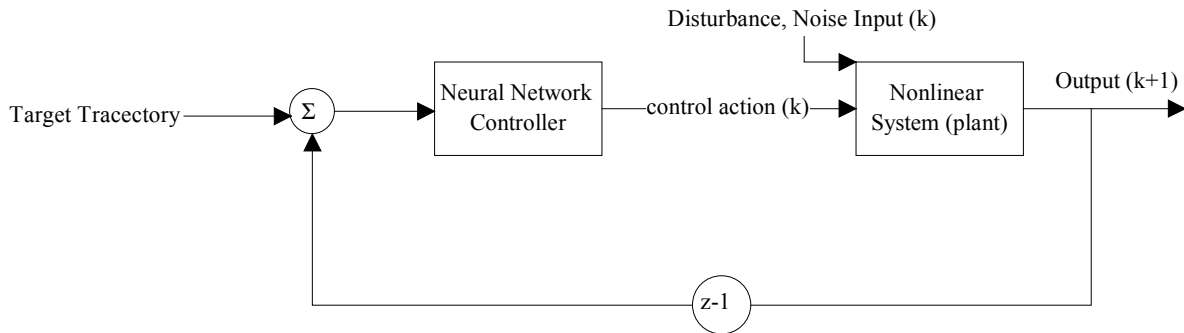
Figure 24: Non-Linear Feedback Control Process

The network was trained with a modified back-propagation algorithm in conjunction with a standard non-linear optimization technique. In this application the neural networks are an integrated part of a larger system and thus there are no a-priori target outputs for them to follow. They also act as subcomponents of a system, with their behavior constrained by interconnections with other system components and the overall performance requirements.

This algorithm has been implemented only in simulation, where results showed it to be effective in achieving the control objective.

References

1. "Some General Results on the Optimal Ramp Control Problem", H. Zhang, S.G. Ritchie, W.W. Recker; Transportation Research - C, Vol. 4c no. 2, 1996.

2. "An Integrated Traffic Responsive Ramp Control Strategy via nonlinear State Feedback", Hongjun Zhang, Stephen Ritchie, Institute of Transportation Studies, UC Irvine, UCI-ITS-WP-95-2, 1995

3. "Freeway Ramp Metering Using Artificial Neural Networks", H. Zhang, S.G. Ritchie, Transportation research. Part C, Emerging technologies. Vol. 5C, no. 5, October 1997.

3.6. DYNAMIC METERING CONTROL ALGORITHM

The MIT algorithm consists of four operational elements: 1) state estimation, 2) O-D prediction, 3) local metering control, and 4) area-wide metering control. A local feedback control algorithm (ALINEA) and an area-wide control model are integrated in a hierarchical structure to form the basis of this algorithm. A rolling horizon approach is used in combining the area-wide and local control modules.
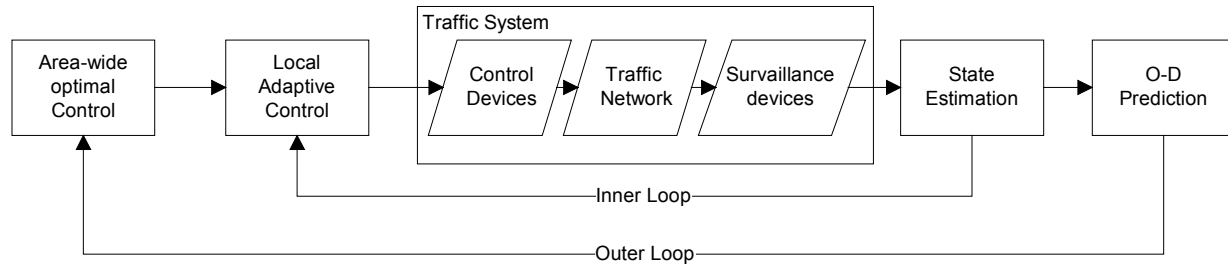
Figure 25: Dynamic Control Structure

The state estimation module is used to process the surveillance data and estimate the current network state. Time-dependent O-D flows are predicted in real-time for use as inputs to the area-wide module.

The local adaptive control algorithm is controlled by the distributed local controllers. Each controller reacts independently to the changes in local traffic conditions. The control values produced by the area-wide algorithm provide nominal set values for the local controllers, which are then compensated for traffic disturbances and prediction errors based on local information. A linear-quadratic feedback control model is used for this process.

The area-wide control module is based in a centralized, predictive controller. Coordination is achieved by system-wide optimization in which all control parameters are synchronized to improve the overall system performance. The O-D prediction is used to predict the future traffic state and generate the traffic control scheme accordingly. The mainline and ramp traffic dynamics are modeled with a discrete, macroscopic flow model using a general function for the fundamental diagram. After that the linear objective function with non-linear constraints is solved using the Frank/Wolfe algorithm. The control settings generated by this area-wide algorithm subsequently provide the set value for the local control module.

This algorithm has only been tested in simulation.

Reference

1. "Development and Evaluation of a Dynamic Metering Control Model", Owen Chen, Anthony Hotz, Moshe Ben-Akiva, IFAC Transportation Systems; Chania, 1997

3.7. METERING MODEL FOR NON-RECURRENT CONGESTION

This algorithm uses a two-segment linear flow density model. Kalman filtering and auto-regressive moving average techniques are used for estimating link densities and ramp queue lengths from point volume and occupancy detector data and traffic system model parameters.

A dynamic equation for density evolution according to the flow conservation law is formulated to describe the freeway traffic system and ramp traffic dynamics. The traffic evolution equations act as the essential constraints for optimizing metering rates. Other constraints are the lower and upper physical bounds on the mean link densities, the maximum and minimum allowable metering rates and the maximum allowable ramp queue length. Traffic flow or throughput is then solved for within the objective function using linear programming mathematics.

This algorithm has been tested via simulation, but no implementation is reported.
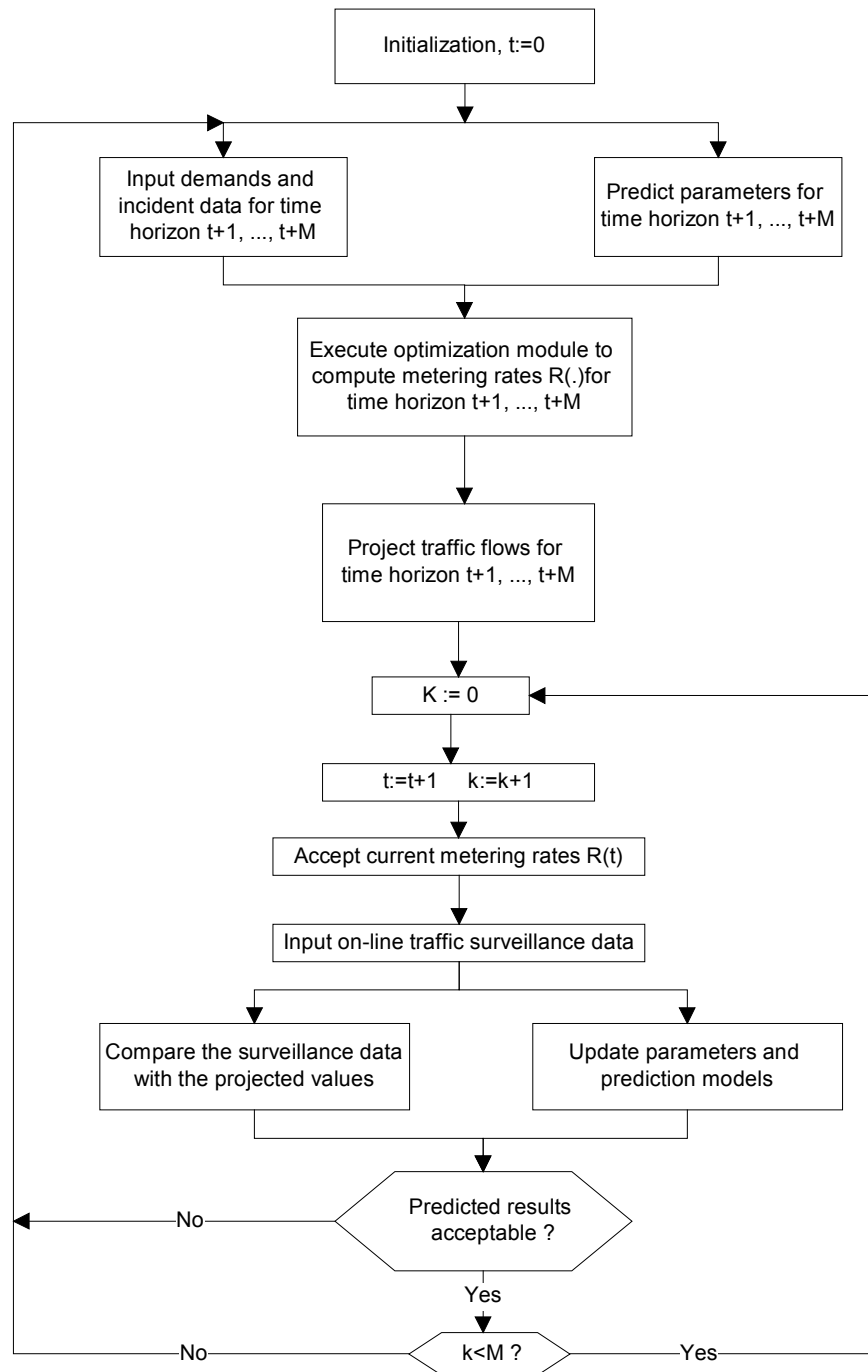

Figure 26: Maryland Algorithm Operational Flow Chart

References

1. "Integrated Real-Time Ramp Metering Model for Non-recurrent Congestion: Framework and Preliminary Results", Gang-Len Chang, Jifeng Wu, Stephen Cohen, Transportation Research Record 1446, 1994.

4. PROPOSED FUTURE DIRECTIONS

The authors consider that two of the leading approaches for the future implementation of coordinated traffic responsive ramp metering systems are on-line simulation and adaptive fuzzy logic. This is based upon the research undertaken in developing chapters 2 and 3 of this report. The following two portions of this chapter provide an overview of the proposed on-line simulation and adaptive fuzzy logic approaches. Further research will be needed for both approaches in order to develop detailed strategies for implementation.

4.1. ONLINE SIMULATION

4.1.1. Introduction

This section proposes and describes a freeway control system, <u>hierarchic</u> and <u>dynamic</u> characteristics being its unique features.

The <u>hierarchic</u> characteristics of the proposed system permit stages of development which allow each earlier stage to become an integral part of later stages. The implemented stages of development would depend upon the local situation but might include pre-timed fixed-time control, fixed-time demand-responsive control, fixed-time demand-capacity responsive control, and dynamic freeway control. Thus, it is possible for an operating agency to use the proposed freeway control system in stages of development and in accordance with local constraints.

The <u>dynamic</u> characteristics of the proposed freeway control system provide adjustments for short- and long-term changes in freeway demands, capacities, and operational conditions. Adjustments procedures range from manual adjustment for the long-term changes to automatic adjustment for both short- and long-term changes. In the automatic adjustment procedure, current and historical data are processed, and demands and capacities for the next time period are predicted. A system-wide optimization process selects the control strategy; the strategy is then implemented. Demands, capacities, and operational conditions are continuously monitored, and if changes are detected, new control strategies are determined and implemented.

This section will give particular attention to developing control strategies that are responsive to incident situations. An incident situation is defined as a situation at a point in time and space when a random event occurs; the event significantly reduces the capacity of a freeway section. The incident situation may be an accident , stopped vehicle, obstruction, and/or distraction on, or near the freeway lanes. It may or may not modify the control strategy depending upon the demand level and the amount of the reduced freeway capacity.

4.1.2. Proposed Structure

An overview flow chart of the proposed dynamic freeway control system hierarchy is shown in Figure 27. It contains four major processors: initialization processor, estimation processor, optimization processor, and tactics processor. The interactions of the four processors are briefly described in the next paragraph, followed by a more detailed description of each processor.
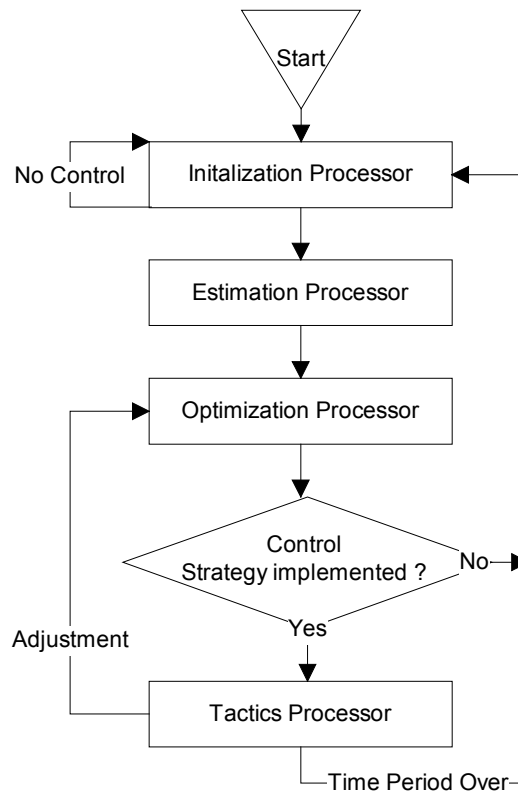
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  │  └────────┤     Tactics Processor     │              │
  │           └──────────────────────────┘              │
  │                        └── Time Period Over ─────────┘
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Figure 27: Hierarchical Algorithm Operational Flow Chart

The initialization processor determines whether control should be considered. When control is considered, the initialization processor calls the estimation processor. The estimation processor prepares necessary demand and capacity input data for the optimization processor. The optimization processor calculates the optimum system-wide control strategy, using a linear programming formulation. If a control strategy is not implemented, the system control is returned to the initialization processor. If a control strategy is implemented, the tactics processor is called. The tactics processor throughout the time period continually compares predicted demands with measured demands, predicted capacities with measured capacities, and predicted operational conditions with measured operational conditions. If the tactics processor detects a significant change, the input data is adjusted and the optimization processor calculates a new system-wide control strategy. When the time period is over, the initialization processor is called, and control for the next time period is considered.

4.1.3. Initialization Processor

Surveillance can be considered as a continuous function, while control is for selected periods of time which are determined by the manual decision switch, master time clock, and/or surveillance data algorithm.

The manual decision switch is the master controller in that the operator can select one of the three states: "no control", "consider control", or "decision to control". The "no control" state precludes consideration and implementation of control and terminates control if it is occurring. The "consider control" state passes the control to the master time clock where control possibilities are further considered. The "decision to control" state bypasses the master time clock and the surveillance data algorithms and passes control to the estimation processor.

The master time clock is the next level in the initialization processor. It, like the manual decision switch, can be set to select one of three states as a function of time: "no control", "consider control", or "decision to

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control". The "no control" state precludes consideration and implementation of control and terminates control if it is occurring. The "consider control" state passes the control to the surveillance data algorithms where control possibilities are further considered. The "decision to control" state bypasses the surveillance data algorithms and passes control to the estimation processor.

The surveillance data algorithms are contained in the last level of the initialization processor. The surveillance data algorithms select one of two states: "no control" or "consider control". The "no control" state is selected when no existing or impending operational difficulties are detected by the surveillance data algorithms. The "consider control" state is selected when existing or impending operational difficulties are detected by the surveillance data algorithms; control is then passed to the estimation processor.
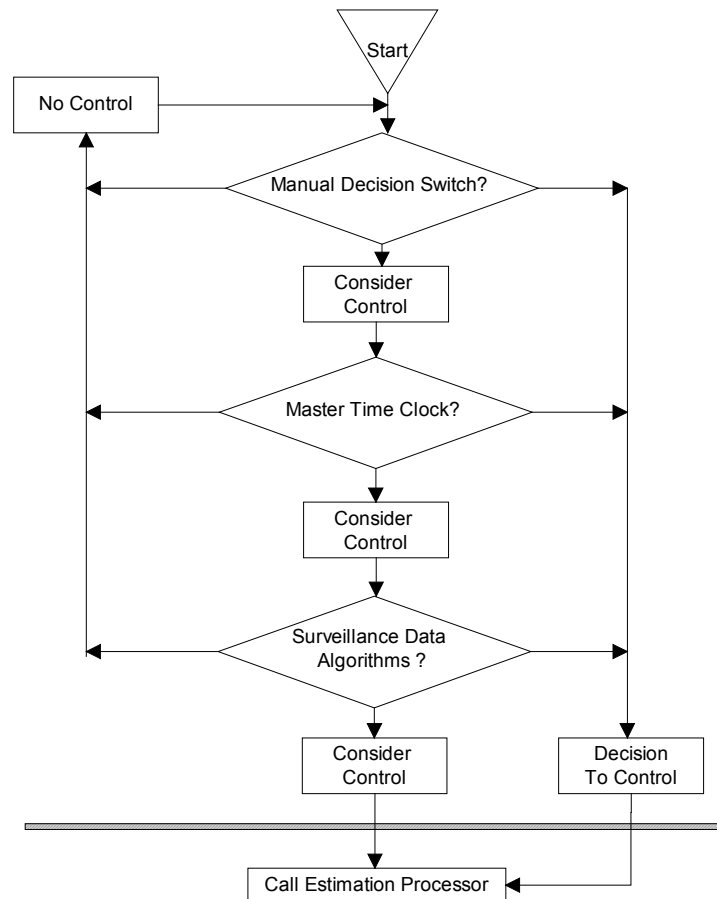

Figure 28: Initialization Processor

4.1.4. Estimation Processor

The demand and capacity estimation processor is called by the initialization processor whenever the states of "decision to control" or "consider control" are reached. This processor predicts as accurately as possible the set of demand and capacity parameters needed in the fixed-time control strategy determination for the next time period. Two types of input data are required by this processor: stored historical demands and incident-free capacities, and measured demands and capacities for the last time period.

The historical demands and incident-free capacities are stored in the computer memory in two sets of arrays (demand and capacity). There is one demand array for each week-day; this array is updated every week. Each demand array is two dimensional, with columns representing freeway inputs (mainline input and each on-ramp input) and rows representing time periods (perhaps 15 minute periods) during the day. The best estimate of traffic demand for a particular day at a specified freeway input location and during a specified time period

is placed in each cell of the set of demand arrays; the estimate is based solely on historical data. The capacity array consists of a single row of freeway subsection cells; each cell entry represents the incident-free capacity for a particular freeway subsection.

Continuous freeway surveillance provides measured demands for each freeway input and current estimated capacities for each freeway subsection. These demands and capacities provide two additional arrays: a single row of current freeway input demands and a single row of current freeway subsection capacities.
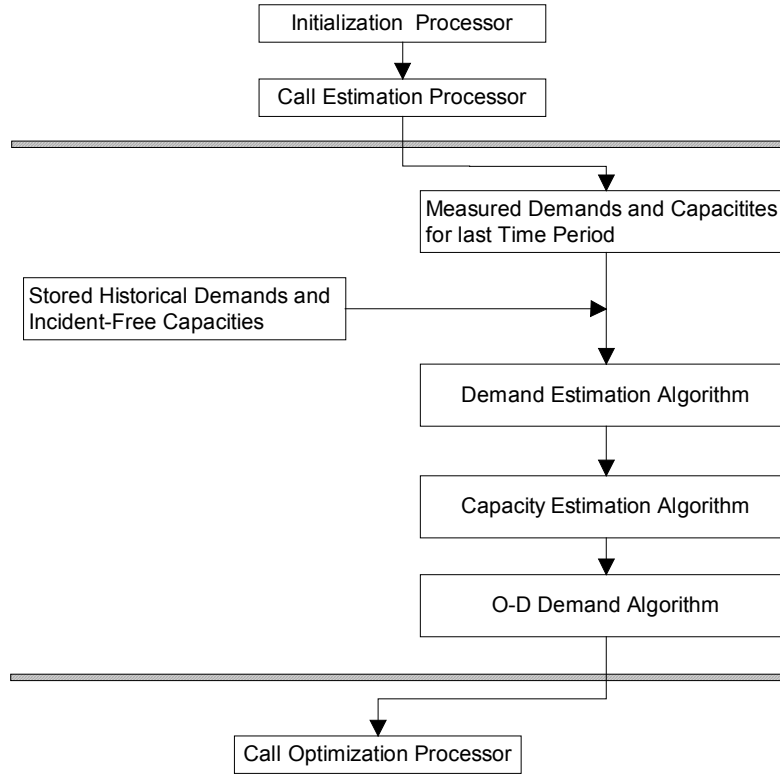
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                    │ Call Optimization Processor│
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```

Figure 29: Estimation Processor

A demand estimation algorithm processes the historical and current measured demands and provides estimates of freeway input demands and output flows for the next time period. The demand estimation algorithm might take the simple ratio form:

$$d_{i,\,t+1} = \frac{D_{i,\,t+1}}{D_{i,\,t}} \, (d_{i,\,t})$$

where

$d_{i,\,t+1}$	demand for input i in the next time period t+1
$d_{i,\,t}$	demand for input i in the last time period t
$D_{i,\,t+1}; D_{i,\,t}$	stored historical demand input i for the time periods t+1 and t

Further research may indicate the need for a more sophisticated algorithm.

A capacity estimation algorithm processes the historical and current measured capacities and provides estimates of freeway subsection capacities for the next time period. The capacity estimation algorithm might contain a set of flow-occupancy models; one for each freeway subsection. The flow-occupancy measurements for the last time period would be used to calculate the appropriate parameters for a flow-

occupancy model, the model then being solved to determine the current capacity. This calculated current capacity would be compared with stored incident-free capacity. This procedure might be particularly helpful under non-incident conditions, but where capacities are reduced because of poor visibility, adverse weather, or unusual traffic composition. Measured traffic flows downstream of incidents would be utilized to determine capacity estimates for incident situations.

Finally, the estimation processor utilizes an O-D demand algorithm which converts the previously estimated freeway input demands and output flows for the next time period to an origin and destination demand table. The freeway inputs are considered as origins, and the freeway exits (off-ramp and mainline output) are considered as destinations. The O-D demand algorithm is essentially a distribution model which allocates input demands to various freeway exits. The coefficients of the distribution model are determined from previous origin and destination field studies. These coefficients are stored in the computer with one array for each time period.

There are no options in the estimation processor. If it is called by the initialization processor, it estimates demands, capacities, and O-D patterns for the next time period, and passes these estimates to the optimization processor.

4.1.5. Optimization Processor

The optimization processor is called by the estimation processor: its purpose is to select the optimum control strategy for the entire freeway system and to determine whether it should be implemented. The optimization process is formulated as a linear programming formulation.

Freeway design parameters, a specified freeway system objective, and a set of constraints are required in the linear programming formulation. The primary purpose of the freeway design parameters is to provide the spatial configuration of the various freeway inputs and outputs in relation to the freeway subsections. The specified objective of the linear programming formulation could be maximization vehicle (or passenger) input or maximization of vehicle miles (or passenger miles) of travel. The constraints of the linear programming formulation may include the specifying of minimum level of service for freeway users, balancing freeway input queues, establishing limits (minimum and/or maximum) for freeway input rates, etc.

$$\text{MAX} \sum_{i=1}^{N} P_i \cdot L_i \cdot x_i$$

P_i = Average Vehicle Occupancy At Origin i

L_i = Average Trip Length From Origin i

x_i = Vehicles Entering At Origin i

Subject To The Following Constraints:

$$\text{max } q_j = \sum_{i=1}^{N} a_{ij} \cdot x_i \leq c_j$$

$$\text{max } R_i \geq x_i \geq \text{min } R_i$$

$$W_i \leq \text{max } W_i$$

max q_j = maximum flow on section j

a_{ij} = the proportion of traffic that enters at origin i and is destined to pass through subsection j

x_i = allowable input flow at origin i

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max R_i = maximum allowable metering rate for freeway origin i

min R_i = minimum allowable metering rate for freeway origin i

W_i = waiting time at origin i

max W_i = maximum waiting time at origin i

The linear programming formulation must be very efficient in terms of storage requirements and, particularly, computational time. An upper-bounding type linear programming formulation may be most appropriate. The outputs of the linear programming formulation consist of a set of freeway input metering rates (control strategy), expected freeway traffic performance and ramp queue lengths, and predicted measures of effectiveness.

The O-D demand and capacity estimates coupled with the L. P. objective and set of constraints may result in a non-feasible solution. When this occurs the constraints are modified (one at a time) until a feasible solution is found. In addition the operator is alerted to the situation and the modified constraints are identified.
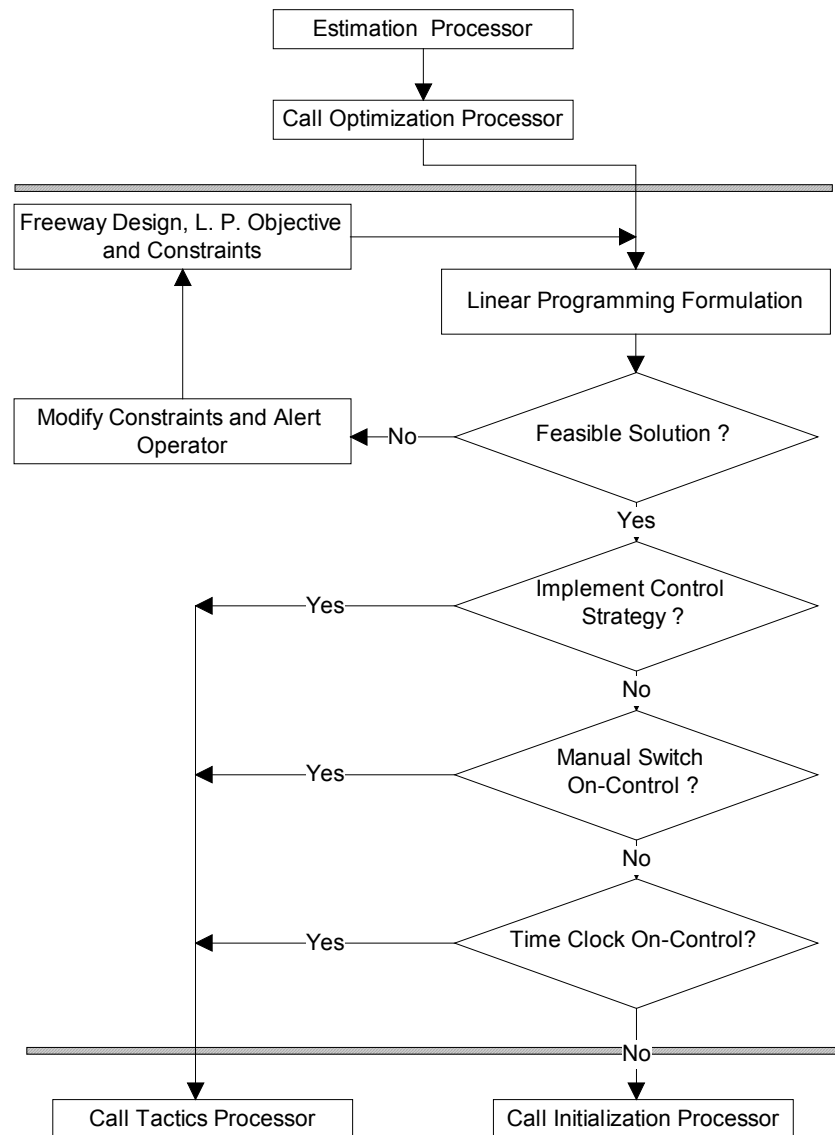
Figure 30: Optimization Processor

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The control strategy is implemented if any calculated metering rate is less than its corresponding predicted freeway demand input. The control strategy can also be implemented if either the manual decision switch or the master time clock in the initialization processor is set for "decision to control". If the control strategy is not implemented, the initialization processor is called. If the control strategy is implemented, the tactics processor is called.

4.1.6. Tactics Processor

The tactics processor is called by the optimization processor when the control strategy is implemented. Five verification checks are made in sequence and iterated until either the time period is over or a particular check is not verified.

The first check is a time block which maintains the implemented control strategy for a minimum period of time (on the order of 1 to 5 minutes). This insures that new control strategies are not continually updated because of extremely short-time variations.

The second check involves a comparison between predicted and measured freeway input demands and output flows. If the predicted demands are not significantly different from the measured demands, the implemented control strategy is maintained. If, however, the measured demands begin to differ significantly from the predicted demands, the O-D pattern is modified, and the optimization processor is called; thus permitting the control strategy, within a time period, to be redetermined and implemented due to unexpected changes in demand and/or O-D patterns.
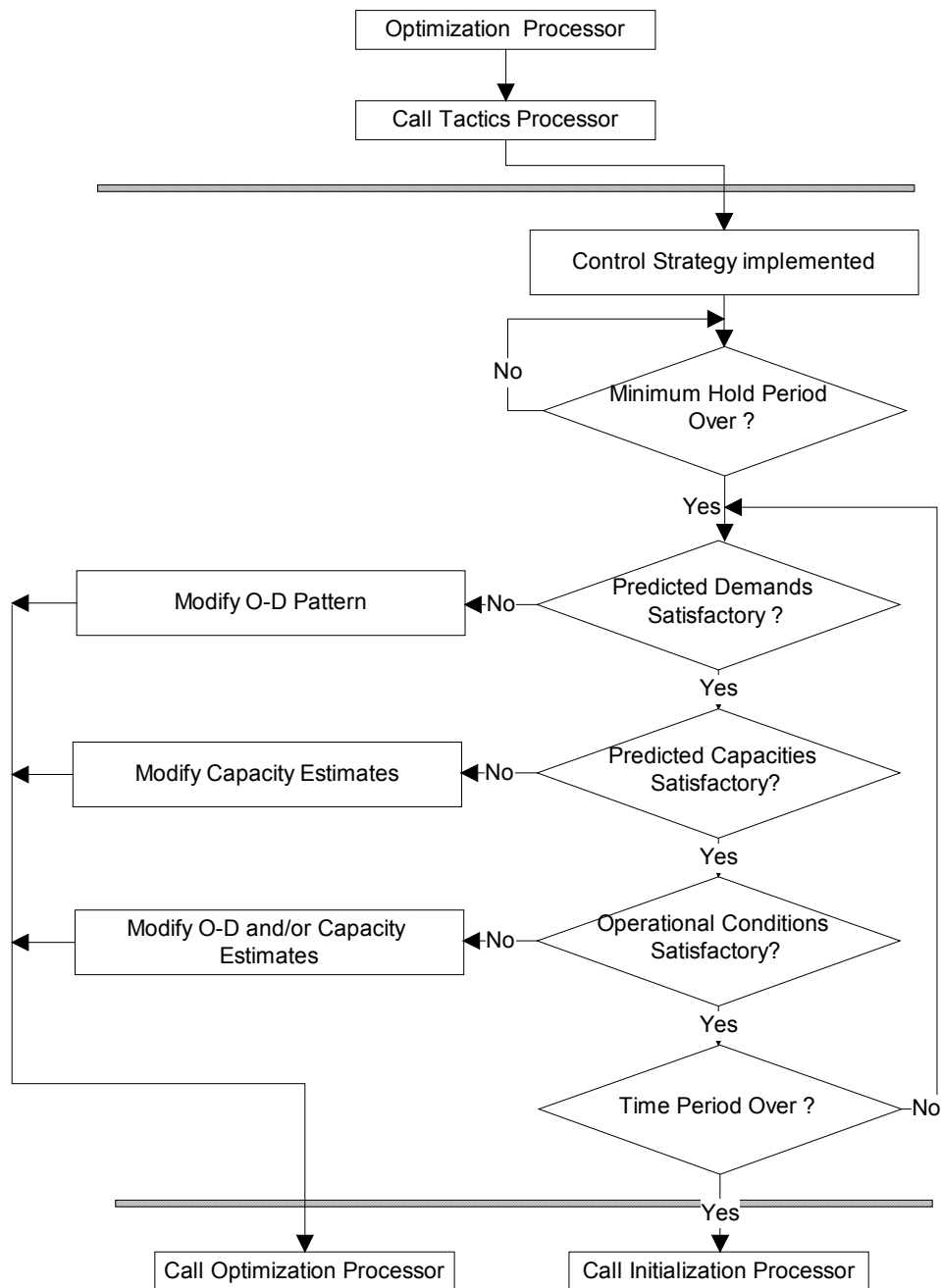
Figure 31: Tactics Processor

The third check involves a comparison between predicted and measured freeway subsection capacities. If the predicted capacities are not significantly different from the measured capacities, the implemented control strategy is maintained. If, however, the measured capacities begin to differ significantly from the predicted capacities, the freeway subsection capacities are modified, and the optimization processor is called, thus permitting the control strategy, within a time period, to be redetermined and implemented due to unexpected changes in freeway capacities. Unexpected capacity changes could occur because of weather conditions, traffic composition, incidents, etc.

The fourth check involves a comparison between predicted and measured operational conditions along the selected freeway and at ramps. If the measured operational conditions are similar to the predicted operational conditions, the implemented control strategy is maintained. If, however, the measured

operational conditions begin to differ significantly from the predicted operational conditions, the input to the linear programming formulation is modified, and the optimization processor is called. Thus permitting the control strategy, within a time period, to be redetermined and implemented due to unexpected operational conditions. Unexpected operational conditions might include operational difficulties in merging, weaving, and/or diverging areas; unexpected queue length at on-ramps; unexpected off-ramp queues; etc.

The fifth and final check determines whether the time period is over or not. If the time period is not over, another cycle of four of the five checks is undertaken. When the time period is over, the initialization processor is called.

4.1.7. Summary

This section proposed and described a dynamic freeway control system hierarchy; hierarchic and dynamic characteristics being its unique features. The proposed overall structure of the approach was provided. Each of the four integral processors was described in a step-by-step fashion.

This section has two primary purposes: to stimulate freeway operation managers to consider further the potential hierarchic and dynamic characteristics of freeway control systems using on-line simulation; and, to encourage the freeway operations researcher to consider further research into the control elements identified.

4.2. ADAPTIVE FUZZY CONTROL

4.2.1. Introduction

In the last decade a broad variety of deterministic and/or stochastic models have been developed to solve complex traffic and transportation engineering problems. Usually these mathematical models use different formulae and equations to solve such problems. However, when solving real life problems like ramp metering, linguistic information is often encountered that is often difficult to quantify using "classical, crisp" mathematical techniques. This linguistic information represents subjective knowledge. Since we are unable to quantify some linguistic information, different assumptions are made in the models. Through the assumptions made by an analyst when forming a mathematical model, the linguistic information is very often ignored. On the other hand, a wide range of traffic and transportation engineering parameters are characterized by uncertainty, subjectivity, imprecision, and ambiguity. Human operators, e.g. in Traffic Management Centers, use this subjective knowledge on a daily basis when making decisions. When solving real-life traffic and transportation problems in the future not only objective knowledge (formulae and equations) or only subjective knowledge (linguistic information) should be used. The existence of linguistic information, i.e. subjective knowledge, cannot and should not be ignored. Fuzzy Logic is an extremely suitable concept with which to combine subjective knowledge and objective knowledge.

In the classical theory of sets and logic, very precise bounds separate the elements that belong to a certain set from the elements outside the set. Element x's membership in a set A described in the classic theory of sets by the membership function $\mu_A(x)$, as follows:

$$\mu_A(x) = \{ \begin{array}{l} 1\,(\text{yes, true}),\text{if and only if } x \text{ is a member of A} \\ 0\,(\text{no, false}),\text{if and only if } x \text{ is } \underline{\text{not}} \text{ a member of A} \end{array}$$

Many sets encountered in reality do not have precisely defined bounds that separate the elements within the set from those outside the set, e.g. travel time, traffic state etc. More than 30 years ago Zadeh [ZADEH, 1965] extended the classical crisp concept of sets and introduced a new concept of a fuzzy set. The membership function for fuzzy sets can take any value from the closed interval [0,1]. Fuzzy set A is defined as the set of ordered pairs

$$A = \{ x, \ \mu_A(x) \},$$

where $\mu_A(x)$, is the grade of membership of element x in set A. The greater $\mu_A(x)$, the greater the truth of the statement that element x belongs to set A.

Fuzzy control is a control method based on fuzzy logic. Just as fuzzy logic can be described simply as "computing with words rather than numbers", fuzzy control can be described simply as "control with sentences rather than equations". In general a fuzzy logic control system is a nonlinear mapping of an input data (feature) vector into a scalar output (the vector output case decomposes into a collection of independent multi-input/single-output systems). The basic elements of a fuzzy controller are: fuzzyfication, inference (rule-base) and defuzzyfication (see Figure 32). The system state, e.g. the traffic state on the mainline of a freeway, is measured via sensors, e.g. traffic detectors. The measured variables, e.g. speed and flow, are the input into the fuzzy controller. The crisp values are then fuzzified, inferred, and defuzzified to get a crisp output value for the actuators, e.g. the specific metering rate for a ramp metering signal. This control variable influences the system, e.g. the traffic on the mainline of a freeway. The time interval for the described control loop depends on the detection intervals and the minimum time a specific control variable, e.g. the metering rate, has to be implemented.
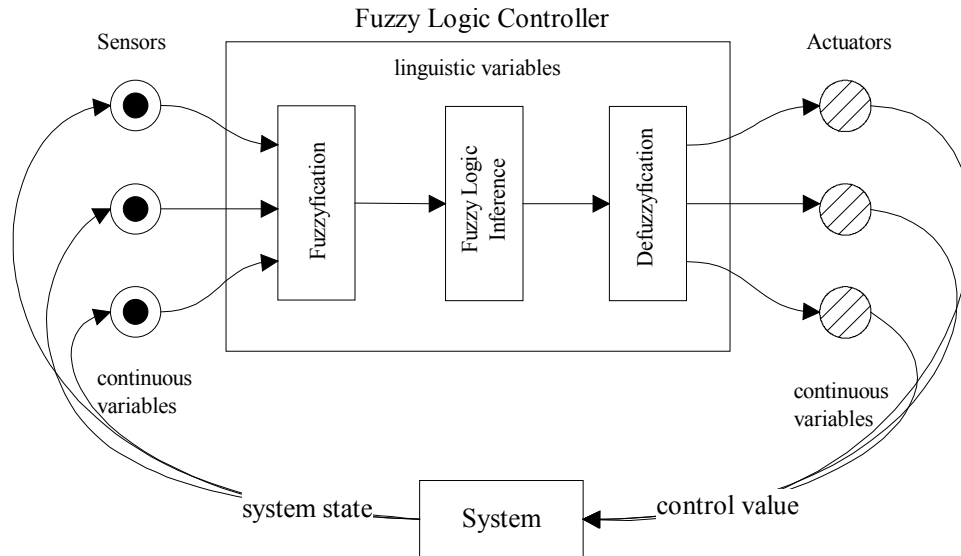

Figure 32: Fuzzy Control - General

The following sections are divided into five subparts. A general fuzzy logic controller for ramp metering is introduced and the three main parts, fuzzification, inference, and defuzzyfication are briefly described. Then further improvements based on recent developments in the field of soft computing are proposed to overcome one problem of fuzzy logic controllers which is the comprehensive design process based on the developer's knowledge and ability. Two different approaches, neuro-fuzzy control (ANFIS) and evolutionary fuzzy systems, to construct and calibrate a general fuzzy controller automatically (adaptive components) are mentioned. The result is the initial design of an adaptive fuzzy ramp metering control algorithm

Today two fuzzy logic based ramp metering algorithms have been implemented or tested, one in Seattle and one in Zoetermeer (Netherlands). The Seattle fuzzy logic approach is a coordinated ramp control algorithm, that appears to have been successfully implemented in the field and future expansion is planned. In the Netherlands a local traffic responsive fuzzy logic system has been tested. The evaluation results appeared very promising and the fuzzy algorithm outperformed two well-know local traffic responsive approaches (ALINEA and Demand-Capacity [RWS-Strategy]).

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4.2.2. Proposed Structure

Fuzzy logic seems to be well-suited for ramp metering for several reasons. The rule base, defined as the set of rules in the fuzzy logic algorithm, incorporates human expertise. Since rules are easy to define, alter or eliminate fuzzy logic allows simple development and modification. Fuzzy logic control is especially suitable when an accurate system model is unavailable. Without question, the freeway's complexity, nonlinear nature, and non-stationary behavior makes obtaining a model extremely difficult. Most traditional controllers are only as good as the system model and usually force nonlinear systems into a linear context. Because a fuzzy controller can handle nonlinear systems with unknown models, it has a distinct advantage over traditional controllers for the ramp metering problem.

To develop a ramp metering algorithm various input data from different sources or locations could be used. It is important to gain detailed knowledge from the current traffic conditions of the controlled area. Therefore occupancy or speed/flow from different mainline detector stations could be integrated as input data. By using the bottleneck capacity-reserve downstream the possibility to create a coordinated ramp metering system and to distribute the necessary metering rate over several on-ramps exists. Also additional input data like queue length on the on-ramps, predicted traffic data or public transport information could easily be integrated into the control scheme.

The output of the fuzzy control algorithm could be the specific metering rate or the cycle time for an on-ramp.

A general fuzzy logic controller for ramp metering is introduced and the three main parts, fuzzification, inference, and defuzzyfication are briefly described. After the theoretical description of the three parts of a fuzzy logic ramp metering controller a simple example is described. To overcome the conventional problems of the calibration process of fuzzy controllers an adaptive component, like a neural network or an evolutionary algorithm, could be added. Two different approaches, neuro-fuzzy control (ANFIS) and evolutionary fuzzy systems, to construct and calibrate a general fuzzy controller automatically (adaptive components) are mentioned. The result is the initial design of an adaptive fuzzy ramp metering control algorithm.

Fuzzyfication

The first block inside the controller is fuzzification, which converts each piece of input data to degrees of membership by a lookup in one or several membership functions. The fuzzification block thus matches the input data with the conditions of the rules to determine how well the condition of each rule matches that particular input. There is a degree of membership for each linguistic term[2] that applies to that input variable.

The designer of a fuzzy control algorithm is inevitably faced with the question of how to build the termsets. There are two specific questions to consider: (i) How does one determine the shape of the sets? and (ii) How many sets are necessary and sufficient? According to fuzzy set theory the choice of the shape and width is subjective, but a few rules of thumb apply.

- A term should be sufficiently wide to allow for noise in the measurements.

- A certain amount of overlap is desirable; otherwise the controller may run into poorly defined states, where it does not return a well defined output.

Speed or traffic flow could be classified according to the "Level of service" concept of the HCM. You get five classes of speed/flow according to the traffic state of the freeway (LOS A, LOS B, LOS C; LOS D, LOS E, LOS F), the same is possible for the occupancy as a input. As a starting point, all membership

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[2] Term: Humans describe special properties with terms, like the height of a man is described with the terms, "big", "small" etc.

functions for a particular input should be symmetrical triangles with the same width and at least with an overlap of 50%. The number of inputs from the mainline depends on the type and location of the detector stations. Additional input data (queue length, predicted traffic data, public transport information) could be coded with a similar procedure.

Not only the input variable have to be fuzzified but also the output variable. The membership function for the output could also be of triangular form. Three different values "high" "medium" and "low" could describe the metering rate (cycle time). The center of the triangular should be determined accordingly to the specific minimum (e.g. 240 vehph) and maximum (e.g. 960 vehph) metering rates.

Inference

The rules, sometimes called the knowledge base, are the heart of a fuzzy logic controller. Rules are based on expert opinions, operator experience, and system knowledge. Basically a linguistic controller contains rules of the following format.

<p align="center">IF <premise> THEN<consequent></p>

There is also the possibility to combine several premises with operators.

<p align="center">IF <premise 1> AND/OR <premise 2> AND/OR <premise 3> .....</p>

<p align="center">THEN <consequent></p>

Rule evaluation, based on fuzzy set theory, uses fuzzy operators to perform logical operations such as the complement, intersection, and union of sets. Complementation corresponds to one minus the membership degree in fuzzy set theory. For the AND-operation, analogous to the intersection of sets, usually the minimum of the given memberships is taken, but there are several other operators available. For the OR-operation, analogous to the union of sets, usually the maximum of the given membership degrees is taken, but there are also several other operators available. Each rule in the knowledge base can be weighted, especially if some rules seem to be more reliable or meaningful than others this is a very useful method.

If two different rules produce similar outputs a further reduction method is necessary. The two most common methods are the maximum and the additive method. The maximum method of rule deduction takes the maximum degree of membership for the output, since this corresponds to the union of two output sets. The additive method adds the two output degrees together. These two rule deduction methods produce different result, and the one that it most appropriate depends on the application.

After the fuzzy matching step, a fuzzy inference step is invoked for each of the relevant rules to produce a conclusion base on their matching degree. How should the conclusion be produced? There are two methods: (i) the clipping method and (ii) the scaling method. Both methods generate an inferred conclusion by suppressing the membership function of the consequent. The extent to which the membership functions are suppressed depends on the degree to which the rule is matched. The lower the matching degree, the more severe the suppression of membership functions. The clipping and scaling method produce their inferred conclusion by suppressing the membership function of the consequent differently. The clipping method cuts off the membership function whose value is higher than the matching degree. The scaling method scales down the membership function in proportion to the matching degree. Because a fuzzy rule based system consists of a set of fuzzy rules with partially overlapping conditions, a particular input to the system often "triggers" multiple fuzzy rules (e.g. more than one rule will match the input to a nonzero degree). Therefore a method is needed to combine the inference results of these rules. This is accomplished typically by superimposing all fuzzy conclusions about a variable. Figure 34 shows an inference diagram and all the above described steps can be followed easily. If the output variable is described by a fuzzy set the controller is called Mamdani fuzzy controller.

The consequent could also be chosen as a crisp value (singleton) or a linear combination of the crisp input values. This type of controller is called Sugeno-Takagi fuzzy controller. The rules could be described as followed:

$$\text{IF } \langle premise \rangle \text{ THEN } z = k$$

There is also the possibility to combine several premises with operators.

$$\text{IF } \langle premise\ 1 \rangle \text{ AND/OR } \langle premise\ 2 \rangle \text{ AND/OR } \langle premise\ 3 \rangle \text{ .....}$$

$$\text{THEN } z = k$$

This Controller is often used in combination with neural networks and has special properties which are very helpful for various learning techniques. All the operators are identical to the Mamdani type controller, but the interpretation is often not as intuitive.

The number and type of rules for a ramp metering algorithm depends on the specific site, the number of detector stations the implemented control strategy etc. The number and type of input data should describe the current traffic situation as precise as possible and based on this a corresponding metering rates (cycle time) could be determined. A typical rule could be of the following format:

$$\text{IF } \langle traffic\ flow = LOS\ B \rangle \text{ AND/OR } \langle speed = LOS\ B}$$

$$\text{THEN } \langle metering\ rate = low \rangle$$

The rules are based on expert opinions, operator experience, and system knowledge. They can either be extracted manually, e.g. from expert interviews, or automatically (see "adaptive component" discussed later) by learning them from existing input-output data. When applying a neural network based learning technique the design of a Sugeno type controller is often necessary. The choice of the different operators is of minor importance on the final result and can be modified easily.

Defuzzyfication

For a fuzzy system whose final output needs to be in a crisp (nonfuzzy) form (specific metering rate, cycle time), a conversion from the final combined fuzzy conclusion into a crisp one is needed. This step is called defuzzyfication. There are two major defuzzyfication techniques: (i) the Mean of Maximum method and (ii) the Center of area or the centroid method. The mean of maximum defuzzyfication calculates the average of all variable values within maximum membership degree.

For the Defuzzyfication process in a ramp metering algorithm a center of gravity approach could be used, this helps to suppress parameter variations and stochastic disturbances, and the fuzzy logic algorithm will produce an appropriate output given uncertain or incomplete information, e.g. from the inductive loop detectors. The crisp output of the controller is the metering rate (cycle time) of the controlled on-ramp.

Example of a simple ramp Metering Fuzzy Controller

To describe the different procedures of a fuzzy controller a very simple example of a local traffic responsive ramp metering algorithm based only on mainline detector data is constructed. Similar to the occupancy control strategy a detector is located upstream of the on-ramp and is collecting speed and flow data every minute as input for the controller. The flow is described by the terms "low" and "high". Speed can either by "low" or "fast". The output of the fuzzy controller is the metering rate for the corresponding on-ramp. The two membership functions for the metering rate are "high" and "low". For every membership function of the controller a triangular shape is assumed. The implemented rules are:

1. IF $\langle traffic\ flow = high \rangle$ AND $\langle speed = low \rangle$

   THEN $\langle metering\ rate = high \rangle$

2. IF $\langle traffic\ flow = high \rangle$ AND $\langle speed = high \rangle$

   THEN $\langle metering\ rate = high \rangle$

3. IF $\langle traffic\ flow = low \rangle$ AND $\langle speed = low \rangle$

THEN <metering rate = high>

4. IF <traffic flow = low> AND <speed = high>

THEN <metering rate = low>

	"low"	"high"
Speed	30 mil/h	60 mil/h
Flow	1333 vehph	2666 vehph
Metering Rate	480 vehph	720 vehph

Table 1: Parameters of the triangular membership functions

In Table 1 and Figure 33 the parameters and the shape of all the membership functions are illustrated. All membership functions for the input- and output-values are symmetrical triangles with the same width and an overlap of 50%.
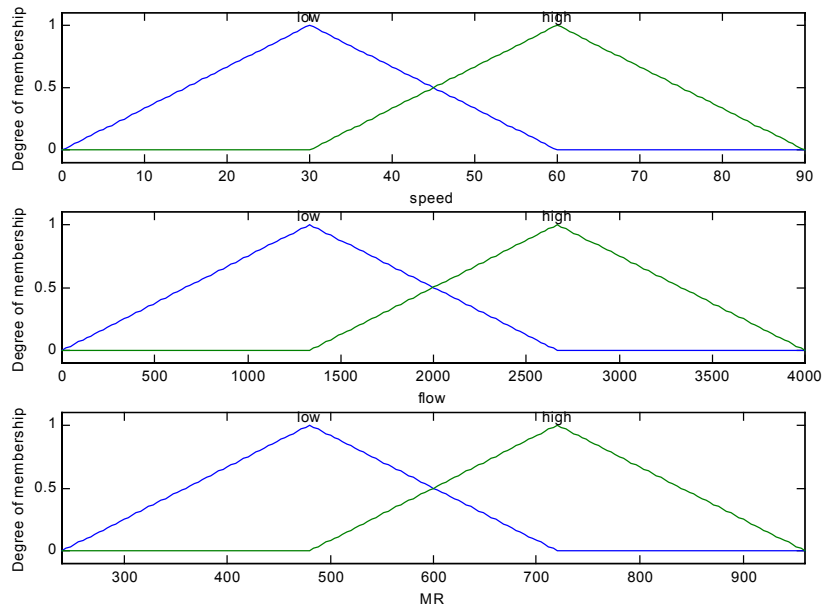
Figure 33: Membership Functions for Speed, Flow and Metering Rate

Figure 34 describes the principle of the inference process of the fuzzy controller. The minimum operator is implemented for the AND-operation and the "center of gravity"-method for the defuzzyfication. The example is evaluated for a speed of 45 mil/h and a flow of 2350 veh/h (see Figure 35). The corresponding metering rate is 640 veh/h.

This simple example already illustrates the very high number of degrees of freedom of a fuzzy logic controller. Thus the calibration process is very comprehensive and difficult. In the following section two methods are briefly described, which extract the information of existing data, e.g. already existing algorithms. This information can be incorporated into a fuzzy logic algorithm and a fast implementation and calibration is the result.
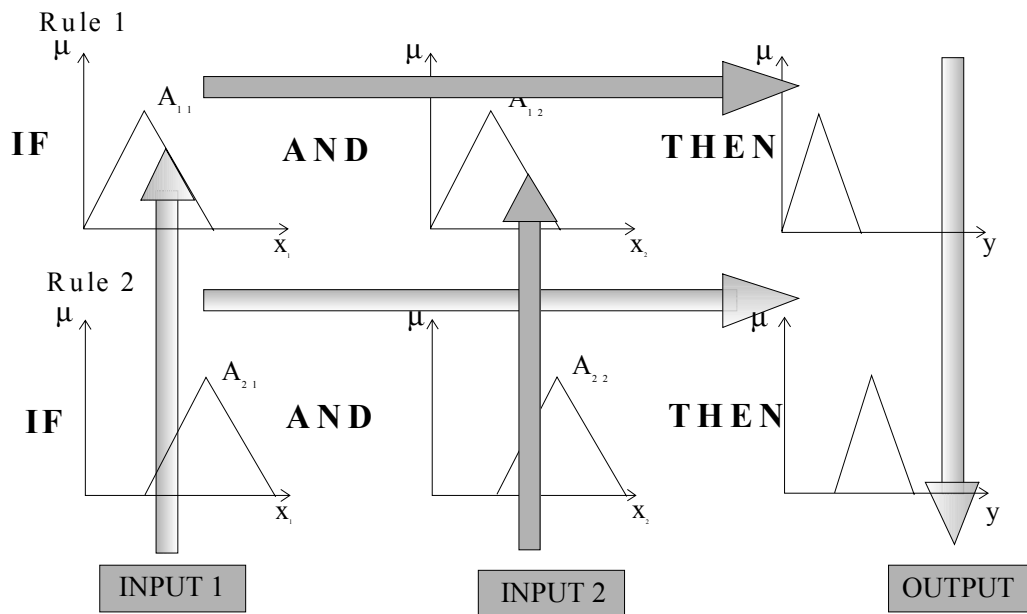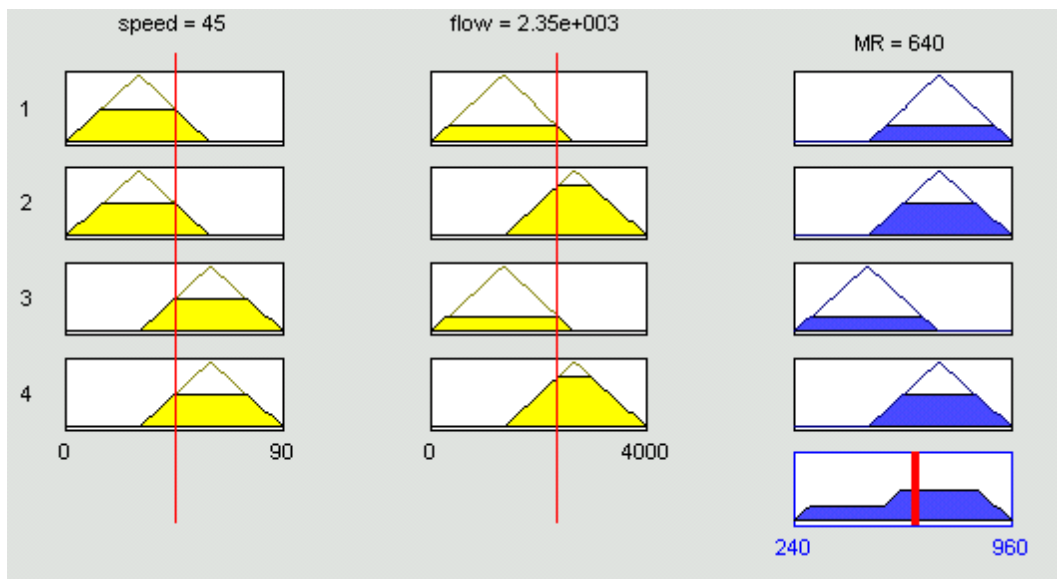
Figure 34: Fuzzy Logic Conceptual Process

Figure 35: Ramp Metering Fuzzy Logic Controller, 2 Inputs - 1 Output

Adaptive Component

A fuzzy system can be used to solve a problem if knowledge about the solution in the form of linguistic if-then rules exists. By defining suitable fuzzy sets to represent linguistic terms used within our rules, a fuzzy system from these rules can be created. A formal model of the problem of interest is not necessary, and also need training data, which may be expensive to obtain, are not needed. On the other hand without if-then rules a fuzzy system is almost impossible to derive, and to make the fuzzy system work a long tuning process may be needed. For this stage of implementation process there are no formal methods, so that only heuristics can be applied. The expert knowledge for a fuzzy ramp metering system might be obtained e.g. from operators at a TMC, from researchers etc, but the calibration/tuning effort for each on-ramp controller is almost always very high.

In addition to the already described algorithm an adaptive component could be added to the fuzzy logic system. The idea of an adaptive fuzzy system is to find the parameters of a fuzzy system by means of learning/optimization methods obtained from neural networks or evolutionary computing. An advantage of an adaptive fuzzy system is the possibility to incorporate already existing information of other algorithms or to emulate them in an early stage of development or implementation. The developed rule-base and the membership functions with the learning/training results can be cross-checked. This can be done offline or online during the use of the fuzzy system. The design process gets more efficient and reliable.

In this section two methods for tuning the parameters of the membership functions of the antecedent and consequent of the rule-base are described, the expert has to determine the rule-base and there are no automatic modifications. If nothing about the rules is known, there are also similar procedures existing that allow determining the rules automatically, but these are not described in this paper.

Basically there are two different approaches of learning/training a fuzzy control system. The first one is to provide an input-output data set and to incorporate the information contained in the data set into the fuzzy control system either by modifying/adding rules or by calibration of the membership functions. For a ramp metering algorithm an input-output database could be generated by recording the input and output data of a general or already existing ramp metering algorithm, e.g. ALINEA [Papageorgiou et al., 1991] etc. This data set is then used for training/learning of our adaptive fuzzy system. The result is a fuzzy control algorithm emulating the chosen algorithm, e.g. ALINEA, and producing similar results. This can either be helpful for a fast implementation and a later extension of the fuzzy system or for the validation of the manually calibrated system. A neuro-fuzzy system seems to have the capabilities for doing this.

The second possibility is to observe traffic data and to develop a objective function and to determine a target value. The effect of our fuzzy ramp metering algorithm is measured via simulation, e.g. FREQ. The objective (target value) should be reached as good as possible by modifying either the rules or the properties of the membership functions. The described process could be viewed as an optimization process. For solving this type of problem an evolutionary fuzzy system is probably the best choice.
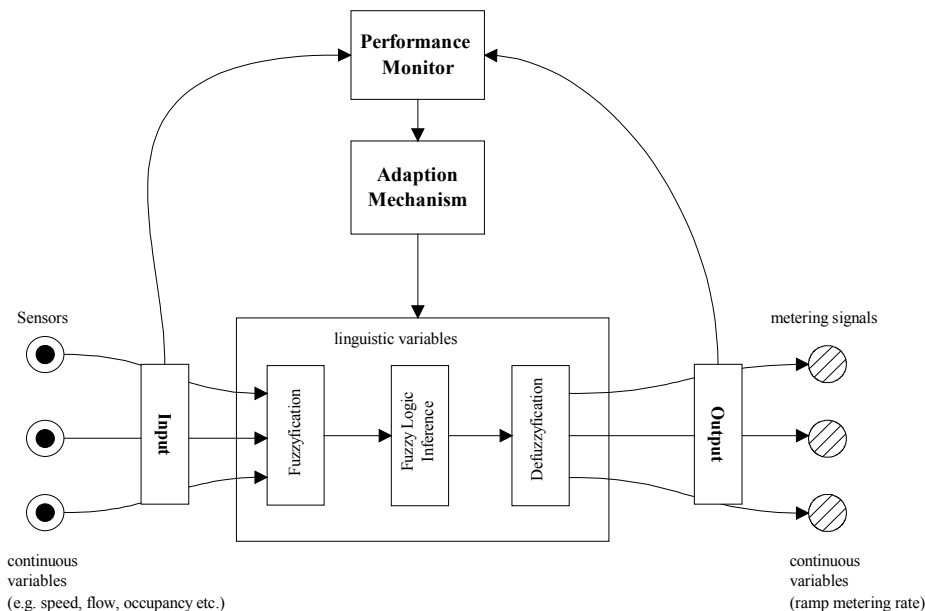

Figure 36: Adaptive Fuzzy Control

Neuro-Fuzzy System

A very interesting approach for an adaptive fuzzy control system is the combination of a neural network and a fuzzy system to obtain the advantages of both paradigms while avoiding their individual drawbacks.

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On the one hand, the theory of fuzzy logic provides a formal framework to abstract the approximate-reasoning characteristics of human decision making and, furthermore, conveys an excellent mode of knowledge representation in the form of if-then rules. However, a common bottleneck in a fuzzy logic control system is their dependence on the specification of good rules by human experts. Neural networks, on the other hand, attempt to replicate the learning capabilities possessed by biological species, but it not always possible to extract and interpret the learned knowledge within them. The integration of these two paradigms is called neuro-fuzzy systems and tries to capture the capabilities and advantages of both neural and fuzzy systems. One of the most popular systems of this type is called ANFIS (Adaptive Neuro-Fuzzy Interference System) [Jang, 1993].
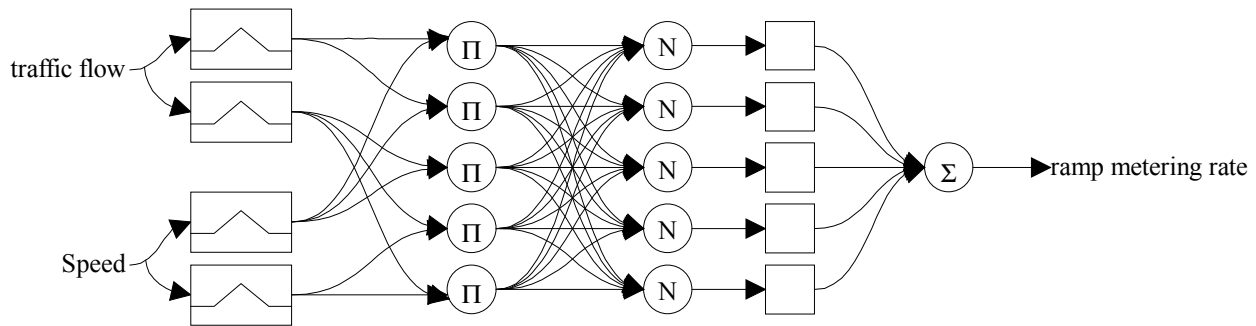

Figure 37: ANFIS-Architecture for a Ramp Metering Algorithm

ANFIS is based on special hybrid architecture. I represents a Sugeno-type fuzzy system in a special five-layer feedforward network architecture (see Figure 37). Only differentiable functions are allowed, this makes it easy to apply standard learning procedures from neural network theory. For ANFIS a mixture of backpropagation (gradient decent) and least square estimation is used to learn the patterns of the provided traffic data - ramp metering rate (cycle time) data set. Backpropagation is used to learn the antecedent parameters, e.g. the membership functions, and least square estimation is used to determine the parameters of the linear combinations in the rules' consequent. A step in the learning procedure has two parts. In the first part the input patterns, traffic data, are propagated, and the optimal consequent parameters are estimated by an iterative least mean squares procedure, while the antecedent parameters are assumed to be fixed for the current cycle through the training set. In the second part the patterns are propagated again, and in this epoch backpropagation is used to modify the antecedent parameters, while the consequent parameters remain fixed. This procedure is then iterative. After learning all the parameters a calibrated Sugeno-type fuzzy control system is received, which can easily be interpreted. It will produce similar results as the algorithm used for receiving the training data set.

Evolutionary Fuzzy System

The identification of parameters in a fuzzy model can be viewed as an optimization problem, finding parameter values that optimize the model based on given evaluation criteria. Therefore, search and optimization techniques can be applied to parameter identification as well. Evolutionary Computation is a class of computation techniques that are based on Darwin's models of biological evolution, it includes genetic algorithms, evolutionary strategies, and evolutionary programming. These approaches are global search and optimization techniques modeled from natural genetics, exploring search space by incorporating a set of candidate solutions in parallel. All of them can perform search and optimization in a large and complex space.

A evolutionary approach maintains a population of candidate solutions where each candidate solution is usually coded as a string (genetic algorithm: binary string) called a chromosome. A chromosome, also referred to as a genotype, encodes a parameter set (i.e., a candidate solution) for a set of variables being optimized. Each encoded parameter in a chromosome is called a gene. A decoded parameter set is called a phenotype. A set of parameters, e.g. the properties of the membership functions of the fuzzy control algorithm, forms a population , which is evaluated and ranked by a fitness evaluation function. The fitness

evaluation function plays a critical role in an evolutionary approach because it provides information about how good each candidate solution is. This information guides the search of an evolutionary algorithm. More accurately, the fitness evaluation results determine the likelihood that a candidate solution is selected to produce candidate solutions in the next generation. The evolution from one generation to the next one involves mainly three steps: (i) fitness evaluation, (ii) selection, (iii) reproduction. First, the current population is evaluated using the fitness evaluation function and then ranked based on their fitness values. Second, "parents" are stochastically selected from the current population with a bias that better chromosomes are more likely to be selected. Third, "children" are produced from selected "parents", using two genetic operations: crossover and mutation. This cycle of evaluation, selection, and reproduction terminates when an acceptable solution is found, when a convergence criterion is met, or when a predetermined limit number of iterations is reached.
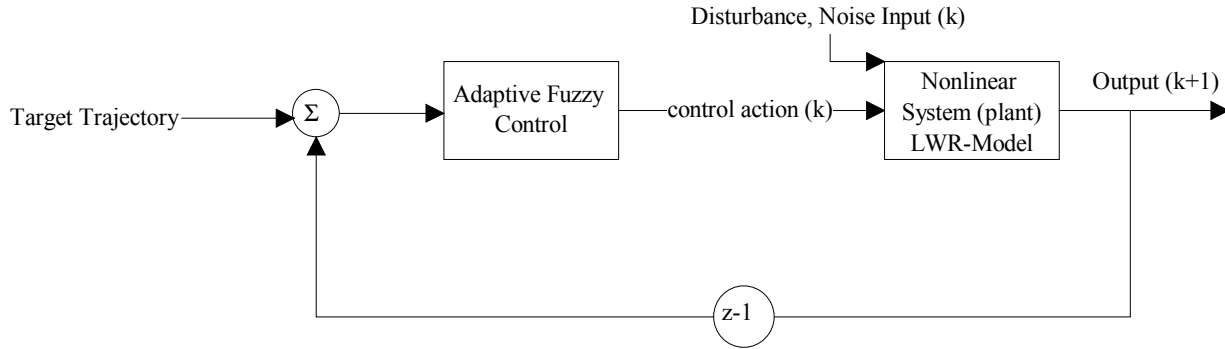

Figure 38: Adaptive Fuzzy Control - Evolutionary Algorithm

For the calibration of a fuzzy ramp metering algorithm, the properties of the membership functions can be coded as a chromosome and optimized with the above mentioned procedure. In this case a Mamdani-type control model can be used. The nonlinear plant (see figure 38) could be modeled with the Lighthill, and Whitham, and Richards traffic flow model (LWR-Model). This model provides a simple and tractable framework for traffic simulation and control studies. It gives good results in describing such traffic phenomena as shock waves at bottlenecks, progression of a traffic hump, and starting and stopping traffic at intersections. The noise or disturbance vector is given by the measured, incoming traffic flow on the mainline. The target value or objective of a traffic responsive fuzzy ramp metering algorithm is to maintain the desired level of service for the freeway system being controlled, such that the freeway system is utilized as fully as possible. The fundamental diagram tells us that there is a limit to how much traffic a freeway lane can carry. This limit, often termed capacity, represents the most efficient use of a freeway facility and is therefore a desirable objective to achieve. The error between the objective (target value) and the actual determined flow is the evaluation function and should be minimized with the above described method. Different constraints, such as maximum/minimum metering rates or maximum queue length on the on-ramp, can be added easily. The result of the optimization is a calibrated Mamdani-type fuzzy ramp metering system, that is easy to interpret and adapts itself to the given environment.

4.2.3. Summary

This section of the paper proposed and described two different approaches of adaptive fuzzy ramp metering algorithms. A general fuzzy logic control algorithm for ramp metering was briefly described and further improvements based on recent developments in the field of soft computing were proposed to overcome one problem of fuzzy logic controllers, the comprehensive design process based on the developer's knowledge and ability. The results were two adaptive fuzzy ramp metering control algorithm.

First a neuro-fuzzy system was described based on the ANFIS architecture. The objective was to emulate an existing algorithm and to calibrate a fuzzy system by learning from existing input-output data sets.

Second an evolutionary fuzzy system was introduced, self adaptation being its unique feature. Both adaptive fuzzy algorithms seem to be very promising but further investigations are necessary.

5. CONCLUSIONS

The objective of this report was to introduce different coordinated traffic responsive ramp control algorithms, implemented or not-implemented, but based on promising new mathematical techniques. A total of 17 different ramp metering approaches was described, 10 of them implemented and 7 proposed in the literature.

For the already implemented algorithms, the historical background, the network, the algorithm and the main references are described.. The proposed ramp control approaches are briefly described and the literature references are included. These two chapters provide a comprehensive resource for researchers and developers in the field of ramp metering control strategies as a starting point for there literature review and analysis.

Two possible directions of ramp metering for the future are qualitatively described. Based on the literature review, online simulation and fuzzy logic seem to be two very powerful approaches to be considered in the future. The <u>hierarchic</u> and <u>dynamic</u> characteristics of the online simulation ramp control system are its unique features. The on-line simulation approach is designed to handle both recurring and non-recurring congestion situations. The adaptive fuzzy logic control approach allows a fast and reliable calibration of the existing parameters and the controller adapts itself to a new environment or to changes of the traffic patterns. Two different adaptive components, neuro-fuzzy systems (ANFIS) and evolutionary strategies are introduced.

Further research is needed to allow a successful implementation of these new approaches. Freeway ramp control is now over thirty years old. Much has been accomplished - much remains.

ACKNOWLEDGEMENTS

REFERENCES

D. DRIANKOV, H. HELLENDORN, M. REINFRANK; An Introduction to Fuzzy Control; Springer Verlag; 1993.

E. MAMDANI; Application of Fuzzy Algorithms for Control of Simple Dynamic Plant; Proceedings of the IEE 212, page 1585 - 1588; 1974.

A. D. MAY; A Dynamic Control System Hierarchy; Proceedings of Research Directions in Computer Control of Urban Traffic Systems; Pacific Grove 1979.

A. D. MAY; Traffic Flow Fundamentals, Prentice Hall, 1990

K. M. PASSINO, S. YURKOVICH; Fuzzy Control; Addison-Wesley; 1998.

G. PIOTROWICZS J. ROBINSON; Ramp Metering Status in North America; DOT-T-95-27; Federal Highway Administration, Washington D.C.; 1995

T. J. ROSS; Fuzzy Logic with Engineering Applications; McGraw-Hill; 1995.

H. TAALE, J. SLAGER, J. ROSLOOT; The Assessment of Ramp Metering Based on Fuzzy Logic; 3rd ITS World Congress in Orlando, 1996.

D. TEODOROVIC; Fuzzy Logic Systems for Transportation Engineering: The State of the Art; Transportation Research Part A 33; page 337 - 364; 1999.

L. H. TSOUKALAS, ROBERT E. UHRIG; Fuzzy and Neural Approaches in Engineering; John Wiley & Sons; 1997.

L. ZADEH; Fuzzy Sets; Information and Control 8, page 338 - 353; 1965.

APPENDIX - RAMP METERING DEPLOYMENTS

RAMP METERING IN THE UNITED STATES

State	City	Population [Thousand]³	# of Ramps	WWW
Alabama	Birmingham	258	0	http://www.dot.state.al.us/
Alaska	Anchorage	250	0	http://www.dot.state.ak.us/
Arizona	Phoenix	1503	65	
	Tuscon	449	0	http://www.dot.state.az.us/
Arkansas				http://www.ahtd.state.ar.us/
California	Fresno	396	15	http://www.dot.ca.gov/
	Los Angeles	4000	808	
	Oakland	367	0	
	Orange County	590	278	
	Sacramento	367	0	
	San Bernadino	500	51	
	San Diego	1171	134	
	San Francisco	735	0	
	San Jose	838	96	
Colorado	Colorado Springs	345	0	http://www.dot.state.co.us/
	Denver/Aurora	739	30	
Conneticut				http://www.state.ct.us/dot/
Delaware				http://www.state.de.us/deldot/
Florida	Jacksonville	679	0	http://www.dot.state.fl.us/
	Miami	365	0	

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³ CIA World Factbook 1998

	Tampa	285	0	
Georgia	Atlanta	401	5	http://www.dot.state.ga.us/
Hawaii	Honolulu	423	0	http://www.hawaii.gov/transportation/index.html
Idaho				http://www.state.id.us/itd/itdhmpg.htm
Illinois	Chicago	2721	110	http://www.dot.state.il.us/
Indiana	Indianapolis	746	0	http://www.ai.org/dot/
Iowa				http://www.state.ia.us/government/dot/
Kansas	Witchita	320	0	
Kentucky	Louisville	260	0	http://www.kytc.state.ky.us/
Louisiana	New Orleans	476	0	http://www.dotd.state.la.us/
Maine				http://www.state.me.us/mdot/homepage.htm
Maryland	Baltimore	675	0	http://www.mdot.state.md.us/
Massachusetts	Boston	558	0	http://www.magnet.state.ma.us/mhd/home.htm
Michigan	Detroit	1000	50	http://www.magnet.state.ma.us/mhd/home.htm
Minnesota	Minneapolis/St. Paul	617	310	http://www.dot.state.mn.us/
Mississippi				
Missouri				http://www.modot.state.mo.us/

State	City			URL
	Kansas City	441	0	
	St. Louis	351	0	
Montana				http://www.mdt.mt.gov/
Nebraska	Omaha	364	0	
Nevada	Las Vegas	376	0	http://www.state.nv.us/ndot/index.html
New Hampshire				
New Jersey	Newark	268	0	http://www.state.nj.us/transportation/
New Mexico	Albuquerque	419	0	http://www.state.nm.us/state/transport.html
New York	Buffalo	310	0	http://www.dot.state.ny.us/
	New York	7380	75	
North Carolina	Charlotte	441	0	http://www.dot.state.nc.us/
North Dakota				
Ohio	Cincinnati	345	0	http://www.dot.state.oh.us/
	Cleveland	498	0	
	Columbus	657	0	
	Toledo	317	0	
Oklahoma	Oklahoma City	469	0	http://www.dot.state.oh.us/
	Tulsa	378	0	
Oregon	Portland	480	60	http://www.odot.state.or.us/
Pennsylvanina	Philadelphia	1478	12	http://www.dot.state.pa.us/penndot/geninfo.nsf/homepage?readform
	Pittsburgh	350	0	

State	City	Number	URL
Rhode Island			http://www.doa.state.ri.us/dot/index.htm l
South Carolina			http://www.dot.state.sc.us/
South Dakota			
Tennessee	Memphis	596	0
	Nashville	511	0
Texas			http://www.dot.state.tx.us/
	Arlington	249	0
	Austin	541	0
	Corpus Christi	280	0
	Dallas	1053	5
	El Paso	599	0
	Fort Worth	479	0
	Houston	1744	19
	San Antonio	1067	0
Utah			http://www.dot.state.ut.us/
	Salt Lake City	172	8
Vermont			http://www.aot.state.vt.us/
Virginia			http://www.vdot.state.va.us/
	Arlington	392	26
Washington			http://www.wsdot.wa.gov:80/
	Seattle	524	54
West Virginia			http://www.wsdot.wa.gov:80/
Wisconsin			http://www.dot.state.wi.us/
	Milwaukee	590	43
Wyoming			http://wydotweb.state.wy.us/

RAMP METERING OUTSIDE THE UNITED STATES

State	City	Population	# of Ramps	WWW
Argentina	Buenos Aires	2960	0	
Australia	Sydney	3713	0	
	Melbourne	3189	0	
Austria	Vienna	1560	0	
Brasil	Sao Paolo	9842	0	
	Rio de Jainero	5547	0	
Britain	London	6962	0	
	Bimingham	265	6	
	Glasgow	680	1	
China	Peking	7362	0	
Canada	Toronto	635	10	http://www.mto.gov.on.ca/english/travel ler/compass/compass/rms.htm
France	Paris	2152	3	http://www.sytadin.tm.fr/index_paris.ht ml
Germany	Munich	1244	3	www.bayerninfo.de
	Duisburg	536	28	
Italy	Rome	2693	0	
	Milano	1371	0	
	Turin	961	0	http://www.peektraffic.nl/en/product/UT S_Utopia.htm

Japan	Tokyo	8021	0
	Kobe	1518	2
Mexico	Mexico City	8235	0
Netherlands	Coentunnel		5
	Amsterdam	723	4
	Zoetermeer	104	9
New Zealand	Auckland	321	2
Russia	Moskau	8436	0
South Korea	Seoul	10776	0
Spain	Barcelona	1596	0
	Madrid	2976	0
Sweden	Stockholm	703	2