Adaptive Fuzzy Systems for Traffic
Responsive and Coordinated
Ramp Metering

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ABSTRACT
This paper describes new adaptive fuzzy algorithms for coordinated ramp metering. The new model family named ACCEZZ (Adaptive and Coordinated Control of Entrance Ramps with Fuzzy Logic) was developed to overcome the limitations of existing coordinated ramp metering algorithms. Each model is explained, evaluated via simulation, and compared to other ramp metering approaches in several scenarios.

Coordinated ramp metering is achieved in the ACCEZZ models by applying fuzzy control to a series of entrance ramps where the interdependency of ramp operations is taken into account. A simple fuzzy ramp metering controller for each metered on-ramp is the core of each version of the ACCEZZ models. Learning/Optimization methods drawn from both neural network theory and genetic algorithms are used to find the optimal ramp metering strategy. The resulting systems are either called neuro-fuzzy or genetic fuzzy ramp metering.

The performance of the ACCEZZ models was assessed in a simulation context with a microscopic traffic flow model and compared with the results of five different standard ramp metering algorithms: demand-capacity, occupancy strategy, ALINIA, Denver's HELPER algorithm, and Minnesota's Zone approach. The total time spent in the system was used to evaluate the overall system performance of a strategy, since it includes both travel times and ramp delays. Additionally, the traffic densities, waiting times, queue lengths, fuel consumption, and pollutants were compared.

One of the ACCEZZ models will be installed in Munich at the Olympic interchange of the ring road this autumn within the MOBINET project.
INTRODUCTION

In the last decade a broad variety of deterministic and/or stochastic models have been developed to solve the complex coordinated ramp metering problem. Using these mathematical techniques, different formulae and equations have been applied to solve this problem. However, when solving real life problems like traffic responsive and coordinated ramp metering, linguistic information is often encountered that is often difficult to quantify using "classical", crisp mathematical techniques. This linguistic information represents subjective knowledge. When solving real-life traffic and transportation problems in the future not only objective knowledge or subjective knowledge should be used.

Fuzzy logic is an extremely flexible concept to combine subjective knowledge and objective knowledge. 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. The fuzzy controller compensates for poor, inaccurate measurements. Fuzzy control is especially suitable when an accurate system model is unavailable. Without question, traffic's complexity, nonlinear nature, and non-stationary behavior make exact quantifying a control 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. Successful implementations in Seattle and Amsterdam already showed this (1).

In the remainder of this paper, the main characteristics of the ACCEEZ models are described. The test site and the methodology of the evaluation are explained and the simulation results of several ramp metering algorithms in three different scenarios are presented.

THE ACCEEZ MODELS

The heart of the ACCEEZ model family is a fuzzy controller (see Figure 1). The general fuzzy ramp metering controller used in the ACCEEZ models has a total of seven inputs (see Figure 3). These inputs and the number of fuzzy sets were identified as the most important ones by analyzing existing algorithms, considering a typical German detector setup, and testing in simulation (2). Local speed, local traffic flow and local occupancy on the mainline are measured immediately upstream of the on-ramp merge. Because the fuzzy controller used in this research is applied for both congested and free-flow traffic, it is preferable to consider the local occupancy as a clear mainline input variable instead of traffic flow. Traffic flow may have the same values for light and congested traffic because of the characteristic form of the fundamental diagram. An additional advantage of choosing the occupancy rather than the flow as an input variable arises from the fact that the occupancy at capacity seems to be less sensitive with respect to weather conditions and other operational influences. The downstream volume/capacity ratio (v/c ratio) is the measured downstream volume (flow) divided by the capacity of the major downstream bottleneck. The downstream bottleneck capacity can be calculated from historical frequencies of measured maximum flows on the mainline. The v/c ratio is integrated into the control logic because it is a very intuitive and popular measurement in traffic engineering of the bottleneck behavior and it ensures the feedback of the system output. The downstream speed is the one associated with the downstream flow. The queue occupancy input is from a detector typically located at the end of the ramp storage. The check-in occupancy input is from a detector located at the ramp metering stop line. The detector data from the on-ramp should help to avoid a spillback of the queue onto the secondary road network. All of the inputs use 1-minute data because sharp oscillations are smoothed while still providing a quick response to the changing traffic conditions. The output of the fuzzy controller, the metering rate, is also controlled speed input.

This standard rule base for the ACCEEZ models was determined from heuristic expertise, knowledge and simulation testing (1). One of the main objectives during the design process of the rule base was to take advantage of the properties of fuzzy control systems, which are known to be easy to understand, transparent, and intuitive. Thus, the ACCEEZ rule base contains as many rules as necessary but not as many as possible.

The clear definitions for each fuzzy input and output variable, the rules need flexibility. Hence, each rule is assigned a weight indicating its importance (see Table 1). If a rule is more important of more reliable than other rules, it has a greater weight. Another factor to consider is that the rule base does not consider all of the possible input combinations individually. If the rule base were incomplete it is possible to find rules that would be activated for certain inputs. This problem is solved by completing the rule base with the local occupancy input (see Figure 1, III, called the first block of rules. Because the entire range of local occupancy inputs is considered, at least one of these three rules will fire all the time. The second block of rules, rules No. IV to No. VII adjust the mainline set according to the mainline speed coupled with either the local occupancy or the local flow. The empirical knowledge about the fundamental relationship between flow and speed is used to get a more specific congestion index. Note
that rules III and IV have relatively higher weights. The reason for this is to restrict the metering rate when the vehicles are unable to merge onto the freeway’s mainstream. When the main direction is highly congested, a secondary queue of metered vehicles may form. To maximize the system-wide benefit in this event, the vehicles are typically better off steered on the on-ramps than contributing to a mainline bottleneck at the merge. Rule No. VIII and IX form the most important block of rules. The objective of rule VIII is to mitigate the formation of a downstream bottleneck. When congestion begins to form downstream of the on-ramps, a restrictive metering rate is desirable to prevent or delay the breakdown. The high weighting of this rule reflects that this is the primary way in which coordinated ramp metering benefits mainline efficiency. This rule guarantees a first level of coordination of all on-ramps upstream of the major bottleneck. All other rules depend just on the local traffic conditions, only rule No. XIII takes further downstream traffic conditions into consideration. Rule IX is designed to prevent excessive queue formation on the on-ramps and to avoid a spillback onto its secondary road network. The weighting of this rule was adjusted to achieve the desired balance between alleviating mainline congestion and maintaining the desired number of stored vehicles.

For the AND-operation within the ramp metering algorithm, analogous to the intersection of sets, the minimum of the given membership degrees is used. For the OR-operation, analogous to the union of sets, the maximum of the given membership degrees is used. Before calculating a numerical result, the activation step scales each rule’s output class by its activation degree. The multiplication method is used because it produces a slightly smoother control signal than the clipping method. 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). If two different rules produce similar outputs, a further reduction method is necessary, the so-called accumulation step. The sum method of rule deduction calculates the sum of the algebraic values for each rule. This method is expected to be less sensitive to input data detected by the fuzzy AND method. In the rule, the maximum method will choose the faulty value because it is the most extreme, the sum method will average each rule contribution. By averaging rule outcomes, the control action should be smoother. The implemented logical operations and inference methods in the ramp metering algorithm represent the most widely used standard techniques of fuzzy control.

Of course, the above described fuzzy ramp metering controller could also be used as a simple coordinated traffic responsive metering algorithm without any further coordination and adaptation procedures. In the ACCEZZ models, based on this simple fuzzy controller, the shape of each input or output fuzzy set at each on-ramp location of the metered freeway is adjusted dynamically. In other words, one way of modifying the behavior of the ramp metering algorithm is by recalibrating the parameters of each fuzzy set, i.e. redefining the linguistic variables. This is particularly useful when there are changes in the traffic patterns or if the data are inaccurate. The tuning of the FIS can be done automatically by learning/optimization procedures. Learning/optimization methods obtained from neural network theory (4) or evolutionary algorithms (5) are used to find the optimal parameters of the fuzzy system. The resulting systems are either neural-fuzzy or genetic fuzzy ramp metering (see Figure 3). A so-called ANFIS (5) architecture is used for the neuro-fuzzy system. In each ACCEZZ model coordinated ramp metering is achieved by applying fuzzy control to a series of entrance ramps where the interdependence of ramp operations is taken into account. A special two-stage process is integrated into the control architecture, including a common bottleneck performance measurement and a dynamic freeway traffic model. As a performance monitor of the entire traffic system a traffic system model and a queuing model are integrated into the ramp metering approach. The control inputs are the major downstream bottleneck are considered in each upstream ramp system. The second stage of coordination of the proposed algorithm is to capture the dynamic traffic state evolution and to coordinate all interacting ramps to achieve a global system optimum. By considering the freeway as a control system instead of one section at a time, the adaptive fuzzy approaches should avoid an oscillatory ramp metering rate and should achieve equilibrium more quickly and smoothly. The calculated metering rates provide a significantly improved coordination strategy.

The neuro-fuzzy ACCEZZ ramp metering model implements a Takagi-Sugenoma type model that partitions the input space using differentiable functions (see Figure 2 and 3). The metering rate, the output of the ACCEZZ model, is calculated by a linear combination of the inputs every minute. The nine rules of the general fuzzy ramp metering algorithm are used and they remain unchanged during the adaptation process. ACCEZZ is based on the hybrid architecture of ANFIS. It represents the general fuzzy ramp metering system in a five-layer feedforward network architecture. The objective of the learning process of the fuzzy parameters is to minimize the total time spent in the metered freeway system (TTS). For this purpose a macroscopic traffic flow model and a deterministic queuing model are used to calculate the objective value (error) within the learning procedure. These simple models provide a simple framework for traffic simulation and control studies. The macroscopic traffic flow model METANET (6) gives good results in describing such traffic phenomena as hump waves at bottlenecks and the
progression of a traffic shock. The integration of a traffic model which evaluates the different coordinated ramp metering strategies consisting of all the single fuzzy controllers for the metered freeway helps to find (as the result of the learning procedure) the same system-wide strategy. A special hybrid learning algorithm has been developed and can be applied. More specifically, in the forward pass of the hybrid learning algorithm, the outputs go forward and the consequent parameters are identified by the least-squares method. In the backward pass, the error signals propagate backwards and the premise parameters are updated by gradient descent. During the learning procedure the shapes of the membership functions are changed, the rule base is considered to be exact and thus not changed during the learning process. A total of 1000 epochs was used for learning the optimal strategy for the next time interval.

In the novel genetic fuzzy ACCEZZ architecture the traffic performance is measured via detectors and controlled by ramp meters at the freeway entries (see Figures 2 and 3). The noise or disturbance vector is given by the measured traffic flow on the mainline. The control action is determined every minute by the fuzzy control algorithm. Again the coordination between consecutive ramps is again guaranteed by a two-stage approach. The first stage of coordination is embedded in the single fuzzy controller of each on-ramp as a specific input of the major downstream bottleneck and corresponding via (Rule No. XII). The second stage of coordination is included in the genetic algorithm. The genetic algorithm determines the optimal coordinated parameters of the fuzzy ramp metering controllers based on a macroscopic traffic system model. An optimal solution is determined and implemented. The objective of the optimization is to minimize the total time spent in the system. For this purpose the macroscopic traffic flow model METANET and a deterministic queueing model are used. The integration of a traffic model which evaluates the different overall strategies consisting of all the single fuzzy controllers for the metered freeway helps to find (as the result of the optimization procedure) the best system-wide strategy of all single traffic responsive ramp metering controllers. For the genetic fuzzy ACCEZZ model the parameters of the fuzzy system have to be converted into a real valued string called chromosome with a gene representing each parameter. In the genetic fuzzy ACCEZZ models a special novel coding scheme for the membership functions was used. The distances between starting points or, endpoints of the fuzzy sets were encoded depending on the shape of the triangle or polygon. With this intelligent coding even more complicated constructions can be incorporated into the genetic algorithm. For example, it is desirable that the set of parameters is monotonically increasing because they represent linguistic terms like "low", "medium", "high". Then each center (parameter) is coded as the positive distance from the previous center (parameter). This ensures that during the whole optimization procedure "low" is less than "medium", "medium" is less than "high", etc. The genetic optimization ends if it converges or after the pre-determined number of iterations (500) and the optimal coordinated fuzzy strategy is implemented for the next time interval. Like in the fuzzy-fuzzy system only the input and output fuzzy sets are modified, the rule base is not influenced by the optimization. One could think about this tuning procedure of the fuzzy parameters within the ramp metering algorithm like the optimal interpretation of universal if-then rules. The linguistic terms within the rules are flexible depending on the current traffic state in the system.

An ideal controller model for a freeway system should match different properties at different time scales. Most existing algorithms, however, use only one time scale, which may limit their effectiveness to cope with various flow phenomena occurring on different time scales. To integrate prediction capabilities into the new algorithms, real time data are used, combined with historical data, to predict future traffic conditions and make control decisions based on predicted future states. In the ACCEZZ model family, different time scales are used to overcome the limitations of existing algorithms and to demonstrate the flexibility of the developed ramp metering approach. A medium-term time prognosis of 15 minutes based on the last control period and a long-term time scale of one day based on the idea of repeating traffic patterns are independently integrated into the models. The ACCEZZ model family consists of a total of five different versions of the algorithms:

- **Neuro-Fuzzy Online**: This model uses a special neuro-fuzzy architecture and a macroscopic traffic flow model. The integrated prognosis is based on the traffic demand of the last 15 minutes.

- **Neuro-Fuzzy Offline**: A neuro-fuzzy model in combination with a macroscopic traffic system simulation is used. The demand of an entire day is estimated for the learning procedure.

- **Genetic Fuzzy Online**: A genetic algorithm with a traffic system model is fitness function is used to optimize the fuzzy ramp metering controllers. The measured traffic flows from the last 15 minutes are considered the best estimate for the next 15-minute time interval.

- **Genetic Fuzzy Offline**: The genetic optimization procedure of the fuzzy system uses a macroscopic traffic system model to estimate the performance of a fuzzy control strategy. The strategy is optimized for an entire day based on the predicted traffic demand for that specific day.

- **Genetic Fuzzy Reality**: Instead of using a traffic model to estimate the performance of a control strategy, the strategy is implemented in reality and the effects are directly measured with a comprehensive detection system.
Under the assumption that demand and capacity patterns are similar for certain periods, the control strategy is optimized for the next day of the same type.

SIMULATION ENVIRONMENT FOR THE EVALUATION

In the following, a simulation-based evaluation of different ramp control strategies for a particular 26 km freeway segment located on the northbound direction of Autobahn No. 9 (A9) in Munich, Germany (see Figure 4) is described. The A9 northbound direction is a two to three-lane freeway which shows recurrent daily congestion patterns, especially during the afternoon peak hours from approximately 16:00 to 19:00. There are two freeway interchanges and 6 on-ramps and 3 off-ramps located within the analyzed freeway section. All on-ramps had enough storage space in each simulation scenario, no overt spillback onto the secondary road network was observed. The methodology employs the versatile, easy to use microscopic simulator AIMSUN2 which was selected after an evaluation of the most widely used ones. The simulator was enhanced to include an interface that allows the integration of different ramp control schemes. The previously described versions of the ACCEZ models, neuro-fuzzy online/offline and genetic fuzzy online/offline/reality have been calibrated, evaluated and compared with the results of standard ramp metering algorithms.

Evaluation Scenarios

The primary purpose of the evaluation is to provide empirical information on the value of the introduction of ramp metering on this freeway and especially the use of different ramp control algorithms. Traffic demands and conditions are based on field-collected data, collected on Friday, April 11, 1997. The simulation program AIMSUN2 was calibrated with these data under no-control conditions to provide a quasi real-life evaluation environment. Since there is no alternative route existing the diversion effect was not investigated. To demonstrate the influence of the number of metered on-ramps and their importance on the freeway performance two different recurrent congestion scenarios were designed. To prove that ramp metering can also help to combat non-recurrent congestion an incident was superimposed on the given demand in the incident scenario. Under the assumption that under control conditions the parameters of the simulation do not change, three different control scenarios were examined in this analysis:

3-On-Ramp Scenario: Three on-ramps upstream of the major bottleneck, located at the merge of two freeways, are metered (there are no on-ramps installed on the freeway and there are no plans to install ramp meters on this freeway in the near future) (see Figure 4). The objective is to alleviate the recurrent congestion pattern based on field measured data from April 11, 1997.

5-On-Ramp Scenario: Five on-ramps and two freeway-to-freeway connector ramps upstream of a major bottleneck are metered to combat the recurrent congestion on the A9 freeway on April 11, 1997.

Incident Scenario: A one-hour incident between 13:00 - 14:00 on the shoulder lane of the three-lane freeway between Freimann and Kirchberg is assumed. Three ramps are metered to manage the associated non-recurrent congestion. It is assumed that there is an incident detection algorithm included in the traffic management system which detects this incident immediately.

For each scenario the no-control case on one hand and different ramp metering strategies on the other hand are compared. Two standard local traffic responsive strategies and three coordinated traffic responsive algorithms were selected for the comparison with the ACCEZ models. A detailed description of these algorithms can be found in (2).

The demand-capacity strategy and the occupancy strategy are selected for comparison as most widely used local strategies. Both were calibrated and linked to the simulation. Additionally, three different coordinated ramp metering algorithms have been re-programmed, validated and simulated. Coordinated traffic responsive ramp control algorithms can be categorized into three different types: cooperative, competitive and integral approaches (7). One algorithm out of each group was selected for this evaluation. Denver’s HELPER Ramp Algorithm was used as a cooperative algorithm and Monopolistic St. Paul’s Zone Algorithm was a competitive ramp metering approach. Both were programmed and calibrated based on public and published information (2). ALINSA is originally a local traffic responsive strategy, but since it was reported to perform almost as satisfactorily as METAFLINE it was included in the evaluation as an integral ramp metering algorithm because of fewer calibration efforts. ALINSA is already implemented on three on-ramps on the A94 Autobahn in Munich. The implemented settings were used for this evaluation.

A sensitivity analysis of several simulated days and of stochastic effects of the simulation showed that all the evaluation results are significant. All the analyzed criteria within the evaluation scenarios were aggregated macroscopic indicators and the relative values for the different algorithms did not change by varying the random effects (number) of the simulation or under other recurring congestion patterns (days).
Simulation Environment

A microscopic model was used as an evaluation environment to compare the different ramp metering algorithms. ADMSU2 follows a microscopic simulation approach. This means that the behavior of each vehicle in the network is simulated throughout the simulation period using several parameterized models. These behavioral car-following models and lane-changing decision models are integrated into the simulation environment. The simulation tool is capable of communicating with an external application by so-called dills. All the ramp metering algorithms received the necessary detector data and sent the cycle time of each individual on-ramp to the simulation.

The A priori calibration process for the evaluation tool employed in this study is an iterative multi-stage process. Traffic demand and supply serve as input to the ADMSU2 model, and the ADMSU2 model predicts traffic performance. The model provides predictions of traffic performance and the average subraction speed which were compared with the field conditions. When a close agreement was reached, the model could be considered as having been calibrated. Otherwise, the model parameters were slightly modified. A total of fifty iterations was necessary to achieve a good match between the field-measured and the simulated traffic conditions.

Performance of the 3On-Ramp Scenario

The relative value (see Table 2) and the progression (see Figure 5) of the usual time spent in the system (TTS) is an indication of the extension of congestion, the travel time, the average speed, and the amount of delays. The analysis of the TTS for the different ramp metering strategies shows that the genetic fuzzy reality strategy outperformed the other ACCEZZ strategies and even performed best overall. TTS was decreased by 3% compared to the best non-ACCEZZ model, the Zone algorithm. All ACCEZZ models performed better than all other tested ramp metering algorithms. This genetic fuzzy reality strategy was only tested for the 3-on-ramp scenario. It was expected to perform as the best aggressive fuzzy strategy, because it directly adjusts its evaluation environment (real). All other fuzzy strategies use a macroscopic traffic system model within the calculations for evaluating the different ramp metering settings. The two models, macroscopic traffic system models and ADMSU2, do not match perfectly. It was also expected that the offline fuzzy models perform slightly better than the online models because the macroscopic traffic flow model was slightly more exact for these cases.

One can see the savings in veh/h in the metering cases during the two congestion peaks between 11:00 and 18:00. Before and after this period no savings in TTS can be observed, because the traffic demand is much smaller in the morning and in the evening. At most the on-ramp demand during this time is even smaller than the metering rate. This means that there is no queue and almost no delay on the metered on-ramps. When the genetic fuzzy reality algorithm is applied to the A9 Autobahx, the TTS becomes 13,632 veh/h which is a 17% improvement compared with the no-control case. For the congestion interval the total time spent decreased by 34% for the genetic fuzzy reality ACCEZZ model. This is significant in view of the fact that the most important inflows into the motorway, namely, the upstream main flow and the A9 entrances, are not controlled in this scenario. It is a considerable reduction confirming the significance of ramp metering for reducing recurrent congestion on urban freeways, which was already reported from previous simulation studies and field trials (8,9,10,11,12).

The HELPER strategy was the least efficient strategy in the 3-on-ramp scenario, but still with a 18% reduction of TTS. This has to do with the order of the on-ramps. The HELPER algorithm decreases the metering rate for the next upstream on-ramp, no matter how the local traffic conditions are. At the A9 Autobahx the most important metered on-ramp is Frankfurt Ring, the first one, but the one that is farthest away from the bottleneck and the occurrence of the initial breakdown in flow and speed. The strategy was originally designed for the large metering system in Denver with much more metered on-ramps and a setup with the most influential on-ramp at the downstream end of a group of metered on-ramps.

Generally speaking, all local strategies performed less efficient than the coordinated strategies, except for the HELPER algorithm. ADINS was the best local strategy, but as mentioned earlier it can be considered a coordinated strategy for recurrent congestion. Under these ideal conditions, i.e. every input and output flow was measured exactly, the Minnesota Zillow algorithm reduced the TTS by 85% (congestion interval: 78%).

The improved freeway mainline operations on the metered freeway, particularly the reduction in stop-and-go conditions, led to a substantial reduction in emissions and fuel (see Table 3). The altered ramp acceleration behavior and the additional waiting time result in localized emission and fuel consumption increases. The large-scale metering system favorably influences air quality and fuel consumption significantly as to offset any localized emission and fuel consumption increases. The comparison of the total fuel consumption and the emissions of the different metering algorithms shows only minor differences. Generally speaking, the ACCEZZ models performed slightly better than all the other ramp control approaches. The fuel consumption was reduced by the genetic fuzzy reality ramp metering algorithm during the congestion intervals by 29%, NOx by 38%, CO by 31%, and HC by 26%.
In summary, all ramp metering strategies significantly improved the freeway system operations, total fuel consumption, and emissions by avoiding extensive queues and delays on the on-ramps. The genetic fuzzy reality ACCEZZ model performed best in almost all categories, except that the queue length and the waiting time were slightly higher than in the ALINEA and Zone scenarios. A sensitivity analysis for the genetic fuzzy reality ACCEZZ model showed that a slight modification of the maximum cycle times, 20 seconds instead of 15 seconds, could dominate the congestion on the mainline completely while producing only approximately 15% longer queue lengths and waiting times.

Performance of the 5-On-Ramp Scenario
The second evaluation scenario includes five metered on-ramps: Frankfurter Ring, Freimann, Kurfürsten-, A29 Stuttgart, and A99 Salzburg. The A29 entrance ramps are high-volume freeway-to-freeway congested ramps. A two-lane metering is assumed for both ramps to keep the queue lengths and waiting times in a reasonable range. The idea behind metering these freeway-to-freeway ramps is to eliminate the merging conflicts as the main cause for the recurrent flow breakdown on the A9 Autobahn. The three other scenarios are standard on-ramps.

The ACCEZZ strategies performed better than all other strategies with regard to TTS, exactly as in the 3-on-ramp scenario (see Table 2). The adaptation procedures led to very similar results regardless of the application of the traffic system model (continuous) or the adaptation mechanism (neural network based learning/genetic optimization). This is somewhat surprising even if TTS is the objective within all the learning/optimization procedures. The evaluation of the strategies with the macroscopic traffic system model in the different adaptation mechanisms leads to very similar optimal fuzzy set parameters and, as demonstrated by the simulation, to a very good overall performance.

Since the traffic densities remain far below critical densities, much higher speeds were achieved on the freeway and the mainline total travel time decreased by 23% when the genetic fuzzy offline ramp control was introduced. Total ramp delays increased substantially as expected but overall system TTS was reduced by 14%. For the congested period the overall reduction is 24%. All metering strategies improved the traffic system operation by at least 11% (congestion interval: 21%). The introduction of coordinated ramp metering leads to a further improvement of 3% in TTS (congestion interval: 3%). This means the difference between local and coordinated control decreased compared to the 3-on-ramp scenario, where this difference was approximately 4% (congestion interval: 6%). This can easily be explained by the additional metered high-volume freeway-to-freeway ramps. Each strategy controls those most influential on-ramps, because of queue constraints, almost all the time with the minimum cycle times. Thus the control behavior of all strategies was similar and the measurable differences decreased.

The savings of TTS during the congested time interval are slightly higher than in the 3-on-ramp scenario. Especially the less efficient algorithms in the 3-on-ramp scenario could improve by nearly 3-4% in the 5-on-ramp scenario. The on-ramp delays are much higher than in the 3-on-ramp scenario but the further decrease in freeway travel time leads to the slightly better TTS for each ramp metering strategy. The much higher waiting times on the metered on-ramps lead to a higher TTS for the 5-on-ramps scenario, if the entire evaluation period is analyzed.

The demand-capacity was the least efficient in this TTS category. This result is not unexpected, since this algorithm is a typical feedforward, open-loop strategy and its performance typically deteriorates the larger the metered freeway system gets. The IHELPERS algorithm performed much better than in the 3-on-ramp scenario because the most important metered on-ramp (A99 Salzburg) is now located next to the bottleneck. ALINEA was the best non-fuzzy algorithm.

Compared to the 3-on-ramp scenario, the fuel consumptions and emissions for the entire freeway system increased, because of the excessive queues and waiting times, mainly on the freeway-to-freeway ramps (see Table 3). The drawback on the on-ramps was not compensated by the increased free-flow speeds on the mainline during the entire study time and the associated reduction in fuel consumption and the emissions for the mainline direction. The genetic fuzzy offline ACCEZZ model produced the lowest fuel consumption and. All pollutants were at least reduced by 18% for the congestion interval. The most impressive reduction was observed for NOx (36%).

Since the current behavior of all the algorithms was very similar, no significant difference between local and coordinated algorithm was observed. The adaptive fuzzy strategies performed very well again and the genetic fuzzy offline ramp metering strategy can be considered the best overall strategy. As in the 3-on-ramp scenario, the neuro-fuzzy offline and the genetic fuzzy offline algorithms performed slightly better than their online counterparts.
Performance of the Incident Scenario

In the previous scenarios, recurrent congestion was considered, which is forming on the freeway because the motorway capacity is exceeded by the uncontrolled demand. Non-recurrent congestion is caused by unpredictable capacity reducing incidents. The accident in the shoulder lane reduced the capacity of this 3-lane segment by one third. The non-recurrent congestion was superimposed on the recurrent congestion of Friday, 11.04.1997.

The ACCEZ models consider the influence of an incident via a suitable modification of the fundamental diagrams. For the activation of this modification inside the traffic system model, the severity (number of blocked lanes) and the duration of the incident was assumed to be detected and exactly estimated. All the other algorithms were also adjusted during the incident (3). These modifications include the implementation of special incident rates, incident capacity or desired incident occupancies etc.

This is the first and only time another ramp metering algorithm produced a higher reduction in TTS (see Table 2). The application of the HELPER algorithm leads to a 0.4% (congestion interval: 0.5%) improvement compared with the genetic fuzzy offline case. Compared to the recurrent 3-on-ramp scenario, where the HELPER algorithm performed worst, the situation changed completely. The incident is located in the immediate vicinity of the detector of the Kleefangpark entrance, in the recurrent 3-on-ramp scenario the least important on-ramp of the three. This on-ramp now becomes very important since it is located right into the incident. This is exactly the setup the HELPER algorithm is designed for, the first metered on-ramp right next to the bottleneck. Due to the disturbances caused by the incident, HELPER detects the incident and immediately adjusts the ramp metering rates of the upstream on-ramps. For every incident location outside of the 3-on-ramp segment the results of the HELPER algorithm would get worse.

As expected, all the coordinated algorithms performed better than the local approaches. The local closed-loop strategy ALINEA performed better than the feed-forward strategies, demand-capacity and occupancy strategy. Papageorgiou et al. (10) already reported that ALINEA was found to be inferior to coordinated ramp metering in the case of an incident. ALINEA, as all control-theoretic algorithms, is based on methods which attempt to regulate conditions around some nominal state, recognizing that the behavior of the system is nonlinear, but using linear approximating techniques. When traffic conditions change rapidly, as in the incident scenario, these linear approximations are inappropriate. The demand-capacity performed least efficiently, because the set value (bottleneck capacity) is additionally controlled by the "incident metering". This leads to high fluctuations in the flow and to high amplitudes within the control trajectory.

A problem of the simulated coordinated ramp metering approaches (Denver's HELPER and Minnesota's Zone), is that they get caught in a cycle between queue override activations and restrictive metering rates. The fuzzy logic ramp metering algorithms overcome this problem by providing smooth transitions rather than threshold activations. In addition, the fuzzy logic controllers evaluate several rules in parallel and then determine one metering rate based on all factors rather than modifying a series of adjustments.

All the algorithms, even the local ones, significantly improved fuel consumption and emission. As a result of the genetic fuzzy offline ramp metering, the fuel consumption was reduced by 26%, NOx by 3%, CO by 28%, and HC by 24% for the congestion interval (see Table 3). As in all the other scenarios ramp metering substantially improved the freeway system performance. The coordinated ramp metering strategies demonstrated their strength in fighting non-recurrent congestion. Again the ACCEZ models performed very well, the genetic fuzzy offline approach performed second best in the TTS analysis and best in the waiting time, queue length, fuel consumption and emission comparison.

CONCLUSIONS

The contribution of this research lies in the application of the theoretical principles of neuro-fuzzy and genetic fuzzy control to the coordinated ramp metering problem. Furthermore, a simulation environment was produced for the simulation-based comparative evaluation of known ramp metering algorithms. In this context it was shown that all developed versions of the ACCEZ model family do substantially improve the traffic conditions for the freeway analyzed.

The genetic fuzzy reality version of the ACCEZ models will be implemented in Munich this autumn at the Olympic interchange of the Middle Ring Road.
REFERENCES


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TABLE 2 Total Time Spent in the System
TABLE 3 Fuel Consumption and Emissions.

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FIGURE 4 Test Site
FIGURE 5 Total Time Spent in the System -3-On-Ramp Scenario
<table>
<thead>
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<th>No. of Rule</th>
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<td>III</td>
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<td>VIII</td>
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<td>IX</td>
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<td>20-30:00 Scenario</td>
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FIGURE 1 Fuzzy R-amp Metering
FIGURE 2 Membership Functions – Neuro-Fuzzy (upper portion), Genetic Fuzzy (lower portion)
FIGURE: Neuro-Fuzzy and Genetic Fuzzy ACCEZZ Model
Evaluation Scenarios
- A95 Salzburg (fwy-2-fwy),
- A99 Stuttgart (fwy-2-fwy),
- Kiefersgarten,
- Freimant and
- Frankfurter Ring metered

FIGURE 4 Test Site (3-On-Ramp Scenario and 5-On-Ramp Scenario)
FIGURE 5 Total Time Spent in the System - 3-On-Ramp Scenario