Density Based Ramp Metering Algorithm Development Taking Emission into Account

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Abstract: Ramp metering has been proved to be an effective measure of relieving freeway congestion, and it also owns many other benefits such as reducing total vehicle travel time, reducing automobile emissions and so on. This paper tries to develop one ramp metering algorithm which could also take emissions reduction into account. The algorithm occupies two objectives, the primary is to minimize total vehicle travel time, and the secondary is to reduce ramp emissions as much as possible. According to the statistical analysis result, this paper gets some conclusions that the density based ramp metering algorithm is effective in reducing the total vehicle travel time and could reduce on-ramp emissions and queues a lot more than ALINEA strategy. Especially, on large uphill gradient condition density based algorithm could reduce the total emissions much more than ALINEA algorithm.

Key Words: emission reduction, ramp metering algorithm, Input-Output density measurement, PARAMICS

1. INTRODUCTION

1.1 Background

Traffic emission is one of the biggest sources of the environmental pollution in cities; the emission of vehicles contains several harmful substances, like carbon dioxide (CO2), carbon monoxide (CO), oxides of nitrogen (NOx) and hydrocarbons (HC) etc. Therefore, it is essential to reduce traffic emissions on road as much as possible through traffic management. By regulating the entering flow rate ramp metering can break up large platoons of vehicles to make it easier and safer for motorists to merge onto the freeway. Thus, it has been suggested in recent years that ramp metering would reduce automobile emissions as the smoother mainline traffic flow.
Several attempts have been made in the last decades toward the development of efficient ramp metering control strategies. Papageorgiou M. presented a paper of local feedback control law for on-ramp metering in 1991, it explained the ALINEA ramp metering strategy and recommended \( k=70 \text{ veh/h} \) to be a good parameter value for a real life experiment (Papageorgiou et al., 1991). And later researchers proposed a modification to the ALINEA control law to prevent excessively long ramp queues from interfering. Recently, Kaan Ozbay submitted comprehensive Mixed-Control ramp metering algorithm, which takes ramp queues into account (Ozbay et al., 2003). The Mixed-Control ramp metering is coordinated with the density and ramp queues changes, and the density value is calculated by the relationship of occupancy and density. According to the study on environment, ramp metering may reduce emissions by maintaining the free-flow traffic. However, when the on-ramp emission increases highly, the net value of emission change may be negative even though there is reduction of mainline emission (Kang, S. and Gillen, D., 1999).

Various ramp metering algorithms have been proposed to calculate the regulating rate that determines the entering vehicles number from the on-ramp. These strategies are applied by different traffic parameters, such as occupancy, upstream flow, downstream flow, ramp queues and density occupied by the occupancy calculation etc. However, there is still no algorithm developed by the section density and vehicle emissions. Thus, we try to develop one ramp metering algorithm using density which would also take emissions into account. The algorithm not only would minimize total vehicle travel time but also reduce ramp emissions as much as possible.

1.2 Literature

One of the most important measures of effectiveness for ramp metering is the total vehicle travel time spent on the network. Referring to the Input-Output model (Papageorgiou et al., 2002), the minimization of the total vehicle travel time (TVTT) spent on traffic network is equivalent to the maximization of the exit flow for each time step. For ramp metering it means that we have to control the network traffic condition which the maximum exit flow would be output.

Based on this theory, a number of ramp metering algorithms have been developed in recent years, such as Demand-Capacity algorithm, Occupancy strategy, ALINEA algorithm etc. They are all designed to obtain the maximum downstream flows. ALINEA algorithm is one of the typical feedback ramp metering strategies, it aims to adjust the ramp metering rate by keeping the downstream occupancy at a pre-specified level called the critical occupancy set-point so as to occupy the maximum downstream throughout flow.

According to the researches on vehicle emissions due to ramp metering, ramp metering shifts congestion off the mainline roads while inducing more flow demand on ramps. So the emissions impact by ramp metering can be categorized into two main kinds: mainline smoothing and ramp congestion.

\[
E_{total} = E_{freeway} + E_{ramp}
\]  

(1)

The freeway overall traffic flow is smoother and faster, thus the emissions can be reduced. However, when vehicles on-ramp are metered, the ramp density will be increased and traffic situation becomes worse, this slow and stop-and-go traffic conditions always cause higher emissions.
The emission change of two ramp metering algorithms can be expressed as,

\[ \Delta E_{\text{total}} = \Delta E_{\text{freeway}} + \Delta E_{\text{ramp}} \]  

(2)

Some researchers suggest that ramp metering may reduce emissions by maintaining the smooth flow traffic, and the net value of emission change may be negative if the on ramp emission is significantly high (Kang, S. and Gillen, D., 1999).

1.3 Motivation

Within the traditional traffic stream models like Greenshield, Greenberg and Underwood we know that at the critical density traffic flow reaches the maximum volume. So we try to develop the density based algorithm by controlling the mainline density be in vicinity of the critical value, then we could control the network running in the maximum flow.

In general, the larger the density becomes the more emission will be produced. Thus, we could simply reduce emission by means of reducing the density value.

In conclusion, the density based ramp metering algorithm development consists of two categories, the primary is to control mainline density around critical value so as to minimize total vehicle travel time, and the secondary is to reduce ramp density so as to reduce emissions as much as possible.

2. DENSITY BASED RAMP METERING ALGORITHM DEVELOPMENT

2.1 Input-Output Density Measurement

In order to measure the accurate density of a segment, we propose the Input-Output counting method. It is one of the efficient techniques to measure the density between freeway sections, and we just should count the initial existing vehicles number in the section \( N(t) \), the entering vehicles number \( N_{\text{in}} \) and the leaving vehicles number \( N_{\text{out}} \) between freeway sections during \( \Delta t \) step time.

![Figure 1 Input-Output density counting measurement](image)

Figure 1 shows the concept of Input-Output counting method to measure density. We can use equation (3) to calculate the density value,

\[ \rho(t + \Delta t) = \frac{N_{\text{in}} + N(t) - N_{\text{out}}}{L_{AB}} = \frac{\Delta t \cdot q_{\text{in}} + N(t) - \Delta t \cdot q_{\text{out}}}{L_{AB}} \]  

(3)

Where,
\( \rho(t + \Delta t) \): real-time section density after \( \Delta t \) step time

\( N_{in} \): number of vehicles entering the section

\( q_{in} \): traffic flow rate entering the section

\( N(t) \): initial number of vehicles

\( N_{out} \): number of vehicles exiting the section

\( q_{out} \): traffic flow rate exiting the section

\( L_{AB} \): measurement section length

We know it is essential to determine the exact initial number of vehicles. There are lots of methods to measure the initial vehicles number, such as floating vehicle test method, vehicle ID determination method or by photographic measurement in air.

We could measure the real-time density of ramp merging area in the same way,

\begin{align*}
\rho_{f}(t + \Delta t) &= \rho_{f}(t) + \frac{\Delta t \cdot q_{in}(t) + \Delta t \cdot r(t) - \Delta t \cdot q_{out}(t)}{L_{f}} \quad (4) \\
\rho_{r}(t + \Delta t) &= \rho_{r}(t) + \frac{\Delta t \cdot r_{in}(t) - \Delta t \cdot r(t)}{L_{r}} \quad (5)
\end{align*}

Where,

\( \rho_{f}(t + \Delta t) \): mainline section density

\( \rho_{r}(t + \Delta t) \): ramp section density

\( r(t) \): ramp metering rate

\( \Delta t \): duration of time interval

\( q_{in}, q_{out}, r_{in} \): traffic flow rate at the detector points

\( L_{f} \): mainline section length

\( L_{r} \): ramp section length

### 2.2 PD Control for Ramp Metering

PD control (proportional-derivative controller) is one of the most commonly used feedback control methods (Araki M., 1985), it calculates an "error" value \( e \) as the difference between a
measured process variable and a desired set point \( u \). The controller attempts to minimize the error by adjusting the process control inputs. The error variable \( e \) will gradually go closer and closer to the desired set value \( u \) while the time increases.

If we build the error value as a function of the traffic density, and set \( u \) as our expected value, then the optimal ramp metering rate can be calculated by controlling the density value. The density based ramp metering algorithm design objectives are to maintain the mainline density in the critical value and to reduce the ramp density. Therefore, we could define error functions based on the freeway density and ramp density respectively,

\[
\begin{align*}
    e_1(t) &= |\rho_f(t) - \rho_{cr}| \\
    e_2(t) &= \rho_r(t)
\end{align*}
\]

Where,
\( \rho_f \): Mainline density at \( t \) time step
\( \rho_{cr} \): Mainline critical density
\( \rho_r \): Ramp density at \( t \) time step

And then we should build PD control functions for the error equations,

\[
\begin{align*}
    k_1 e_1(t) + e_1(t) &= 0 \\
    k_2 e_2(t) + e_2(t) &= 0
\end{align*}
\]

Transform equations (4) and (5),

\[
\begin{align*}
    \rho_f(t) &= \lim_{\Delta t \to 0} \frac{\rho_f(t + \Delta t) - \rho_f(t)}{\Delta t} = \frac{q_{in}(t) + r(t) - q_{out}(t)}{L_f} \\
    \rho_r(t) &= \lim_{\Delta t \to 0} \frac{\rho_r(t + \Delta t) - \rho_r(t)}{\Delta t} = \frac{r_{in}(t) - r(t)}{L_r}
\end{align*}
\]

Solute all the equations, we obtain,

\[
\begin{align*}
    r_1 &= \frac{-k_2 e_1(t) L_f}{(\rho_f(t) - \rho_{cr})} + q_{out}(t) - q_{in}(t) \\
    r_2 &= r_{in}(t) + k_2 e_2(t) L_r
\end{align*}
\]

By using Exponential Smoothing model we would select the optimal ramp metering rate, when mainline optimal rate \( r_1 \) is smaller than on-ramp optimal rate \( r_2 \). Otherwise, we just have to choose \( r_1 \). Where, \( \rho_{max} \) is the maximum density value.

\[
\begin{align*}
    \begin{cases}
        r(t) = r_1 & r_1 \geq r_2 \\
        r(t) = r_1 (1 - \frac{\rho_f(t)}{\rho_{max}}) + r_2 \frac{\rho_r}{\rho_{max}} & r_1 < r_2
    \end{cases}
\end{align*}
\]
2.3 Density Based Ramp Metering Algorithm

The density based algorithm attempts to keep mainline volumes below capacity by controlling the mainline density in the vicinity of critical value and reduce ramp emissions wherever possible. The overall structure of the density based algorithm is shown in figure 3.

![Figure 3 Block of density based ramp metering control](image)

The input parameters are flow and density values achieved by sensors and output data are flow, speed, density, queues and emissions values.

3. STATISTICAL ANALYSIS USING PARAMICS

PARAMICS is one of the most reliable microscopic traffic simulation software. We can use it to simulate the network by our new designed metering algorithm before field implementation. The simulation test scenarios have been categorized into three gradient conditions, 0%, 4% and 8%.

We have simulated each ramp metering algorithm respectively for 10 times by changing the seed from 1 to 10, in different seed conditions the vehicle generation distribution occurs differently, so for each seed the Paired t Test should be used in the comparison of two population means.

The t statistical analysis result for each of two algorithms is listed in table 1.

3.1 MOE Analysis

Hypothesis:
\( H_0 \): MOE mean values of two algorithms are the same
\( H_a \): MOE mean value of one algorithm is larger than the other \((y_1-y_2>0)\)

It is found that both of the LINEA and Density-Strategy ramp metering algorithms have reduced the total vehicle travel time. There is no evidence of a statistical difference between ALINEA and Density-Strategy algorithms at the significance of 0.05.

All the ALINEA and Density-Strategy algorithms could reduce freeway emissions in different gradient conditions. Meanwhile there is no evidence of a statistical difference between ALINEA and Density-Strategy algorithms.

Both of the ALINEA and Density-Strategy algorithms have increased ramp emissions and queues, and meanwhile there is statistical evidence to prove that Density-Strategy algorithm is superior to ALINEA algorithm in ramp emissions reduction and queues reduction.

There is no evidence of a statistical difference between no metering algorithm and ALINEA
or Density-Strategy algorithm in total emission reduction, which implies that even though ramp metering could reduce freeway emissions the conclusion for total emissions reduction still remains uncertain. It also shows that with the gradient increasing the Density-Strategy algorithm performs better than ALINEA algorithm in total emissions reduction.

The result can be explained. When ramp metering, vehicles are metered on the ramp, this always leads to congestion on the ramp, which means more long on ramp queues. And the congestion is characterized by slow and stop-and-go traffic conditions, thus emissions on ramp increases much higher than no metering condition. Density-Strategy has been designed to reduce ramp emission if possible; while ALINEA algorithm has disregard this consideration, resulting in much more emissions and queues increasing on ramp.

<table>
<thead>
<tr>
<th>Category</th>
<th>Algorithm</th>
<th>Gradient 0%</th>
<th>Gradient 4%</th>
<th>Gradient 8%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TVTT</strong></td>
<td>y1</td>
<td>ALINEA</td>
<td>Density Strategy</td>
<td>ALINEA</td>
</tr>
<tr>
<td></td>
<td>y2</td>
<td>- 4.84</td>
<td>- 3.21</td>
<td>- 2.59</td>
</tr>
<tr>
<td></td>
<td>No Metering</td>
<td>- 2.59</td>
<td>- 3.01</td>
<td>- 2.62</td>
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<tr>
<td></td>
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<td>1.38</td>
<td>/</td>
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<td>Density Strategy</td>
<td>ALINEA</td>
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<tr>
<td></td>
<td>y2</td>
<td>- 2.36</td>
<td>- 1.12</td>
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<td>- 2.06</td>
<td>- 3.04</td>
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<td>Density Strategy</td>
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<td>/</td>
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<td>Density Strategy</td>
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<td>y2</td>
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<td>- 1.30</td>
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<td>Density Strategy</td>
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<tr>
<td></td>
<td>ALINEA</td>
<td>/</td>
<td>- 2.06</td>
<td>/</td>
</tr>
</tbody>
</table>

3.2 Comprehensive Analysis

ALINEA strategy has the benefit of reducing the total vehicle travel time for the network.
However, there is no evidence to prove that it could reduce the whole network emissions.

Density based control has the benefit of reducing the total vehicle travel time for the network. However, there is no evidence to prove that it could reduce the whole network emissions.

There is evidence of a statistical difference between the density based control and ALINEA algorithm in emissions reduction on large uphill gradient at the significance level of 0.1 through inadequate at 0.05. The density based ramp metering algorithm is superior to ALINEA algorithm in emission reduction on large uphill gradient, nevertheless the TVTT increasing a little.

4. CONCLUSION

Both of the ALINEA and the density based ramp metering algorithms could reduce the total vehicle travel time much more than no metering condition. Both of the two algorithms could reduce freeway emissions, and both of them could increase ramp emissions value. But we cannot prove that anyone of the two algorithms could reduce the whole network emissions.

The Density-Strategy algorithm could reduce much more on ramp emissions and queues than ALINEA algorithm.

On low uphill gradient condition, there is no evidence of a statistical difference between ALINEA and Density-Strategy algorithms in the whole emissions reduction. However, it suggests that density based algorithm could reduce much more emissions than ALINEA algorithm on large uphill gradient ramps.

REFERENCES


