Freeway Traffic Flow Modeling and Control with Emphasis on Congested Off-Ramp Areas

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June 15th, 2015
Outline

Introduction

Calibration of Macroscopic Traffic Flow Models

Real-Time Traffic Control Measures: Case 1 – Route diversion control

Real-Time Traffic Control Measures: Case 2 – Merging traffic control

Conclusions and Future Work
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Calibration of Macroscopic Traffic Flow Models

Real-Time Traffic Control Measures: Case 1 – Route diversion control

Real-Time Traffic Control Measures: Case 2 – Merging traffic control

Conclusions and Future Work
Introduction
- Motivation
- Objectives and Approach

Real-Time Traffic Control Measures: Case 1 – Route diversion control

Real-Time Traffic Control Measures: Case 2 – Merging traffic control

Conclusions and Future Work
• During the last decades, *freeway congestion* has been a major problem especially at urban freeways and peri-urban ring-roads.

• Recurrent traffic congestion is usually encountered at freeway on-ramp areas or freeway-to-freeway merging areas, but, quite frequently, also close to freeway off-ramp areas.

• Expanding the existing infrastructure is not always a feasible option, for economic and environmental reasons, thus *traffic control* has been employed as an efficient way to mitigate the problem of freeway congestion.
• Very **limited technical literature** (and practical systems) addressing appropriate control measures for congested off-ramp areas.

• The main reasons probably being that there is **no direct way**, from the freeway side, to control the freeway exit flow.

• The development of innovative traffic control measures requires the existence of **accurate traffic flow models** that are able to reproduce the traffic conditions at such areas with satisfactory accuracy.

• Although, a high number of traffic flow models has been proposed over the last decades, they have never been validated and compared for congested freeway off-ramp areas.
The objective of this research is **twofold**:

- **First**, it aims to identify suitable macroscopic traffic flow models that can represent the traffic conditions at congested freeway off-ramp areas with sufficient accuracy.
  
  **Approach**: The two most popular macroscopic traffic flow models are validated and compared using real traffic data from a freeway stretch in Athens, Greece, where recurrent traffic congestion is created due to a saturated off-ramp.

- **Second**, it aims to develop innovative real-time traffic control measures for congested freeway off-ramp areas.
  
  **Approach**: Two different network topologies are examined, that are often encountered in reality, and suitable traffic control strategies are proposed for every case.
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Calibration of Macroscopic Traffic Flow Models
- Introduction
- Macroscopic traffic flow models
- Model calibration procedure
- Calibration and validation results
- Conclusions and remarks

Conclusions and Future Work
Introduction

• Macroscopic mathematical traffic flow models are useful tools for:
  – planning of new, or upgraded road infrastructures
  – development and testing of traffic estimation algorithms
  – development and testing of traffic control strategies
  – etc.

• The models include a number of parameters, whose values may differ for different freeway sites.

• Before employing a traffic flow model in practice, it is important to first calibrate it against real traffic data, i.e. to appropriately specify the model parameter values.

• This section calibrates, validates and compares two macroscopic models, regarding the reproduction of traffic conditions at a congested freeway off-ramp area.
Macroscopic traffic flow models:
CTM (Cell Transmission Model)

Model parameters:

\( v_{f,i} \): free flow speed
\( w_i \): congestion wave speed
\( \rho_{\text{max},i} \): maximum density
\( Q_i \): capacity flow

\[
\rho_i(k+1) = \rho_i(k) + \frac{T}{L_i \lambda_i} \left[ q_{i-1}(k) - q_i(k) \right]
\]

\[
q_i(k) = \min\{v_{f,i} \rho_i(k) \lambda_i, Q, w_i \lambda_{i+1} \left[ \rho_{\text{max},i+1} - \rho_{i+1}(k) \right] \}
\]

\[
\bar{Q} = \min\{Q_i, Q_{i+1}\}
\]

\[
v_i(k) = q_i(k) \sqrt{\rho_i(k) \lambda_i}
\]
Macroscopic traffic flow models: CTM (Cell Transmission Model)

At bifurcations:

Model parameters:

\[ q_i(k) = \min\{S_i(k), R_{i+1}(k)/(1 - \beta_i(k)), R_{\text{off-ramp}}(k)/\beta_i(k)\} \]

\[ S_i(k) = \min\{Q_i, v_{f,i} \rho_i(k) \lambda_i\} \]

\[ R_{i+1}(k) = \min\{Q_{i+1}, w_{i+1} [\rho_{\text{max},i+1} - \rho_{i+1}(k)] \lambda_{i+1}\} \]

\[ R_{\text{off-ramp}}(k) = \min\{Q_{\text{off-ramp}}, w_{\text{off-ramp}} [\rho_{\text{max-off-ramp}} - \rho_{\text{off-ramp}}(k)] \lambda_{\text{off-ramp}}\} \]

\[ v_{f,i}: \text{free flow speed} \]

\[ w_i: \text{congestion wave speed} \]

\[ \rho_{\text{max},i}: \text{maximum density} \]

\[ Q_i: \text{capacity flow} \]

\[ w_{\text{off-ramp}}: \text{congestion wave speed (off-ramp)} \]

\[ \rho_{\text{max-off-ramp}}: \text{maximum density (off-ramp)} \]
Macroscopic traffic flow models:

**METANET**

Freeway stretch

\[
\begin{align*}
\rho_i(k+1) &= \rho_i(k) + \frac{T}{L_i \lambda_i} \left[ q_{i-1}(k) - q_i(k) \right] \\
q_i(k) &= v_i(k) \rho_i(k) \lambda_i \\
v_i(k+1) &= v_i(k) + \frac{T}{L_i} v_i(k) \left[ v_{i-1}(k) - v_i(k) \right] + \frac{T}{\tau} \left[ V^e(\rho_i(k)) - v_i(k) \right] - \frac{vT \left[ \rho_{i+1}(k) - \rho_i(k) \right]}{\tau L_i \left[ \rho_i(k) + \kappa \right]} \\
V^e(\rho_i(k)) &= v_{f,i} \exp \left[ -\frac{1}{a_i} \left( \frac{\rho_i(k)}{\rho_{cr,i}} \right)^{a_i} \right] \\
q_{i-1}(k) &= v_i(k), \rho_i(k) \\
q_i(k) &= v_i(k) \rho_i(k) \lambda_i \\
v_i(k+1) &= v_i(k) + \frac{T}{L_i} v_i(k) \left[ v_{i-1}(k) - v_i(k) \right] + \frac{T}{\tau} \left[ V^e(\rho_i(k)) - v_i(k) \right] - \frac{vT \left[ \rho_{i+1}(k) - \rho_i(k) \right]}{\tau L_i \left[ \rho_i(k) + \kappa \right]} \\
V^e(\rho_i(k)) &= v_{f,i} \exp \left[ -\frac{1}{a_i} \left( \frac{\rho_i(k)}{\rho_{cr,i}} \right)^{a_i} \right] \\
q_{i-1}(k) &= v_i(k), \rho_i(k) \\
q_i(k) &= v_i(k) \rho_i(k) \lambda_i \\
v_i(k+1) &= v_i(k) + \frac{T}{L_i} v_i(k) \left[ v_{i-1}(k) - v_i(k) \right] + \frac{T}{\tau} \left[ V^e(\rho_i(k)) - v_i(k) \right] - \frac{vT \left[ \rho_{i+1}(k) - \rho_i(k) \right]}{\tau L_i \left[ \rho_i(k) + \kappa \right]} \\
V^e(\rho_i(k)) &= v_{f,i} \exp \left[ -\frac{1}{a_i} \left( \frac{\rho_i(k)}{\rho_{cr,i}} \right)^{a_i} \right]
\end{align*}
\]

**Model parameters:**

- \( v_{f,i} \): free flow speed
- \( \rho_{cr,i} \): critical density
- \( \alpha_i \): FD parameter
- \( \tau \): time parameter
- \( \nu \): anticipation parameter
- \( \delta \): merging parameter
- \( \varphi \): lane-drop parameter

Calibration of Macroscopic Traffic Flow Models
Macroscopic traffic flow models: METANET

At bifurcations:

\[
\rho_{v,i+1}(k) = \frac{\rho_{i+1}^2(k) + \rho_{off-ramp}^2(k)}{\rho_{i+1}(k) + \rho_{off-ramp}(k)}
\]

\(\rho_{v,i+1} \) : virtual density downstream of section \(i\)

Model parameters:

\(v_{f,i}\): free flow speed

\(\rho_{cr,i}\): critical density

\(\alpha_i\): FD parameter

\(\tau\): time parameter

\(v\): anticipation parameter

\(\delta\): merging parameter

\(\varphi\): lane-drop parameter

no parameters are included!
Model calibration procedure

\[ x(k + 1) = f[x(k), d(k), p] \quad k = 0, 1, \ldots, K - 1 \]
\[ x(0) = x_0 \]

- **x**: state vector
- **d**: disturbance vector
- **p**: parameter vector

\[ J(p) = \sqrt{\frac{1}{K} \sum_{k=1}^{K} [y(k) - y^m(k)]^2} \]

\[ y(k) = g[x(k)] \]

- **y**: model estimations
- **y^m**: real measured traffic data
Attiki Odos freeway stretch:

~6 km long - 3 on-ramps - 3 off-ramps - 11 detector stations
Real traffic data:

DATE: 26/05/2009

DATE: 16/06/2009

DATE: 23/06/2009

DATE: 25/06/2009
Simulation set-up:

- Models’ time step: $T = 5$ s.

- CTM parameter vector: $p_1 = [v_f \ w \ \rho_{\text{max}} \ Q \ w_{\text{off-ramp}} \ \rho_{\text{max\_off-ramp}}].$

- METANET parameter vector: $p_2 = [v_f \ \rho_{\text{cr}} \ a \ \tau \ \nu \ \delta \ \varphi].$

- One single fundamental diagram is considered for all freeway sections.


- Performance index (PI): RMSE of real versus estimated speeds.
Calibration set-up:

- Three derivative-free optimization algorithms are employed:
  - Nelder-Mead algorithm
  - Genetic algorithm
  - Cross-entropy method

- Various calibrations tests were carried out for both models and only the best obtained results are presented in the following.
## Calibration and validation results: Models’ calibration

### CTM

<table>
<thead>
<tr>
<th>Optimization method</th>
<th>Iterations</th>
<th>Cost function evaluations</th>
<th>Computation time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NM</td>
<td>393</td>
<td>609</td>
<td>0.8</td>
</tr>
<tr>
<td>GA</td>
<td>71</td>
<td>36000</td>
<td>34.6</td>
</tr>
<tr>
<td>CE</td>
<td>37</td>
<td>18500</td>
<td>19.7</td>
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</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>CTM parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$v_f$ (km/h)</td>
</tr>
<tr>
<td>Model 1.1 (NM)</td>
<td>100.4</td>
</tr>
<tr>
<td>Model 1.2 (GA)</td>
<td>100.3</td>
</tr>
<tr>
<td>Model 1.3 (CE)</td>
<td>100.4</td>
</tr>
</tbody>
</table>

### METANET

<table>
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<tr>
<th>Optimization method</th>
<th>Iterations</th>
<th>Cost function evaluations</th>
<th>Computation time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NM</td>
<td>204</td>
<td>317</td>
<td>0.5</td>
</tr>
<tr>
<td>GA</td>
<td>51</td>
<td>26000</td>
<td>122.9</td>
</tr>
<tr>
<td>CE</td>
<td>85</td>
<td>42500</td>
<td>197.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>METANET parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$v_f$ (km/h)</td>
</tr>
<tr>
<td>Model 2.1 (NM)</td>
<td>117.8</td>
</tr>
<tr>
<td>Model 2.2 (GA)</td>
<td>118.1</td>
</tr>
<tr>
<td>Model 2.3 (CE)</td>
<td>118.8</td>
</tr>
</tbody>
</table>
Calibration and validation results: Models’ calibration

CTM

Real traffic data

Model 1.1

Model 1.2

Model 1.3

Traffic flow direction

Metropolitan freeway (km)

Time (hours)

METANET

Real traffic data

Model 2.1

Model 2.2

Model 2.3

Traffic flow direction

Metropolitan freeway (km)

Time (hours)
Calibration and validation results: Models’ validation

- **Model validation** aims to test the accuracy and robustness of the produced models. To this end the models are applied using different traffic data sets.

<table>
<thead>
<tr>
<th>Model</th>
<th>CDM</th>
<th>METANET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1.1</td>
<td>14.4</td>
<td>10.1</td>
</tr>
<tr>
<td>Model 2.1</td>
<td>14.7</td>
<td>12.1</td>
</tr>
<tr>
<td>Model 3.1</td>
<td>14.4</td>
<td>12.4</td>
</tr>
<tr>
<td>Model 1.1</td>
<td>18.9</td>
<td>12.4</td>
</tr>
<tr>
<td>Model 2.1</td>
<td>19.7</td>
<td>11.8</td>
</tr>
<tr>
<td>Model 3.1</td>
<td>19.0</td>
<td>12.4</td>
</tr>
<tr>
<td>Model 1.1</td>
<td>16.4</td>
<td>8.4</td>
</tr>
<tr>
<td>Model 2.1</td>
<td>16.8</td>
<td>9.1</td>
</tr>
<tr>
<td>Model 3.1</td>
<td>16.3</td>
<td>8.3</td>
</tr>
<tr>
<td>Model 1.1</td>
<td>14.8</td>
<td></td>
</tr>
<tr>
<td>Model 2.1</td>
<td>16.3</td>
<td></td>
</tr>
<tr>
<td>Model 3.1</td>
<td>14.9</td>
<td></td>
</tr>
</tbody>
</table>

Validation results (PI)
Calibration and validation results:

Models’ validation
Conclusions and remarks

• Two macroscopic traffic flow models were tested and compared regarding the representation of traffic congestion created due to a saturated freeway off-ramp.

• The models’ parameter values were estimated using real traffic data and various optimization algorithms.

• The validation results showed that both models are able to reproduce traffic congestion due to an over-spilling off-ramp with sufficient accuracy.

• METANET model offers a more accurate representation of the prevailing traffic conditions.
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Conclusions and Future Work
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Calibration of Macroscopic Traffic Flow Models

Real-Time Traffic Control Measures: Case 1 – Route diversion control

- Introduction
- Dynamic route diversion concept
- Test network and traffic demand scenarios
- Simulation investigations
- Conclusions and remarks
Introduction

• Freeway congestion due to saturated off-ramps is a particular type of congestion thus different freeway sites may call for different traffic control measures.

• Each situation should be viewed as a particular case and the corresponding network characteristics should be taken into account during the development of traffic control strategies.

• In the first examined case, freeway congestion is created due to the limited capacity of an off-ramp, which is not possible to increase.

• Various route diversion strategies are proposed that aim to reroute the drivers through alternative routes.
Dynamic route diversion concept: Problem description

Consider the following network:
Consider the following network:
Consider the following network:
Consider the following network:

- Primary route → distance-shorter route.
Dynamic route diversion concept:
Problem description

Consider the following network:

- Primary route $\rightarrow$ distance-shorter route.
Consider the following network:

- Primary route distance-shorter route.
- Primary route off-ramp limited capacity.
Consider the following network:

- Primary route distance-shorter route.
- Primary route off-ramp limited capacity.
Consider the following network:

- **Primary route** → distance-shorter route.
- **Primary route off-ramp** → limited capacity.
- Concept: **divert** a portion of traffic, $1 - \beta$, through the alternative route.
The route diversion concept can be applied through:

- Variable Message Signs (VMS)
- Vehicle to Infrastructure Communication

However, drivers are free to ignore messages …that they perceive incompatible with their own criteria!
• The objective of the route diversion system should not only be the system optimal conditions, but must mainly target **user-optimal conditions**.

• Depending on the network topology and traffic conditions, **three different cases** arise:
Dynamic route diversion concept: Problem description

- Case 1: The user-optimal conditions may be achieved before the off-ramp queue spill-over.
- Case 2: The user-optimal conditions are achieved only after the off-ramp queue spill-over and creation of mainstream congestion.
- Case 3: The user-optimal conditions may not be achievable.
Dynamic route diversion concept:
Problem description

- Case 1: The user-optimal conditions may be achieved before the off-ramp queue spill-over.
  - Dynamic route diversion based on reactive travel time estimation.
  - Dynamic route diversion based on off-ramp queue length estimation.

- Case 2: The user-optimal conditions are achieved only after the off-ramp queue spill-over and creation of mainstream congestion.

- Case 3: The user-optimal conditions may not be achievable.
A. Dynamic route diversion based on reactive travel time estimation

\[ \tau(k): \text{reactive (estimated) travel time} \]

\[ \Delta \tau(k) = \tau^s(k) - \tau^p(k) \]

**PI feedback strategy:**

\[ \beta(k) = \beta(k-1) + K_p \left[ \Delta \tau(k) - \Delta \tau(k-1) \right] + K_i \Delta \tau(k) \]

\[ \beta(k) \in [0,1] \]
Dynamic route diversion concept:

Case 1: User-optimal conditions may be achieved before the off-ramp queue spill-over

B. Dynamic route diversion based on off-ramp queue length estimation

\[ w(k) : \text{off-ramp queue estimation} \]
\[ \hat{w} : \text{desired queue level} \]

**PI feedback strategy:**

\[ \beta(k) = \beta(k-1) + K_p \left[ w(k-1) - w(k) \right] \]
\[ + K_i \left[ \hat{w} - w(k) \right] \]

\( \beta(k) \in [0,1] \)
Dynamic route diversion concept: Problem description

• Case 1: The user-optimal conditions may be achieved before the off-ramp queue spill-over.

• Case 2: The user-optimal conditions are achieved only after the off-ramp queue spill-over and creation of mainstream congestion.

• Case 3: The user-optimal conditions may not be achievable.
Dynamic route diversion concept: Problem description

• Case 1: The user-optimal conditions may be achieved before the off-ramp queue spill-over.

• Case 2: The user-optimal conditions are achieved only after the off-ramp queue spill-over and creation of mainstream congestion.
  
  – Dynamic route diversion based on off-ramp queue length estimation.
  
  – Dynamic route diversion through temporary off-ramp closures.

• Case 3: The user-optimal conditions may not be achievable.
Dynamic route diversion concept:  
Case 2: User-optimal conditions may be achieved only after the off-ramp queue spill-over

A. Dynamic route diversion based on off-ramp queue length estimation

\[ w(k) : \text{off-ramp queue estimation} \]
\[ \hat{w} : \text{desired queue level} \]

PI feedback strategy:

\[ \beta(k) = \beta(k-1) + K_p \left[ w(k-1) - w(k) \right] \]
\[ + K_i \left[ \hat{w} - w(k) \right] \]
\[ \beta(k) \in [0,1] \]
Dynamic route diversion concept:

**Case 2: User-optimal conditions may be achieved only after the off-ramp queue spill-over**

B. Dynamic route diversion through temporary off-ramp closures

\[ w(k) : \text{off-ramp queue estimation} \]

\[ \hat{w} : \text{desired queue level} \]

**Bang-Bang feedback strategy:**

\[ \beta(k) = \begin{cases} 
1 & \text{if } w(k) < \hat{w} \\
0 & \text{otherwise} 
\end{cases} \]
Dynamic route diversion concept: Problem description

- Case 1: The user-optimal conditions may be achieved before the off-ramp queue spill-over.
- Case 2: The user-optimal conditions are achieved only after the off-ramp queue spill-over and creation of mainstream congestion.
- Case 3: The user-optimal conditions may not be achievable.
Dynamic route diversion concept: Problem description

- Case 1: The user-optimal conditions may be achieved before the off-ramp queue spill-over.
- Case 2: The user-optimal conditions are achieved only after the off-ramp queue spill-over and creation of mainstream congestion.
- Case 3: The user-optimal conditions may not be achievable.
  - Dynamic route diversion through temporary off-ramp closures.
A. Dynamic route diversion through temporary off-ramp closures

\[ w(k) : \text{off-ramp queue estimation} \]

\[ \hat{w} : \text{desired queue level} \]

Bang-Bang feedback strategy:

\[ \beta(k) = \begin{cases} 
1 & \text{if } w(k) < \hat{w} \\
0 & \text{otherwise} 
\end{cases} \]
Real-time traffic control measures: Case 1 – Route diversion control

Test network: METANET Simulator

Demand profile and O-D rates:

Performance criteria:

Total Time Spent (TTS) in veh · h

Total Disbenefit (TD) in veh · h
Real-time traffic control measures: Case 1

Case 1: User-optimal conditions may be achieved before the off-ramp queue spill-over

A. No route diversion

![Graphs and diagrams showing traffic flow and speed over time with route diversion control simulations.]

<table>
<thead>
<tr>
<th>Route Guidance Policy</th>
<th>TTS (veh-h)</th>
<th>TD (veh-h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. No route diversion</td>
<td>3228</td>
<td>110</td>
</tr>
</tbody>
</table>
Simulation Investigations
Case 1: User-optimal conditions may be achieved before the off-ramp queue spill-over

B. Dynamic route diversion based on reactive travel time estimation

Route Diversion Policy | TTS (veh-h) | TD (veh-h)
--- | --- | ---
A. No route diversion | 3228 | 110
B. Route diversion based on travel times | 2473 | 0.1

(23%) (-100%)

PI-strategy parameters:

\[ K_p = 18, \quad K_i = 6, \quad \hat{\Delta} \tau = 0 \text{ min}, \quad T_c = 2 \text{ min} \]
Simulation Investigations
Case 1: User-optimal conditions may be achieved before the off-ramp queue spill-over

C. Dynamic route diversion based on off-ramp queue length estimation

<table>
<thead>
<tr>
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<td>110</td>
</tr>
<tr>
<td>B. Route diversion based on travel times</td>
<td>2473 (-23%)</td>
<td>0.1 (-100%)</td>
</tr>
<tr>
<td>C. Route diversion based on queue length</td>
<td>2500 (-23%)</td>
<td>13.7 (-88%)</td>
</tr>
</tbody>
</table>

PI-strategy parameters:

- $K_p = 0.02$, $K_i = 0.005$
- $\hat{w} = 25$ veh, $T_c = 2$ min
Simulation Investigations
Case 2: User-optimal conditions may be achieved only after the off-ramp queue spill-over

A. No route diversion

Route Diversion Policy  
TTS (veh-h)  TD (veh-h)
A. No route diversion  3637  34.3
Simulation Investigations
Case 2: User-optimal conditions may be achieved only after the off-ramp queue spill-over

B. Dynamic route diversion based on off-ramp queue length estimation

<table>
<thead>
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</thead>
<tbody>
<tr>
<td>A. No route diversion</td>
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<td>34.3</td>
</tr>
<tr>
<td>B. Route diversion based on queue length</td>
<td>2927 (-20%)</td>
<td>5.9 (-83%)</td>
</tr>
</tbody>
</table>

PI-strategy parameters:

\[ K_p = 0.02, \quad K_i = 0.005, \quad \hat{w} = 25 \text{ veh}, \quad T_c = 2 \text{ min} \]
Simulation Investigations

Case 2: User-optimal conditions may be achieved only after the off-ramp queue spill-over

C. Dynamic route diversion through temporary off-ramp closures

<table>
<thead>
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</tr>
<tr>
<td>C. Route diversion through temporary off-ramp closures</td>
<td>2916 (-20%)</td>
<td>8.3 (-76%)</td>
</tr>
</tbody>
</table>

Bang-Bang strategy:
\[ \hat{w} = 25 \text{ veh}, \ T_c = 2 \text{ min} \]
Simulation Investigations
Case 3: User-optimal conditions may not be achieved

A. No route diversion

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<tr>
<td>A. No route diversion</td>
<td>3979</td>
<td>0</td>
</tr>
</tbody>
</table>

- **Graph (a)**: Queue (veh) vs. Time (hours)
- **Graph (b)**: Δt (min) vs. Time (hours)
- **Graph (c)**: Flow (veh/h) vs. Time (hours)
- **Graph (d)**: Speed (km/h) vs. Time (hours)
B. Dynamic route diversion through temporary off-ramp closures

**Route Diversion Policy**

<table>
<thead>
<tr>
<th></th>
<th>TTS (veh-h)</th>
<th>TD (veh-h)</th>
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</thead>
<tbody>
<tr>
<td><strong>A. No route diversion</strong></td>
<td>3979</td>
<td>0</td>
</tr>
<tr>
<td><strong>B. Route diversion based on temporary off-ramp closures</strong></td>
<td>3263 (-18%)</td>
<td>14.5</td>
</tr>
</tbody>
</table>

**Bang-Bang strategy:**
- \( \hat{w} = 25 \text{ veh} \), \( T_c = 2 \text{ min} \)
Conclusions and remarks

- Various route diversion policies are proposed that aim to prevent recurrent freeway congestion which is triggered by a saturated off-ramp.
- The proposed policies employ simple but efficient feedback laws and attempt to reroute the drivers through alternative routes.
- The simulation results showed that, in all investigated cases, the proposed policies succeed in maintaining the off-ramp queue length within the off-ramp bounds.
<table>
<thead>
<tr>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
</tr>
<tr>
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</tr>
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<td>Conclusions and Future Work</td>
</tr>
</tbody>
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## Outline

<table>
<thead>
<tr>
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</tr>
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<tr>
<td>– Introduction</td>
</tr>
<tr>
<td>– Real-time merging traffic control concept</td>
</tr>
<tr>
<td>– Network description and traffic demand pattern</td>
</tr>
<tr>
<td>– Simulation investigations</td>
</tr>
<tr>
<td>– Conclusions and remarks</td>
</tr>
</tbody>
</table>
Introduction

• In the second examined case, recurrent freeway congestion is created due to congestion on the surface street network.

• The proposed control algorithm aims to maximize the surface street merge area outflow and prevent the off-ramp queue spill over.

• A real traffic network in Santiago, Chile, is utilized to demonstrate the application of the proposed control concept by use of microscopic simulation.
Consider the following network:
Consider the following network:

- The merge area is a **potential bottleneck location**, which may be activated during the peak hours.
Consider the following network:

- The merge area is a potential bottleneck location, which may be activated during the peak hours.
- The congestion on the surface street network may spill back into the freeway through the saturated off-ramp.
The merge area may be a bottleneck location due to a number of reasons:

- High arriving demand (including the surface street and the off-ramp demand).
- Infrastructure layout, e.g. lane drop.
- Strong weaving of traffic streams.
- Downstream urban traffic lights.
- Other capacity reducing events, such as incidents.
Real-time merging traffic control concept

Problem description

Fundamental diagram of a merge area:

Merging traffic control is proposed to restore capacity flow.
Traffic control algorithm goals:

- Maximize the surface street merge area outflow.
- Prevent the off-ramp queue spill-over into the freeway mainstream.
ALINEA feedback control strategy:

\[ q_{AL}(k) = q_{AL}(k-1) - K_P[N(k-1) - N(k-2)] + K_I[\hat{N} - N(k-1)] \]

\[ q_{AL}(k) \in [q_{\min}, q_{\max}] \]

For maximum throughput \( \hat{N} \approx N_{cr} \) (or \( \hat{o} \approx o_{cr} \))
Queue Override control strategy:

\[ q_{QO}(k) = \begin{cases} 
q_{\text{over}}, & \text{if } o_{\text{off}}(k-1) > o_{th} \\
0, & \text{otherwise} 
\end{cases} \]
Real-time merging traffic control concept

Traffic control algorithm

**Final flow decision:**

\[
q_{srf}(k) = q_{AL}(k) \lambda_{srf} / \lambda_{total}
\]

\[
q_{off}(k) = \max \left\{ q_{AL}(k) \lambda_{off} / \lambda_{total}, q_{QO}(k) \right\}
\]

- The final flow decision is implemented through two traffic lights placed at the surface street and the off-ramp upstream of the merge area.
Network description and traffic demand pattern

Autopista Central, Santiago, Chile:

- Congestion during the morning peak hours due to:
  - Limited capacity of the surface street merge area.
  - Strong lane changing maneuvers (weaving) in the merge area.
- This real freeway stretch is utilized to test and demonstrate the application of the proposed control algorithm.
Network description and traffic demand pattern

Microscopic simulation using AIMSUN:

- Freeway stretch: ~7km.
- Surface street network: ~1.52km.
- Detectors at several network locations.
Network description and traffic demand pattern

Microscopic simulation using **AIMSUN**:

- Average traffic demand similar to the real traffic demand.
- Two vehicle types: cars and trucks.
Simulation investigations

No control case

Real-time traffic control measures: Case 2 – Merging traffic control
Simulation investigations

No control case

- 10 AIMSUN replications.
- Performance criteria:
  - Average Vehicles Delay (AVD)
  - Average Harmonic Speed (AHS)

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<tbody>
<tr>
<td>No Control</td>
<td>24.3</td>
<td>24.0</td>
<td>35.1</td>
<td>17.1</td>
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Simulation investigations

No control case

~29 veh (a)

~2850 veh/h (b)
Simulation investigations

Merging traffic control

- ALINEA strategy:
  - $T_c = 30$ s.
  - Input: $N$.
  - $K_p = 110$ h$^{-1}$, $K_i = 80$ h$^{-1}$.
  - $q_{AL}(k) \in [600, 4800]$ veh.
  - $\hat{N} \approx N_{cr}$.

- Queue Override strategy:
  - $T_c = 30$ s.
  - Input: $o_{off}$.
  - $o_{th} \approx 25\%$, $q_{over} = 1600$ veh/h.
Number value investigations:

For $\hat{N} \in [20, 22]$ veh the AVD is minimized.
Simulation investigations
Merging traffic control

\( \hat{N} = 22 \text{ veh} \)

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<td>35.1</td>
<td>17.1</td>
</tr>
<tr>
<td>Control Set-point = 22 veh</td>
<td>6.9</td>
<td>1.8</td>
<td>4.1</td>
<td>14.7</td>
</tr>
<tr>
<td>% Difference</td>
<td>-71.6</td>
<td>-92.5</td>
<td>-88.3</td>
<td>-14.0</td>
</tr>
</tbody>
</table>
Simulation investigations

Merging traffic control

\[ \hat{N} = 22 \text{ veh} \]
Simulation investigations
Merging traffic control

\[ \hat{N} = 22 \text{ veh} \]
Conclusions and remarks

• A control framework is proposed to address the problem of freeway congestion due to an over-spilling off-ramp.

• The control algorithm aims to maximize the surface street merge area outflow and at the same time to prevent the off-ramp queue spill-over into the mainstream freeway.

• The proposed control concept was demonstrated via microscopic simulation using a real traffic network.

• The simulation results showed that the proposed control algorithm improves the prevailing traffic conditions, preventing the formation of congestion and benefiting both the freeway drivers and the surface street users.
Outline

Introduction

Calibration of Macroscopic Traffic Flow Models

Real-Time Traffic Control Measures: Case 1 – Route diversion control

Real-Time Traffic Control Measures: Case 2 – Merging traffic control

Conclusions and Future Work
Outline

- Introduction
- Calibration of Macroscopic Traffic Flow Models
- Real-Time Traffic Control Measures: Case 1 – Route diversion control
- Real-Time Traffic Control Measures: Case 2 – Merging traffic control
- Conclusions and Future Work
To sum-up:

- The two most popular macroscopic traffic flow models (the CTM and METANET model) were validated and compared regarding the reproduction of traffic conditions at congested freeway off-ramp areas.

- The validation results showed that both models are able to reproduce the traffic conditions in such networks, with the METANET model offering a more accurate representation of the prevailing traffic conditions.

- Two different cases of congested freeway off-ramp areas were examined and innovative traffic control measures were proposed for each investigated case.

- The simulation results showed that in both cases the proposed traffic control strategies manage to prevent the off-ramp queue spill-over and the creation of mainstream congestion thus they are both very promising in case of potential field implementation.
Conclusions and Future Work

Future extensions:

• The utilized traffic flow models, and in particular the CTM model can be extended and improved to increase the achieved accuracy.

• More macroscopic traffic flow models can be employed and compared against the utilized models.

• The first examined traffic control case, for congested freeway off-ramp areas, can be extended in order to account for multiple routes.

• In the second traffic control case, a bigger surface street network can be considered taking also into account possible restrictions that may apply due to signalized junctions.

• Finally, field trial of the proposed traffic control strategies would provide more evidence about the achievable level of benefits.
Publications

International journals:


Conferences:

- **Spiliopoulou, A., Kontorinaki, M., Papageorgiou, M., & Kopelias, P.** (2013) Comparative evaluation of macroscopic traffic flow models in freeway off-ramp areas. 6<sup>th</sup> Συνέδριο για την Έρευνα στις Μεταφορές στην Ελλάδα (*6<sup>th</sup> Congress on Transportation Research in Greece*), Thessaloniki, Greece, October 17–18.


This Ph.D. research has been co-financed by the European Union (European Social Fund ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) – Research Funding Program: Heraclitus II. Investing in knowledge society through the European Social Fund.
Thank you for your attention!