Analysis of Flow Features in Queued Traffic on a German Freeway

Ph.D. Dissertation Defense

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Outline

- Objectives
- Background
- Method
- Analysis
  - Diverge Bottleneck Activation & Deactivation
  - Merge Bottleneck Activation
  - Queue Discharge Properties
  - Bottleneck Triggers
  - Reproducibility
- Conclusions and Implications
- Future Research
- Questions
Determine spatial-temporal limits of traffic congestion on the A5 and investigate triggers that led to formation and dissipation of bottlenecks.
Background

- 50 years of freeway bottleneck studies
  - Manually collected data (direct observation, air photos)
  - Limitations of the data analysis methods
    - Short duration
    - Studies at fixed points
    - Lacking activation criteria

- Recent studies of Canadian, British, and US freeways employed more robust data analysis methods – none on German freeways
Literature Review

- Measured variables (velocity and flow) exhibit statistical variations as well as time-dependent changes.

- These plotting techniques make it difficult to distinguish between the two.
Literature Review

- Kerner and colleagues have reported on empirical studies of German freeways – 37 papers

- Three phases of traffic flow (Kerner):
  - Free flow
  - Synchronized flow
  - Traffic jam

- Many of Kerner’s findings are controversial:
  - Spontaneous bottleneck formation
  - Large variation in bottleneck discharge flow
Motivation

- Kerner’s work:
  - Limited number of days and bottlenecks
  - Did not define bottleneck spatial & temporal limits
  - Has not made his data available to other researchers
- This research was motivated by the need for independent analysis of German freeway dynamics
- For the **first time**, German freeway was available for this study
Scope

- Scope initially limited to 10 km section
- Expanded to entire 30 km corridor
  - To trace very long shocks
  - To study merge bottlenecks
Data

- Inductive loop detectors
- 1-minute resolution
- Count and speed in each lane for autos and trucks
- No fixed auto speed limit
- Trucks limited to right lane and 80 km/h
- No ramp metering
- 6 weekdays in 2001
- Good weather
- 81 bottlenecks analyzed
Data
Method - Plot Sensor Data Cumulatively

\[ N(x,t) \]

Travel Direction

\[ Time, t \at \ x \]

Flow Increase

Flow Decrease

Slope = number/time = FLOW


12
Method - Plot A5 Count Data Cumulatively

A5 • Station D21 • Sept. 14, 2001
Choose Oblique Scaling Rate

\[ N(x,t) \]

\[
q_0 = 4910 \text{ vph}
\]

A5 • Station D21 • Sept. 14, 2001

\[ N(x,t) \text{ Cumulative Count} \]

Time

\[ 13:30 - 14:30 \]
Prepare Oblique Axis

A5 • Station D21 • Sept. 14, 2001

$N(x,t)$

$q_0 = 4910 \text{ vph}$

$N(x,t) - q_0 t'$
Oblique Axis Plot

A5 • Station D21 • Sept. 14, 2001

N(x,t)-q₀t'
Annotate with Linear Approximations

A5 • Station D21 • Sept. 14, 2001

$N(x,t) - q_0 t'$

- 5230 vph
- 5510 vph
- 4220 vph
- 4960 vph
- 4060 vph

Time

0 25 50 75 100 125 150 175 200 225 250

N(x,t) – q0t’ = 4,910 vph
Queueing Diagram

\[ N(x_j, t) \]

Time, \( t \)

Travel Direction

\[ x_1 \]

\[ N(x_1, t) \]
Queueing Diagram

\[ N(x_j, t) \]

Travel Direction

Ref. Veh. Trip Time

Time, t

\[ N(x_1, t) \]

\[ N(x_2, t) \]
Queueing Diagram

\[
N(x_j, t)
\]

Ref. Veh. Trip Time

\( t_1 \)

Number of vehicles

Travel Direction

\( x_1 \)

\( x_2 \)

Trip Time

\( N(x_1, t) \)

\( N(x_2, t) \)
Queueing Diagram

\[ N(x, t) \]

\[ N(x_1, t) \]

\[ N(x_2, t) \]

Travel Direction

Time, \( t \)
Queueing Diagram

Time, $t$

$N(x_1, t)$

$N(x_2, t)$

$k$

$N(x_j, t)$

Excess Accumulation

Excess Travel Time = Delay
Method

- Transformed curves of vehicle arrival number vs. time and time-averaged velocity vs. time provide fidelity required to identify key time-dependent traffic features related to active bottlenecks
- **Active** bottleneck exists when upstream traffic is queued and downstream traffic unqueued
- Deactivation occurs with a decrease in flow or when a queue spills back from a downstream bottleneck
Queueing Diagram – A5 Data

LEGEND

N(x,t) - q_0 = 4,300 vph

Time, t @ D20

Bottleneck
Diverge Activation

\[ N(x,t) - q_0 t, \quad q_0 = 4300 \text{ vph} \]

**Legend**
- D20
- D21
- D22
- D23
- D24

**Time, \( t \) @ D20**

- 13:40
- 13:45
- 13:50
- 13:55
- 14:00
- 14:05
- 14:10
Diverge Activation

LEGEND

Time, $t @ D20$

$N(x,t) - q_0 t$, $q_0 = 4,300$ vph
Diverge Activation

\[ N(x,t) = q_0 t, \quad q_0 = 4,300 \text{ vph} \]

LEGEND

Time, \( t \) @ D20

13:40 13:45 13:50 13:55 14:00 14:05 14:10

14:02 D22

D20 D21 D22 D23 D24
Diverge Activation

Time, \( t @ D20 \)

N(x,t) - \( q_0 t \), \( q_0 = 4,300 \text{ vph} \)

LEGEND

D20 D21 D22 D23 D24

Bottleneck

5290 vph

3900 vph
Diverge Activation

Time, $t$ @ D22

V(D22, t) = $v_0 t$, $v_0 = 4511$ km/h^2

Legend

D20 D21 D22 D23 D24

95 km/h

45 km/h
Diverge Activation

\[ N(x,t) - q_0 t', q_0 = 4,300 \text{ vph} \]

\[ V(D22,t) - v_0 t', v_0 = 4,511 \text{ km/h}^2 \]

Time, \( t @ D22 \)

Time, \( t @ D20 \)

LEGEND

D20, D21, D22, D23, D24

14:02 D22

14:02 D22

Bottleneck
Diverge Activation

\[ N(x,t) - q_0 = 4,300 \text{ vph} \]

Legends:
- D20
- D21
- D22
- D23
- D24

Bottleneck at 14:04
Diverge Activation

Time, $t @ D20$

Legend:
- D20
- D21
- D22
- D23
- D24

$N(x,t) - q_0 t, q_0 = 4,300$ vph

Bottleneck
Diverge Activation

LEGEND

Time, t @ D20

N(x,t)|q0t, q0=4,300 vph

V(D20,t)|v0=4,830 km/h

Diverge Activation

Bottleneck
Diverge Deactivation

Graph showing traffic flow at different points D20, D21, D22, D23, and D24 over time from 13:40 to 14:20. The graph plots the number of vehicles $N(x,t)$ against time $t$ with $q_0 = 4300$ vph. The y-axis represents vehicle flow, and the x-axis represents time.

Legend:
- D20
- D21
- D22
- D23
- D24

Bottleneck indicated at D22 with an arrow pointing towards D22 at 14:17.

Equation: $N(x,t) - q_0 t$
Diverge Deactivation

\[ V(D22,t) - v_0t \quad v_0 = 5,615 \text{ km/h}^2 \]

\[ N(x,t) - q_0t \quad q_0 = 4,300 \text{ vph} \]
Shock Speed 21 km/h
Bottleneck Outflow

\[ N(D23, t) - q_0 = 4,730 \text{ vph} \]
Bottleneck Outflow

Bottleneck

Bottleneck Outflow

$N(D_{23}, t) - q_0 \cdot t' \quad q_0 = 4,730 \text{ vph}$

15.4%

$N(D_{23}, t)$

Time, $t \ @ \ D_{23}$
Bottleneck Outflow

Time, $t$ @ D23

$N(D23, t)$ - $q_0 t'$, $q_0 = 4,730$ vph

Bottleneck C1

D22/D23

10.8%
Bottleneck Outflow

\[ N(D23, t) - q(t) = 4,730 \text{ vph} \]

\[ V(D23, t) - v(t) = 4,800 \text{ km/h}^2 \]

Bottleneck C1

D22/D23

Time, \( t \) @ D23
Bottleneck Outflow

Bottleneck C1

- Sept. 14, 2001
- Active 14:02-14:17 between D22 and D23
- Outflow measured at D23

<table>
<thead>
<tr>
<th>Lane</th>
<th>Flow (vph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>4,630</td>
</tr>
<tr>
<td>Left</td>
<td>1,840</td>
</tr>
<tr>
<td>Mid</td>
<td>1,640</td>
</tr>
<tr>
<td>Right</td>
<td>1,150</td>
</tr>
</tbody>
</table>
Diverge Bottleneck Characteristics

- A diverge bottleneck arose between D22 and D24 a total of 21 times over six days
- Durations ranged from 7 to 223 minutes
- Discharge flow characteristics

<table>
<thead>
<tr>
<th>Lane</th>
<th>Average Flow (vph)</th>
<th>Std. Deviation (vph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>4,890</td>
<td>310</td>
</tr>
<tr>
<td>Left</td>
<td>1,970</td>
<td>120</td>
</tr>
<tr>
<td>Mid</td>
<td>1,700</td>
<td>130</td>
</tr>
<tr>
<td>Right</td>
<td>1,220</td>
<td>100</td>
</tr>
</tbody>
</table>

n=21
Isolated Diverge Bottleneck Characteristics

- 12 diverge bottleneck activations were preceded by periods of large pre-queue flows – “isolated”
- “Isolated” discharge flow characteristics

<table>
<thead>
<tr>
<th>Lane</th>
<th>Condition</th>
<th>Average Flow (vph)</th>
<th>Std. Deviation (vph)</th>
<th>Flow Drop (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>Pre-queue</td>
<td>5,110</td>
<td>290</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>4,890</td>
<td>320</td>
<td>4.3</td>
</tr>
<tr>
<td>Left</td>
<td>Pre-queue</td>
<td>2,160</td>
<td>190</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>1,980</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>Mid</td>
<td>Pre-queue</td>
<td>1,740</td>
<td>160</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>1,700</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>Pre-queue</td>
<td>1,210</td>
<td>130</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>1,210</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

n=12
Bottleneck Inflow

Time, $t$ @ D22

Left
$v_0=30$ trucks/hr

Mid
$v_0=80$ trucks/hr

Right
$v_0=400$ trucks/hr

13:02 Activation

N(D22,t)-$q_0$’

Bottleneck Inflow

![Bottleneck Inflow Diagram]

- **Left**: \( q_0 = 1,800 \) vph
- **Mid**: \( q_0 = 1,800 \) vph
- **Right**: \( q_0 = 1,600 \) vph

**Time, \( t @ D22 \)**

- Left: \( 14:02 \) Activation
- Mid: \( 14:00 \)
- Right: \( 14:02 \)
Bottleneck Inflow

Time, $t @ D22$

D22 Right Lane Equivalent Flow (pc/h)
# Isolated Diverge Bottleneck Triggers

<table>
<thead>
<tr>
<th>Date</th>
<th>Bottleneck No.</th>
<th>Off-ramp Flow Surge</th>
<th>High Pre-Queue Flow All Lanes (vph)</th>
<th>High Pre-Queue Flow Right Lane (pc/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep. 19</td>
<td>G14</td>
<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
</tr>
<tr>
<td>Sep. 14</td>
<td>C1</td>
<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
</tr>
<tr>
<td>Sep. 14</td>
<td>C2</td>
<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
</tr>
<tr>
<td>Sep. 14</td>
<td>C8</td>
<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
</tr>
<tr>
<td>Dec. 4</td>
<td>F2</td>
<td></td>
<td>⬤</td>
<td>⬤</td>
</tr>
<tr>
<td>Dec. 4</td>
<td>F9</td>
<td></td>
<td>⬤</td>
<td>⬤</td>
</tr>
<tr>
<td>Sep. 20</td>
<td>E3</td>
<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
</tr>
<tr>
<td>Aug. 17</td>
<td>B2</td>
<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
</tr>
<tr>
<td>Aug. 17</td>
<td>B7</td>
<td>⬤</td>
<td>⬤</td>
<td>⬤</td>
</tr>
<tr>
<td>Aug 17</td>
<td>B8</td>
<td></td>
<td>⬤</td>
<td>⬤</td>
</tr>
<tr>
<td>May 18</td>
<td>A1</td>
<td></td>
<td>⬤</td>
<td>⬤</td>
</tr>
</tbody>
</table>
Diverge Bottleneck Deactivation

- 2 “isolated” diverge deactivations observed between D22 and D24 over 6 days

**Triggers**
- Off-ramp flow drop (all vehicles)
- D25 right lane flow drop (trucks)
Diverge Bottleneck Deactivation

Time, $t$ @ D25

$N(D25, t) - q_0 t'$

- Off-Ramp: $q_0 = 590$ vph
- Right: $q_0 = 350$ trucks/h

31% Bottleneck Deactivation

520 vph

750 vph

520 vph

310 trucks/h

440 trucks/h

30% Bottleneck Deactivation

17:36 B7 Deactivation

17:40

17:50

18:00
Merge Activation

$N(x,t) - q_0 = 4,950 \text{ vph}$

Time, $t @ D6$

Legend:
- D6
- D7
- D8
- D9

Bottleneck

57
Merge Activation

\[ N(x,t) = q_0 t \]
\[ q_0 = 4,950 \text{ vph} \]

Time, \( t \) @ D6
merge activation

\[ N(x,t) = q_0 t' \quad q_0 = 4,950 \text{ vph} \]

\[ k(D7,t) = v_0 = 4,400 \text{ km/h}^2 \]

LEGEND

- D6
- D7
- D8
- D9

Bottleneck

Time, \( t @ D6 \)

Time, \( t @ D7 \)
Merge Activation

\[ V(D6,t) - v_0t', \quad v_0 = 3,880 \text{ km/h}^2 \]

\[ N(x,t) - q_0t', \quad q_0 = 4,950 \text{ vph} \]

LEGEND

- \( D6 \)
- \( D7 \)
- \( D8 \)
- \( D9 \)

Bottleneck

Time, \( t @ D6 \)

Time, \( t @ D6 \)
Merge Deactivation

Time, \( t \) @ D6

\[ N(x,t) - q_0 = 4,950 \text{ vph} \]
<table>
<thead>
<tr>
<th>Time, $t$ @ D6</th>
<th>N(x,t) - $q(t) = 4,950$ vph</th>
</tr>
</thead>
<tbody>
<tr>
<td>15:50</td>
<td></td>
</tr>
<tr>
<td>15:52</td>
<td></td>
</tr>
<tr>
<td>15:54</td>
<td></td>
</tr>
<tr>
<td>15:56</td>
<td></td>
</tr>
<tr>
<td>15:58</td>
<td></td>
</tr>
<tr>
<td>16:00</td>
<td></td>
</tr>
<tr>
<td>16:02</td>
<td></td>
</tr>
<tr>
<td>16:04</td>
<td></td>
</tr>
<tr>
<td>16:06</td>
<td></td>
</tr>
<tr>
<td>16:08</td>
<td></td>
</tr>
<tr>
<td>16:10</td>
<td></td>
</tr>
</tbody>
</table>

**Legend**

- **D6**
- **D7**
- **D8**
- **D9**

**Merge Deactivation**

**Inlet:** $v_0 = 4,310$ km/h^2

**Outlet:** $v_0 = 4,950$ vph
Bottleneck Outflow

\[ N(D8,t) = q(t) - q_0 = 4,900 \text{ vph} \]

\[ V(D8,t) = v(t) - v_0 = 4,425 \text{ km/h}^2 \]

Time, \( t @ D8 \)

14:50 15:00 15:10 15:20 15:30 15:40 15:50 16:00 16:10

Bottleneck E2

D7/D8

\[ q_0 = 4,900 \text{ vph} \]

\[ v_0 = 4,425 \text{ km/h}^2 \]
Bottleneck Outflow

Bottleneck E2

- Sept. 20, 2001
- Active 15:08-16:04 between D7 and D8
- Outflow measured at D8

<table>
<thead>
<tr>
<th>Lane</th>
<th>Flow (vph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>5,150</td>
</tr>
<tr>
<td>Left</td>
<td>2,240</td>
</tr>
<tr>
<td>Mid</td>
<td>1,830</td>
</tr>
<tr>
<td>Right</td>
<td>1,060</td>
</tr>
</tbody>
</table>
A merge bottleneck arose between D7 and D8 a total of 12 times over six days.

- Durations ranged from 7 to 73 minutes.
- Discharge flow characteristics

<table>
<thead>
<tr>
<th>Lane</th>
<th>Average Flow (vph)</th>
<th>Std. Deviation (vph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>5,040</td>
<td>420</td>
</tr>
<tr>
<td>Left</td>
<td>2,090</td>
<td>200</td>
</tr>
<tr>
<td>Mid</td>
<td>1,840</td>
<td>170</td>
</tr>
<tr>
<td>Right</td>
<td>1,110</td>
<td>90</td>
</tr>
</tbody>
</table>

n=12
Isolated Merge Bottleneck Characteristics

- 2 merge bottleneck activations were preceded by periods of large pre-queue flows – “isolated”
- “Isolated” discharge flow characteristics

<table>
<thead>
<tr>
<th>Lane</th>
<th>Condition</th>
<th>Average Flow (vph)</th>
<th>Std. Deviation (vph)</th>
<th>Flow Drop (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>Pre-queue</td>
<td>5,260</td>
<td>60</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>5,130</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>Pre-queue</td>
<td>2,250</td>
<td>70</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>2,220</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Mid</td>
<td>Pre-queue</td>
<td>1,920</td>
<td>40</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>1,840</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>Pre-queue</td>
<td>1,100</td>
<td>50</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>1,070</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

n=2
Merge Activation Triggers

- D6 on-ramp flow surge
- Net lane change to left (D7-D8)
Merge Activation Trigger

\[ N(D6on, t) - q_0 t = 1,570 \text{ vph} \]

Time, \( t \) @ D6
Day A

Oscillation waves

-16.5 km/h
## Oscillation Magnitude

<table>
<thead>
<tr>
<th>Site</th>
<th>Amplitude (vehicles / lane)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>67</td>
</tr>
<tr>
<td>England</td>
<td>22</td>
</tr>
<tr>
<td>Canada</td>
<td>16</td>
</tr>
</tbody>
</table>
Conclusions

- Bottlenecks at **predictable** locations:
  - Merge and diverge areas

- Discharge flows:
  - **Reproducible** across all lanes and lane by lane
  - **Nearly constant** and should be viewed as the bottlenecks’ capacities

- “**two capacity**” theory was validated:
  - in both merge and diverge locations, bottleneck discharge flows were lower than pre-activation flows
Conclusions

- Traffic disturbances:
  - Nearly constant speeds
  - Traveled long distances (20 km) without spreading
- Merge bottlenecks triggers:
  - Increased on-ramp flows
  - Lane changing to the left
- Diverge bottlenecks triggers:
  - Increased off-ramp flows
  - High pre-queue flows in all lanes with notable truck influence in the right lane
Implications/Future Research

- **Unique evaluation** of truck and auto data:
  - Allowed detailed study of bottleneck triggers
- The results of this study should be used to **calibrate**, then **validate** both macroscopic and microscopic traffic flow models of the A5
- The extent to which **speed limits**, both fixed and variable, affect bottleneck formation, should be studied
- The impact of **variable message signs** on congested traffic should also be studied
Acknowledgements

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- Department of Civil & Environmental Engineering at PSU
- Department of Civil Engineering & Geomatics at OIT
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