Freeway On-Ramp Bottleneck Activation, Capacity, and the Fundamental Relationship

Dr. Seoungbum Kim
PhD, Civil Engineering

Benjamin Coifman
Associate Professor, Civil Engineering
Associate Professor, Electrical Engineering

The Ohio State University

20th International Symposium on Transportation and Traffic Theory

July 26, 2013
An on-ramp bottleneck
An on-ramp bottleneck

What we think we know...
a quick review of conventional wisdom
An on-ramp bottleneck

Conventional wisdom

flow (q)
density (k)
distance (x)
time (t)
An on-ramp bottleneck

Conventional wisdom
An on-ramp bottleneck

Conventional wisdom
An on-ramp bottleneck

Conventional wisdom
An on-ramp bottleneck

Conventional wisdom- Identifying when it is active

Queued Upstream
low v
q & k negatively correlated
An on-ramp bottleneck

Conventional wisdom - Identifying when it is active

- Density (k)
- Flow (q)
- Distance (x)
- Time (t)

queued upstream
non-queued downstream

low v – q & k negatively correlated

high v – q & k positively correlated

Non-queued Downstream
Queued Upstream
An on-ramp bottleneck

Conventional wisdom- Measuring capacity

- Distance (x)
- Time (t)
- Flow (q)
- Density (k)

Queued Upstream

Non-queued Downstream

- Low v: q & k negatively correlated
- High v: q & k positively correlated

q upstream of queue likely in excess of capacity so... Do not measure capacity here

Non-queued Downstream
- High v: q & k positively correlated

Queued Upstream
- Low v: q & k negatively correlated
An on-ramp bottleneck

Conventional wisdom - Measuring capacity

- Distance (x)
- Time (t)
- Flow (q)
- Density (k)

Queued Upstream
Non-queued Downstream

Low v
q & k negatively correlated

High v
q & k positively correlated

Discharging q should be at capacity, so measure capacity here

q upstream of queue likely in excess of capacity so... Do not measure capacity here

Non-queued Downstream
- high v
- q & k positively correlated

Queued Upstream
- low v
- q & k negatively correlated
An on-ramp bottleneck

Conventional wisdom

Point bottleneck model

The bottleneck mechanism occurs at a point in space
An on-ramp bottleneck
Conventional wisdom

Point bottleneck model
The bottleneck mechanism occurs at a point in space
... but now drivers change speed instantaneously

![Graph showing distance (x) vs. time (t)]
An on-ramp bottleneck
Conventional wisdom

Point bottleneck model

The bottleneck mechanism occurs at a point in space
... but now drivers change speed instantaneously

... fine model it as if the transition distances are negligible
An on-ramp bottleneck

What we think we know...
a quick review of conventional wisdom

What has been overlooked...
conventional wisdom has failed us
An on-ramp bottleneck

The first crack in the wall

Cassidy and Bertini (1999) use a modified queuing diagram to study an on-ramp bottleneck.
An on-ramp bottleneck

The first crack in the wall

Cassidy and Bertini (1999) use a modified queuing diagram to study an on-ramp bottleneck.

They find the initial queue formation 1 km downstream of the on-ramp.
An on-ramp bottleneck

What we think we know...
a quick review of conventional wisdom

What has been overlooked...
conventional wisdom has failed us

Moving into our work...
consider the microscopic driver behavior
An on-ramp bottleneck

The macroscopic perspective

distance (x)

flow (q)

density (k)

time (t)
An on-ramp bottleneck

The microscopic perspective - what the drivers see

- speed (v)
- spacing (s)
- flow (q)
- density (k)
- distance (x)
- time (t)
- speed (v)
- spacing (s)
An on-ramp bottleneck

The microscopic perspective - what the drivers see

But drivers do not adjust their spacing over a short distance!

A driver will accept a short headway for 20 sec or more so that they can enter a lane that is constrained by downstream conditions.
An on-ramp bottleneck

The microscopic perspective- what the drivers see

But drivers do not adjust their spacing over a short distance!

A driver will accept a short headway for 20 sec or more so that they can enter a lane that is constrained by downstream conditions.

And then will slowly "relax" to their preferred headway.
An on-ramp bottleneck

The microscopic perspective- what the drivers see

But drivers do not adjust their spacing over a short distance!

A driver will accept a short headway for 20 sec or more so that they can enter a lane that is constrained by downstream conditions and then will slowly "relax" to their preferred headway.
An on-ramp bottleneck

The microscopic perspective- what the drivers see

But drivers do not adjust their spacing over a short distance!

A driver will accept a short headway for 20 sec or more so that they can enter a lane that is constrained by downstream conditions.

And then will slowly "relax" to their preferred headway.
An on-ramp bottleneck

The microscopic perspective - what the drivers see

But drivers do not adjust their spacing over a short distance!

A driver will accept a short headway for 20 sec or more so that they can enter a lane that is constrained by downstream conditions and then will slowly "relax" to their preferred headway.
An on-ramp bottleneck

The microscopic perspective—what the drivers see

But drivers do not adjust their spacing over a short distance!

A driver will accept a short headway for 20 sec or more so that they can enter a lane that is constrained by downstream conditions and then will slowly "relax" to their preferred headway.
An on-ramp bottleneck

What we think we know...
  a quick review of conventional wisdom

What has been overlooked...
  conventional wisdom has failed us

Moving into our work...
  consider the microscopic driver behavior

So what, who cares?
  seems like splitting microscopic hairs to me
An on-ramp bottleneck

Simulate vehicle trajectories in the vicinity of an on-ramp bottleneck
An on-ramp bottleneck

Simulate vehicle trajectories in the vicinity of an on-ramp bottleneck

Examine two cases
- without relaxation
- with relaxation
An on-ramp bottleneck

Simulate vehicle trajectories in the vicinity of an on-ramp bottleneck

Examine two cases
- without relaxation
- with relaxation

- RCap: 2200 vph
- Mainline flow: 2080 vph
- Ramp flow: 360 vph
- Free Speed: 60 mph
An on-ramp bottleneck

Simulate vehicle trajectories in the vicinity of an on-ramp bottleneck

Examine two cases
  - without relaxation
  - with relaxation

- RCap: 2200 vph
- Mainline flow: 2080 vph
- Ramp flow: 360 vph
- Free Speed: 60 mph

Many more scenarios can be found in the paper
An on-ramp bottleneck

Without relaxation
An on-ramp bottleneck

Similar to the earlier macroscopic diagram
An on-ramp bottleneck

Without relaxation

With relaxation
An on-ramp bottleneck

initial standing queue forms 0.3 mi downstream of on-ramp
An on-ramp bottleneck

With relaxation

Initial standing queue forms 0.3 mi downstream of on-ramp

Seemingly non-queued at on-ramp immediately after activation
An on-ramp bottleneck

With relaxation

initial standing queue forms 0.3 mi downstream of on-ramp

seemingly non-queued at on-ramp immediately after activation

upstream end of queue first reaches the on-ramp several minutes after activation
An on-ramp bottleneck

downstream end of queue grows to 1.8 mi downstream of on-ramp

initial standing queue forms 0.3 mi downstream of on-ramp

seemingly non-queued at on-ramp immediately after activation

upstream end of queue first reaches the on-ramp several minutes after activation
An on-ramp bottleneck

- Downstream end of queue grows to 1.8 mi downstream of on-ramp.
- Downstream end of queue recedes back towards on-ramp.
- Initial standing queue forms 0.3 mi downstream of on-ramp.
- Seemingly non-queued at on-ramp immediately after activation.
- Upstream end of queue first reaches the on-ramp several minutes after activation.

With relaxation:

- Initial standing queue forms 0.3 mi downstream of on-ramp.
- Seemingly non-queued at on-ramp immediately after activation.
- Upstream end of queue first reaches the on-ramp several minutes after activation.
An on-ramp bottleneck

The macroscopic perspective again

Any sample with relaxing drivers
An on-ramp bottleneck

The macroscopic perspective again

Any sample with relaxing drivers transient short headways translate to...

distance (x) vs time (t)

flow (q) vs density (k)

speed (v) vs spacing (s)
An on-ramp bottleneck

The macroscopic perspective again

Any sample with relaxing drivers transient short headways translate to...

Supersaturated $q$ above sustainable capacity

- Speed ($v$)
- Spacing ($s$)
- Distance ($x$)
- Time ($t$)
- Flow ($q$)
- Density ($k$)
- Speed ($v$)
- Spacing ($s$)
- Distance ($x$)
- Time ($t$)

flow ($q$)
density ($k$)
An on-ramp bottleneck

The macroscopic perspective again

Initial queue formation characterized by supersaturated flows downstream of on-ramp, i.e., $q > 2200$ vph
An on-ramp bottleneck

The macroscopic perspective again

Initial queue formation characterized by supersaturated flows downstream of on-ramp, i.e., $q > 2200$ vph

Far downstream of the on-ramp $q$ never exceeds capacity, 2200 vph
An on-ramp bottleneck

The macroscopic perspective again

We call this the “loading period” because the $q$ over capacity will be stored somewhere further downstream, loading up the segment.
**An on-ramp bottleneck**

The macroscopic perspective again

We call this the “loading period” because the q over capacity will be stored somewhere further downstream, loading up the segment.

We call this the “settling period” because some of the stored vehicles discharge and consume capacity that would otherwise serve the on-ramp.
An on-ramp bottleneck
But what would an empirical study see?

Place a detector at 0.2 mi and look at the measurements...
An on-ramp bottleneck

But what would an empirical study see?
An on-ramp bottleneck

But what would an empirical study see?

q & k positively correlated for several min after activation
An on-ramp bottleneck
But what would an empirical study see?

$q$ & $k$ positively correlated for several min after activation

$v$ drops by 8 mph
An on-ramp bottleneck
But what would an empirical study see?

$q$ & $k$ positively correlated for several min after activation

$v$ drops by 8 mph

If we did not already know that $q > \text{capacity}$
we would not know that the bottleneck was active
An on-ramp bottleneck

But what would an empirical study see?

If we did not already know that \( q > \) capacity
we would not know that the bottleneck was active

Seemingly parabolic \( qk \) curve
An on-ramp bottleneck

But what would an empirical study see?

If we did not already know that $q > \text{capacity}$
we would not know that the bottleneck was active

Seemingly parabolic $qk$ curve
but the high point is actually supersaturated
An on-ramp bottleneck

But what would an empirical study see?
An on-ramp bottleneck

But what would an empirical study see?

If we only had the detector data we would likely conclude bottleneck became active this instant (and we would be wrong)
An on-ramp bottleneck

But what would an empirical study see?

If we only had the detector data we would likely conclude bottleneck became active this instant (and we would be wrong)

By simultaneously determining activation and estimating capacity, we would overestimate capacity by 200 vph
An on-ramp bottleneck

But what would an empirical study see?

Bottleneck active

Flow (vph)

Density (vpm)

Time (sec)

Flow

Density

Speed (mph)

so-called

capacity drop

q starts
to drop

q min

capacity drop
An on-ramp bottleneck

But what would an empirical study see?
An on-ramp bottleneck

But what would an empirical study see?

An empirical study would see $q$ drop around 200 sec, take the highest throughput prior to that point and (erroneously) call it capacity.
An on-ramp bottleneck

But what would an empirical study see?

An empirical study would see $q$ drop around 200 sec, take the highest throughput prior to that point and (erroneously) call it capacity.

This drop would occur several minutes after the bottleneck had actually become active, misslabeling the intervening period as being unqueued.
An on-ramp bottleneck

From our model

Model from Laval and Leclercq (2008)
An on-ramp bottleneck

Conclusions

The point bottleneck model is too simple to capture the entire bottleneck process
An on-ramp bottleneck

Conclusions

The point bottleneck model is too simple to capture the entire bottleneck process.

The bottleneck process occurs over an extended distance.
An on-ramp bottleneck

Conclusions

The point bottleneck model is too simple to capture the entire bottleneck process.

The bottleneck process occurs over an extended distance.

If one fails to recognize the fact that the bottleneck is already active and flows supersaturated due to driver relaxation:

- Overestimate bottleneck capacity
- Record the activation time too late
An on-ramp bottleneck

Conclusions

The point bottleneck model is too simple to capture the entire bottleneck process.

The bottleneck process occurs over an extended distance.

If one fails to recognize the fact that the bottleneck is already active and flows supersaturated due to driver relaxation:

- Overestimate bottleneck capacity.
- Record the activation time too late.

Instead of $q$ dropping "from capacity", we see $q$ drop "to capacity" from supersaturation.
An on-ramp bottleneck

Conclusions

We suspect these confounding effects have largely gone unnoticed due to ambiguity in defining exactly what is "unqueued" conditions
An on-ramp bottleneck

Conclusions

We suspect these confounding effects have largely gone unnoticed due to ambiguity in defining exactly what is "unqueued" conditions.

We seemingly see the unqueued regime of a parabolic qk curve during the first few minutes of activation.
An on-ramp bottleneck

Conclusions

We suspect these confounding effects have largely gone unnoticed due to ambiguity in defining exactly what is "unqueued" conditions.

We seemingly see the unqueued regime of a parabolic $q_k$ curve during the first few minutes of activation.

The driver relaxation process is a confounding factor far below the resolution of conventional macroscopic data, and empirical traffic flow theory studies usually fail to account for it.
An on-ramp bottleneck

Conclusions

These findings provide clues to better interpret past empirical observations
An on-ramp bottleneck

Conclusions

These findings provide clues to better interpret past empirical observations.

Our study should not be viewed as a complete model.
An on-ramp bottleneck

Conclusions

These findings provide clues to better interpret past empirical observations.

Our study should not be viewed as a complete model.

Rather we sought to highlight previously unaccounted for impacts of driver relaxation on bottleneck studies.
An on-ramp bottleneck

Conclusions

These findings provide clues to better interpret past empirical observations.

Our study should not be viewed as a complete model.

Rather we sought to highlight previously unaccounted for impacts of driver relaxation on bottleneck studies.

The forthcoming paper in TR-C has been retitled:

“Driver relaxation impacts on bottleneck activation, capacity, and the fundamental relationship”
Thank you!