A Study of Traffic Disruption and Recovery in Road Networks

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Outline

- One-dimensional cellular automata model
  - Nagel-Schreckenberg dynamics
  - Modeling incidents and lane changing
- One-dimensional systems
  - Stationary process
    - Fundamental diagram
  - Non-stationary process
    - Domain wall model
    - Numerical results
- Two-dimensional systems
- Conclusion

Traffic Disruptions

Traffic disruptions cause bottlenecks, which reduce the network capacity, and usually result in traffic jam.

- vehicle breakdown
- collision
- illegal parking
- roadwork
- roadside breath alcohol test
- train crossing
- pedestrian crossing
- ... ...

Figure: From SunGuide

- Perturbed stationary state
- Transient behaviors
  - Loading process
  - Recovery process

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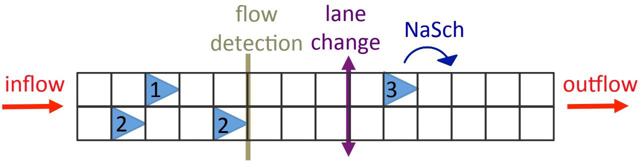
One-Dimensional Cellular Automata (CA)

Traffic model

Two-lane route with open boundary conditions

- Nagel-Schreckenberg model (NaSch): discretizing a lane into cells. For each vehicle at each iteration
  - Acceleration
  - No crash
  - Deceleration
- Simple lane-changing rules
- Defect (incident)



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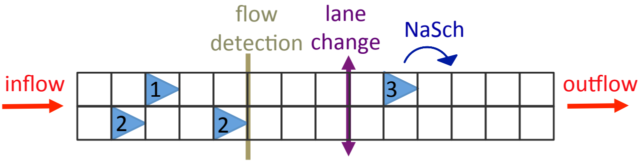

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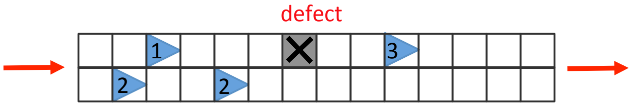


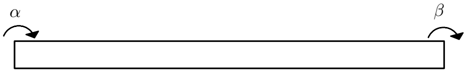
Animation

Two-lane route with a defect

Red: $v = 0$, Orange: $v = 1$, Yellow: $v = 2$, Green: $v = 3$.

FD for The Unperturbed System

Fundamental Diagram (FD) describes the relationship between density ρ and flow J.



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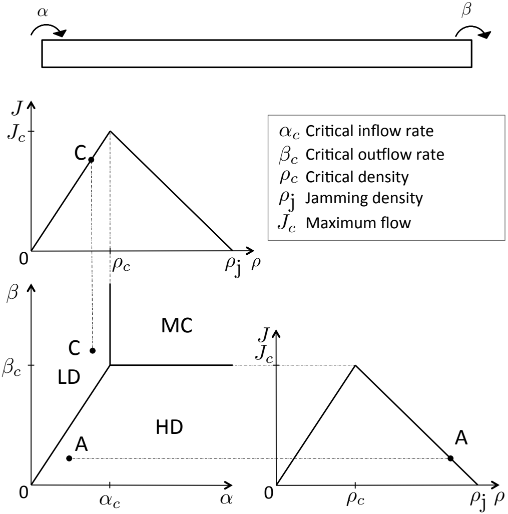

FIGURE: Phase diagram and fundamental diagram for the unperturbed system.

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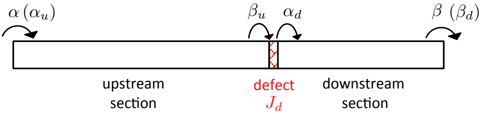

FIGURE: The perturbed system divided into two sections by the defect site.

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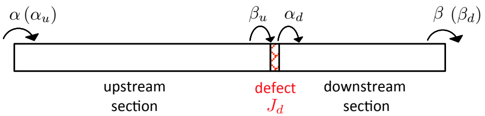

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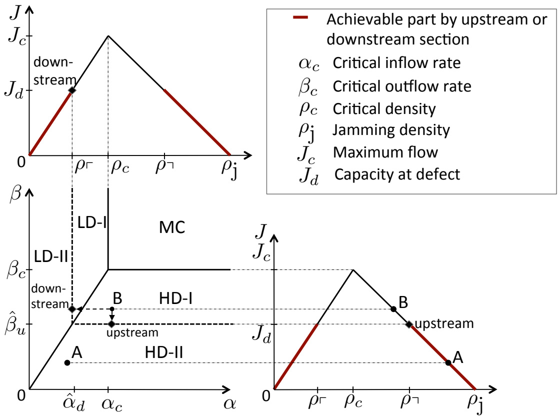

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Empirical Result

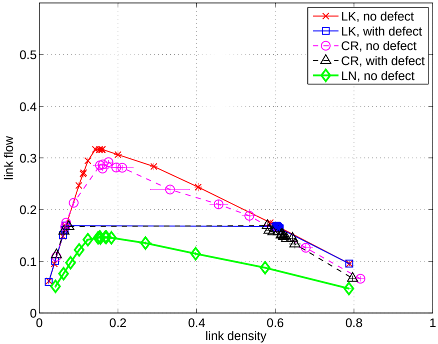

FIGURE: Fundamental diagrams of a link upstream of the defect. (Flow for one-lane route has been divided by 2.) For the 1D system $J_c \approx 0.317$, $\rho_c \approx 0.158$, $J_d \approx 0.165$, $\rho_{\ulcorner} \approx 0.067$, $\rho_{\neg} \approx 0.605$.

- For $\rho \in [0, \rho_{\ulcorner}] \cup [\rho_{\neg}, \rho_{\text{j}}]$ the defect has no impact on either flow or density.
- For $\rho \in (\rho_{\ulcorner}, \rho_{\neg})$ the defect results in phase separation: high density regime in upstream and free flow regime in the downstream.
- The capacity reduces by less than 50%.

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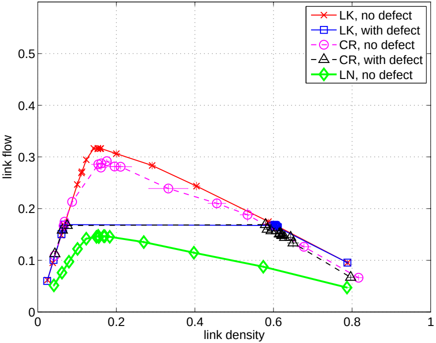

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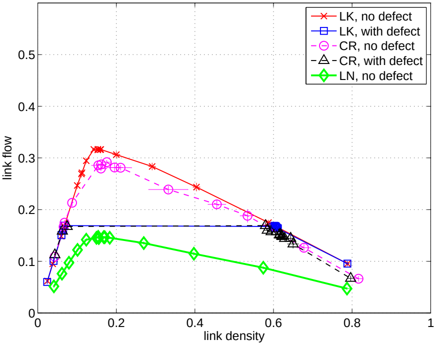

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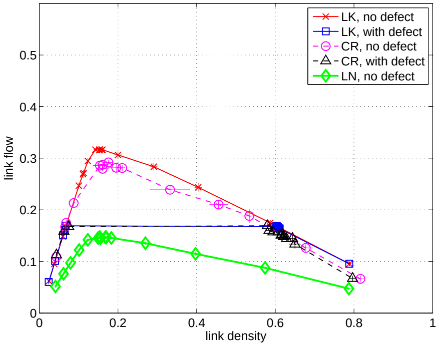

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Domain Wall Model

A domain wall $W_{-|+}$ moves left to right with speed

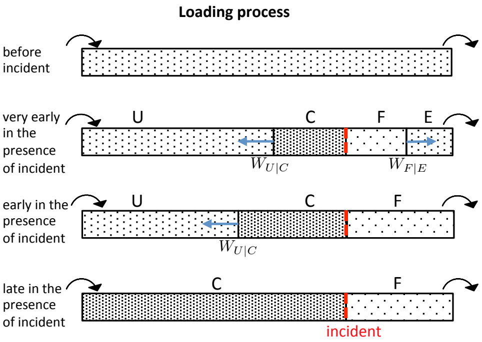
$$V_{-|+} = \frac{J_- - J_+}{\rho_- - \rho_+}, \quad (1)$$

where J_- and ρ_- (J_+ and ρ_+) are flow and density on the left (right) of the wall.

The position of the domain wall at time t satisfies

$$\frac{\mathrm{d}P_{-|+}(t)}{\mathrm{d}t} = V_{-|+}. \quad (2)$$

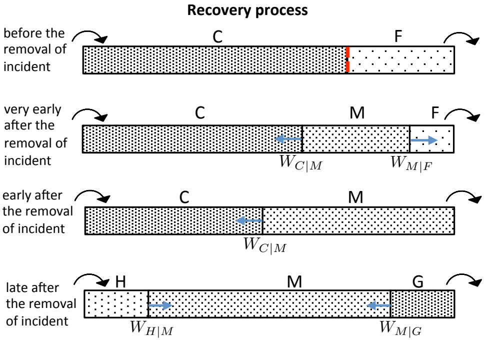
Loading Process



- Once the defect is present, two domain walls at the defect site start and move upstream and downstream respectively.
- The loading process is complete once both of the domain walls have arrived at the boundaries.

Domains: $\mathbf{C} = (\rho_{\neg}, J_d)$ $\quad \mathbf{F} = (\rho_{\ulcorner}, J_d)$ $\quad \mathbf{U} = \mathbf{E} = (\rho_o, J_o)$

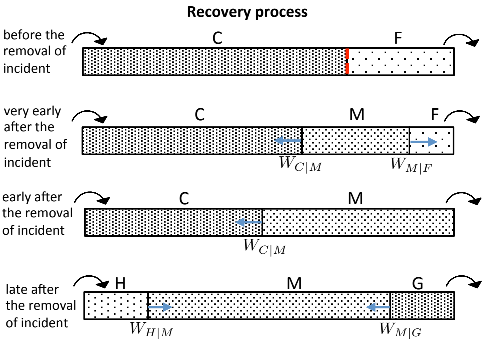
Recovery Process



- Once the defect is removed, two domain walls start at the defect site and move upstream and downstream respectively.

Domains: $\mathbf{M} = (\rho_c, J_c)$

Recovery Process



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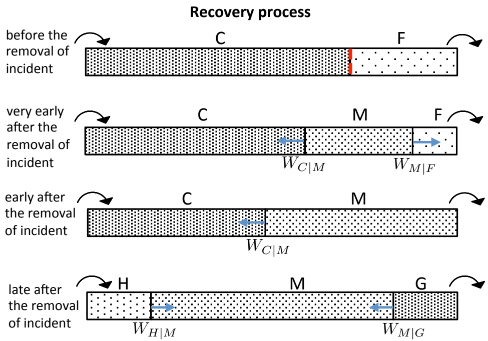
Assume that $\alpha(\rho)$ ($\beta(\rho)$) is a non-decreasing (non-increasing) function of ρ.

For MC it satisfies that $\alpha_c = \alpha(\rho_c)$ and $\beta_c = \beta(\rho_c)$.

Since $\rho_C > \rho_c$ and $\rho_F < \rho_c$, $\alpha(\rho_C) \geq \alpha_c$ and $\beta(\rho_F) \geq \beta_c$.

Recovery Process

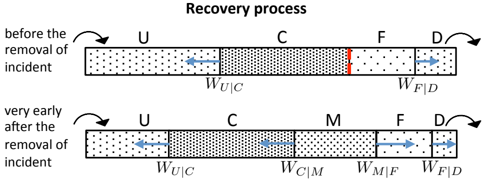


- Once the defect is removed, two domain walls start at the defect site and move upstream and downstream respectively.

Domains: $\mathbf{M} = (\rho_c, J_c)$

* Maximum flow: $\mathbf{H} = \mathbf{G} = \mathbf{M}$
* Low density: $\mathbf{H} = (\rho_o, J_o)$, $\mathbf{G} = \mathbf{M}$
* High density: $\mathbf{H} = \mathbf{M}$, $\mathbf{G} = (\rho_o, J_o)$

More complicated Recovery Process



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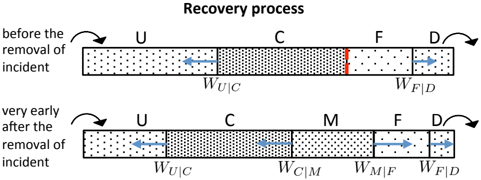


Loading and recovery processes for a route initially in low density regime.

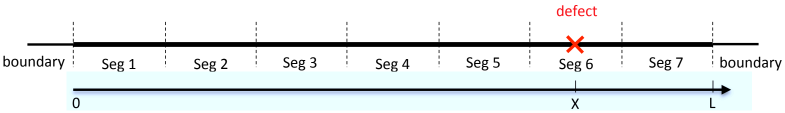
SIMULATIONS

ROUTE PARTITION

A route of two lanes, each consisting of 800 cells.

- In/out boundaries: each consisting of 50 cells
- Seven segments: each consisting of 100 cells ($L = 700$).

The defect is placed at the middle of segment 6 ($X = 550$) for duration Dmin.



OBSERVABLES

- Route-aggregated density and flow
- Segment density and flow

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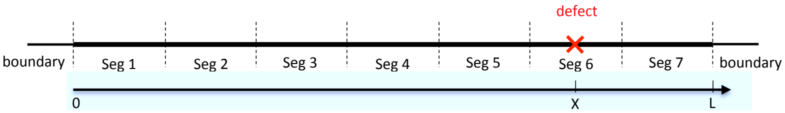

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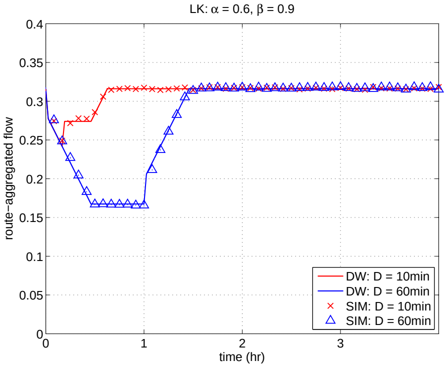
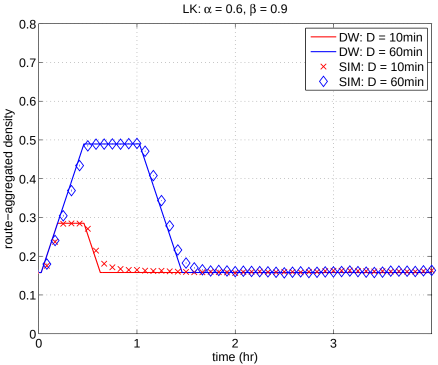
Maximum Flow Case

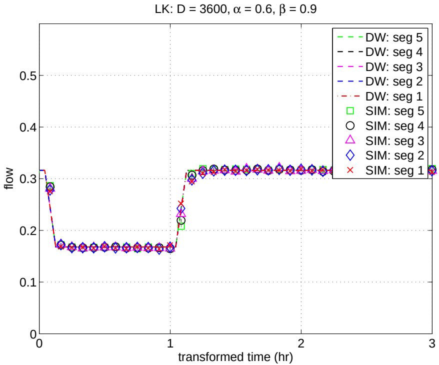


(a) MC: Route-aggregated flow

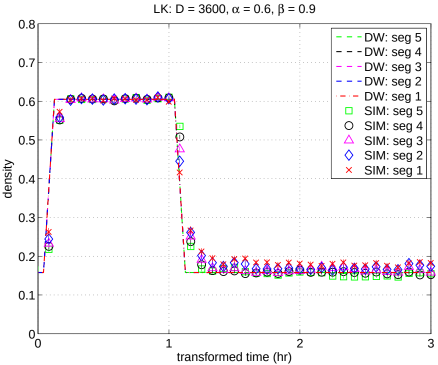


(b) MC: Route-aggregated density

MAXIMUM FLOW CASE CONT.



(c) MC: Segment-aggregated flow

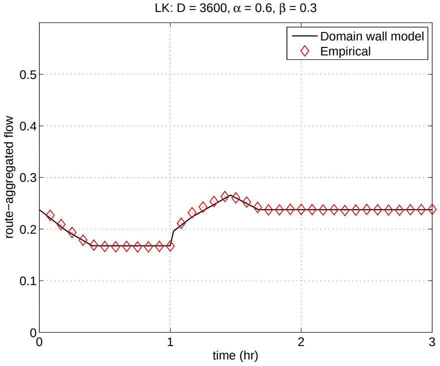


(d) MC: Segment-aggregated density

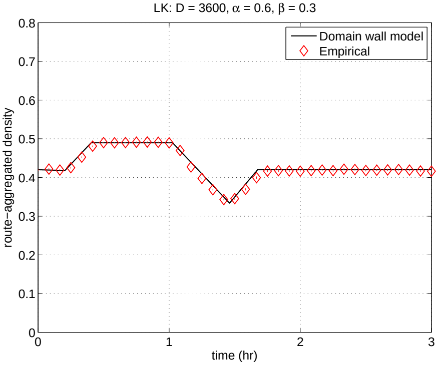
With $D = 60$min, for each upstream segment l, a translation in the time variable

$$t' = \begin{cases} t - (5-l)|V_{U|C}| & \text{for } 0 \le t < D; \\ t - (5-l)|V_{C|M}| & \text{for } D \le t < D + X/|V_{C|M}|. \end{cases}$$

HIGH DENSITY CASE

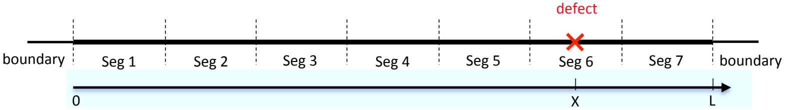


(e) HD: Route-aggregated flow



(f) HD: Route-aggregated density

2D NETWORKS


defect
boundary
Seg 1
Seg 2
Seg 3
Seg 4
Seg 5
Seg 6
Seg 7
boundary
0
X
L

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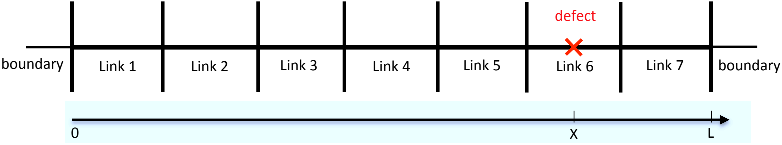
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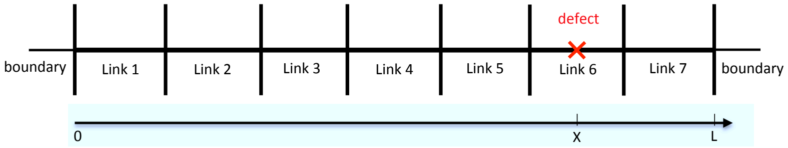
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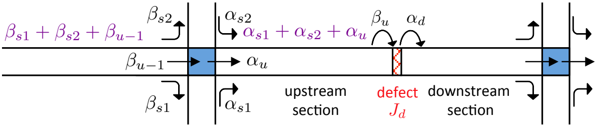
$\beta_{s1} + \beta_{s2} + \beta_{u-1}$
β_{s2}
α_{s2}
$\alpha_{s1} + \alpha_{s2} + \alpha_u$
β_u
α_d
β_{u-1}
α_u
β_{s1}
α_{s1}
upstream section
defect J_d
downstream section

Stationary State

- Fundamental diagram
  - Defect's location matters.
- Heterogeneities in density and flow

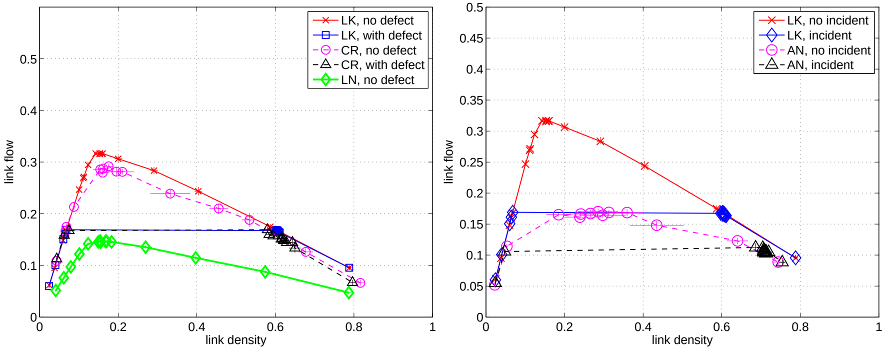

FIGURE: Fundamental diagrams of a link upstream of the defect. The network is governed by CR – cross-over intersection (left) and self-organizing traffic lights – SOTL (right).

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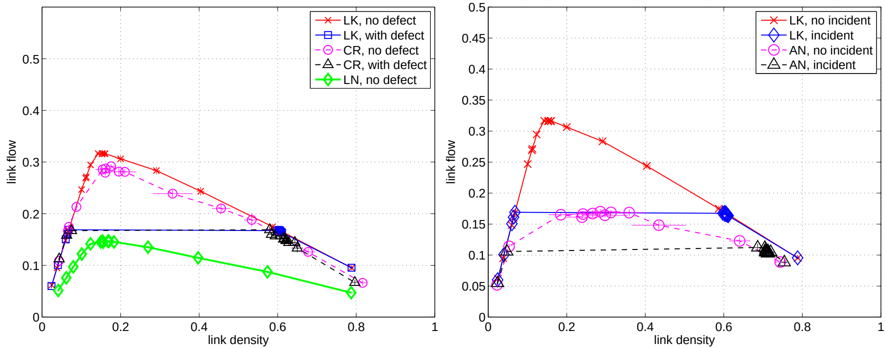

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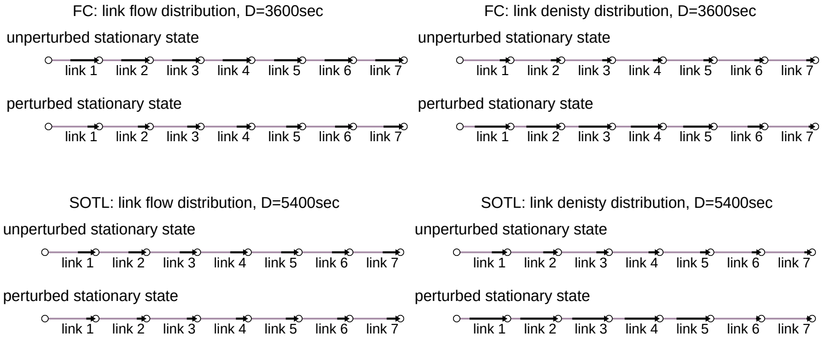


FIGURE: MC: Flow and density distributions of the defect route in the unperturbed and the perturbed stationary states. The network is governed by CR (top) and SOTL (bottom).

NON-STATIONARY STATE

ρ_- and J_- (or ρ_+ and J_+) vary when the domain wall $W_{-|+}$ passes an intersection.

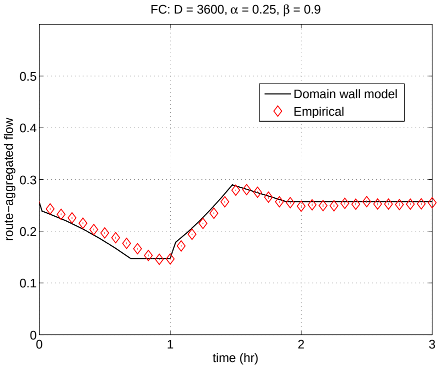
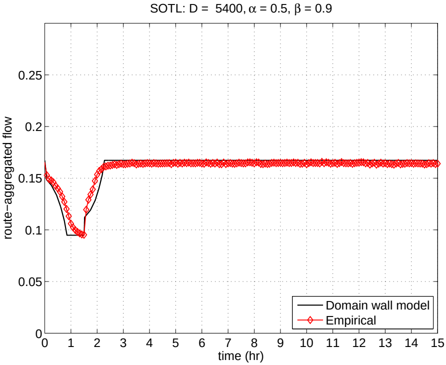


FIGURE: LD by FC: Route-aggregated flow and density.

Non-stationary state cont.



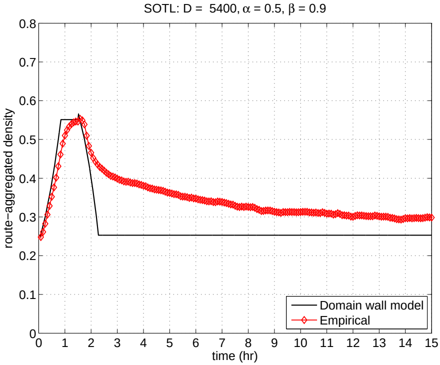


Figure: MC by SOTL: Route-aggregated flow and density.

Significantly long recovery time with respect to route-aggregated density.

Conclusion

We studied the impact of traffic incidents on road networks.

- Stationary state
  Fundamental diagram and phase diagram
- Non-stationary process
  Domain wall model
  The simple model can describe the transient behavior in the loading and recovery process.