Continuum Approximation for System-wide Ramp Metering

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Overview of the presentation

- Background on ramp metering
- Motivation to study system-wide ramp metering
- Methodology
- Numerical solutions
- Ramp demand cases
  - Constant demand
  - Space varying demand
- Limitations of the current methodology
- Future direction

Background

- Traditionally, metering rates for improved efficiency of the transportation network
- Sometimes, favor longer-trip drivers as against to shorter-trip drivers and vice-versa
- Equity issues arise because better transportation measures are obtained at the expense of some drivers.
- Attempts to optimize dual objectives of system performance and equity yielded little success
- Existing operational algorithms lack the flexibility to address both efficiency and equity issues adequately

Motivation

- Existing system-wide algorithms are
  - Not truly system-wide
  - Not based on TF concepts such as congestion propagation characteristics
  - Pre-determined weights
  - Inflexible
- Laval and Leclercq (2009) showed that congestion is not distributed evenly on freeway and ramps. Some ramps get more congested than others
- Metering rates should be varied both spatially and temporally

Methodology (1)

- Consider a long n-lane corridor with several on-ramps and off-ramps spaced evenly
- Both inflows and out flows are treated as continuous variables in time and space
- Congested freeway corridor is modeled as a conservation law

$$k_t + s(k)k_x = \phi^+ - \phi^-$$

- The dynamics on the on-ramps is given by

$$k^x_t + s^x(k^x)k^x_y = 0$$

- Exit flows are assumed Markovian, i.e. $\phi^- = \beta q$

Methodology (2)

- Continuum model for lane changing rates, developed by Laval and Leclercq (2008), is used

$$\phi^+(t,x) = \min\{1, \frac{\mu(k(t,x))}{\lambda(k(t,x))}\}\lambda^x(k^x(t,d))/\delta$$

Where

$$\mu(k) = \min\{(n\kappa - k)w, nQ\}$$
$$\lambda(k) = \min\{uk, nQ\},$$
$$\mu^x(k^x) = \min\{(\kappa - k^x)w, Q\},$$
$$\lambda^x(k^x) = \min\{uk^x, Q\}.$$

- Initial and boundary conditions for the on-ramps are:

$$k^x(0,y) = \alpha(0,x)\delta/u,$$
$$k^x(t,0) = \alpha(t,x)\delta/u,$$
$$q^x(t,d) = \phi^+(t,x)\delta.$$

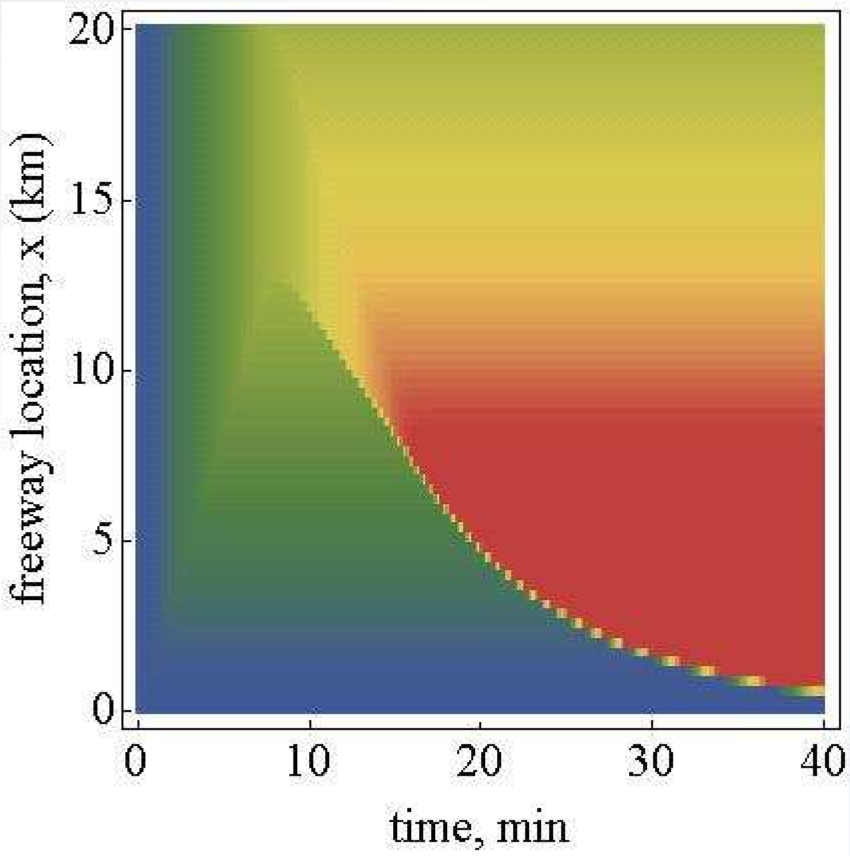
- Similarly, for the freeway: $k(0,x) = 0,$ $k(t,0) = 0.$
- Alpha and beta are on-ramp and off-ramp demands that are flexible to take any demand pattern

Numerical Solutions

- Godunov scheme is applied solving Riemann problem using the sending and receiving functions
- Number of lanes on the freeway=3
- Number of lanes on the on-ramp = 1
- Corridor length =20 kms
- Ramp length =2 kms
- Simulation time = 40 minutes
- Lane capacity = 2500 veh/hr
- Free flow speed = wave speed =100 km/hr
- Spacing between ramps = 1 km

Constant Demands

- On-ramp demand = 1000 veh/hr/km
- Off-ramp demand rate = 0.2 /km



Constant Demands

- 4 regions
- A & B - free-flow states
- C & D - congested states
- A and C are transient
- B and D are steady state
- Sub-regions, C1 and D1 -on-ramps are in free-flow conditions

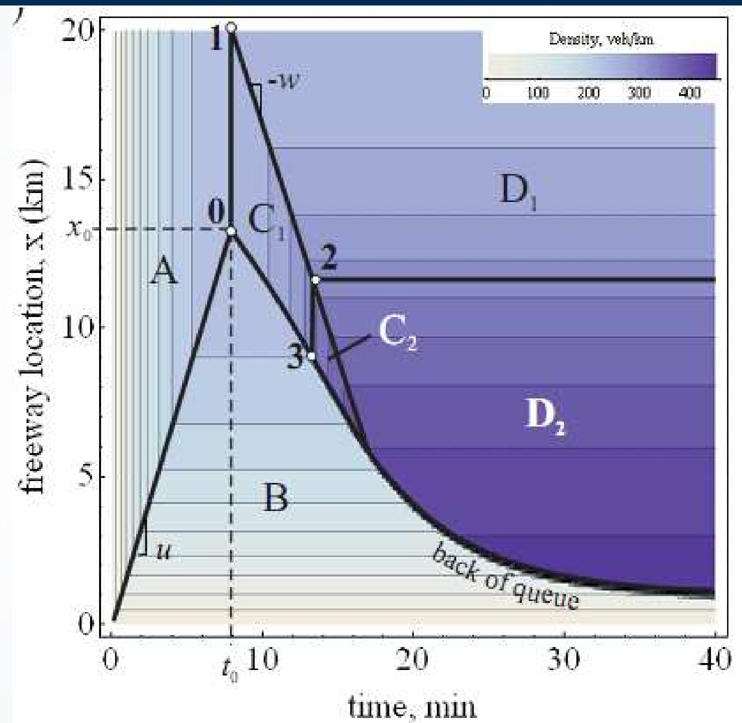
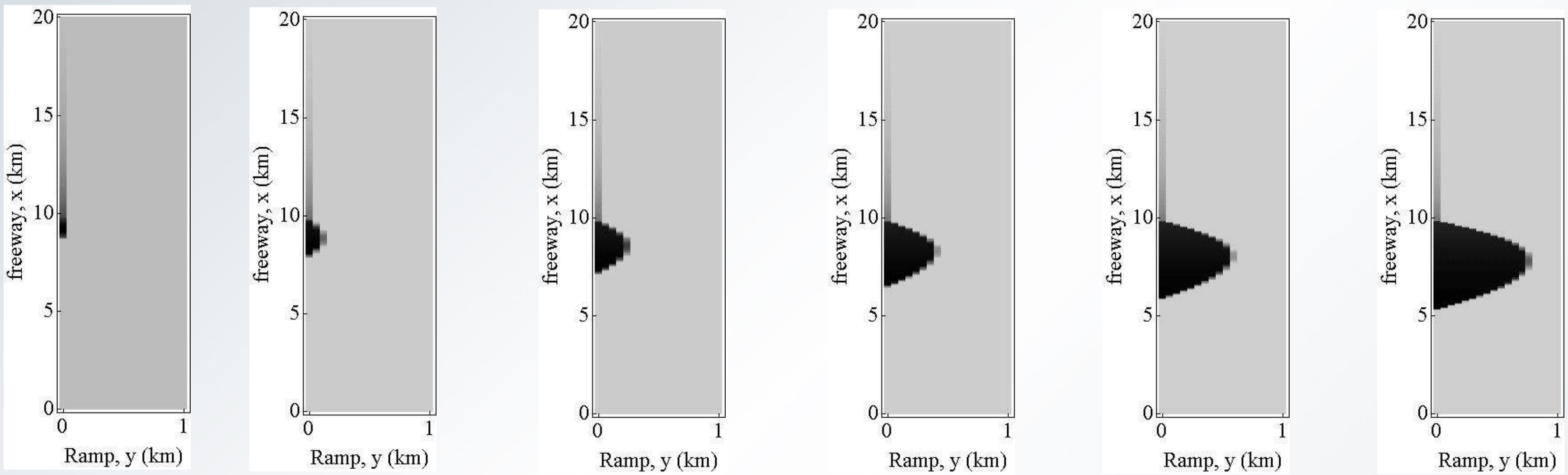


Figure from Laval and Leclercq, 2009

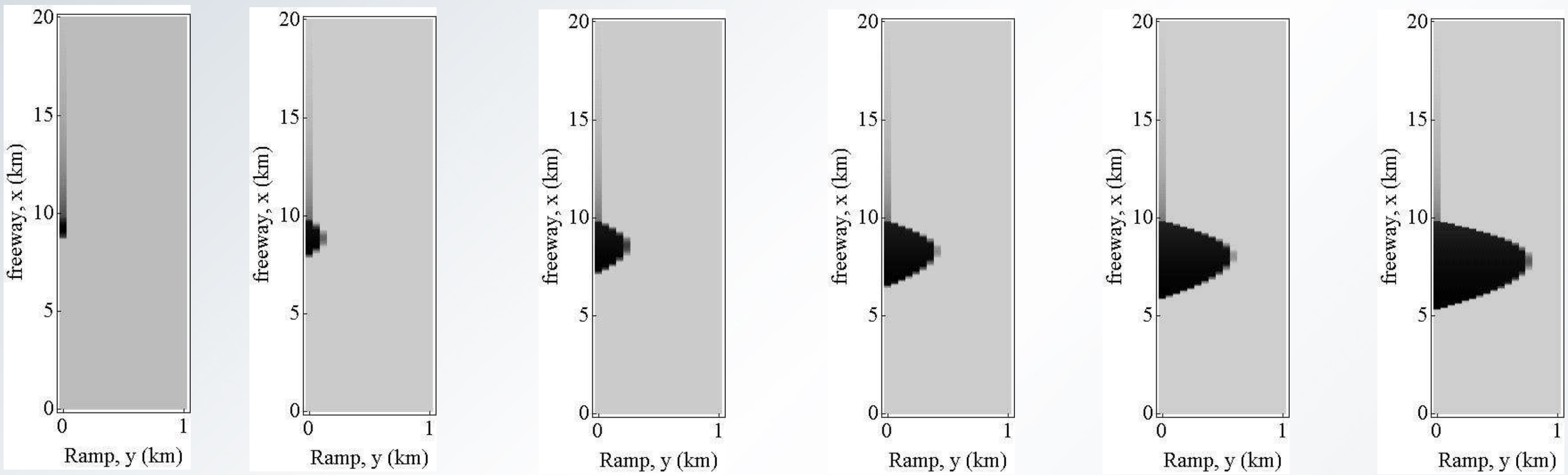
- Sub-regions C2 and D2-on-ramps are congested
- The shape of the regions is general for typical rush-hour patterns

Density along on-ramps (1)



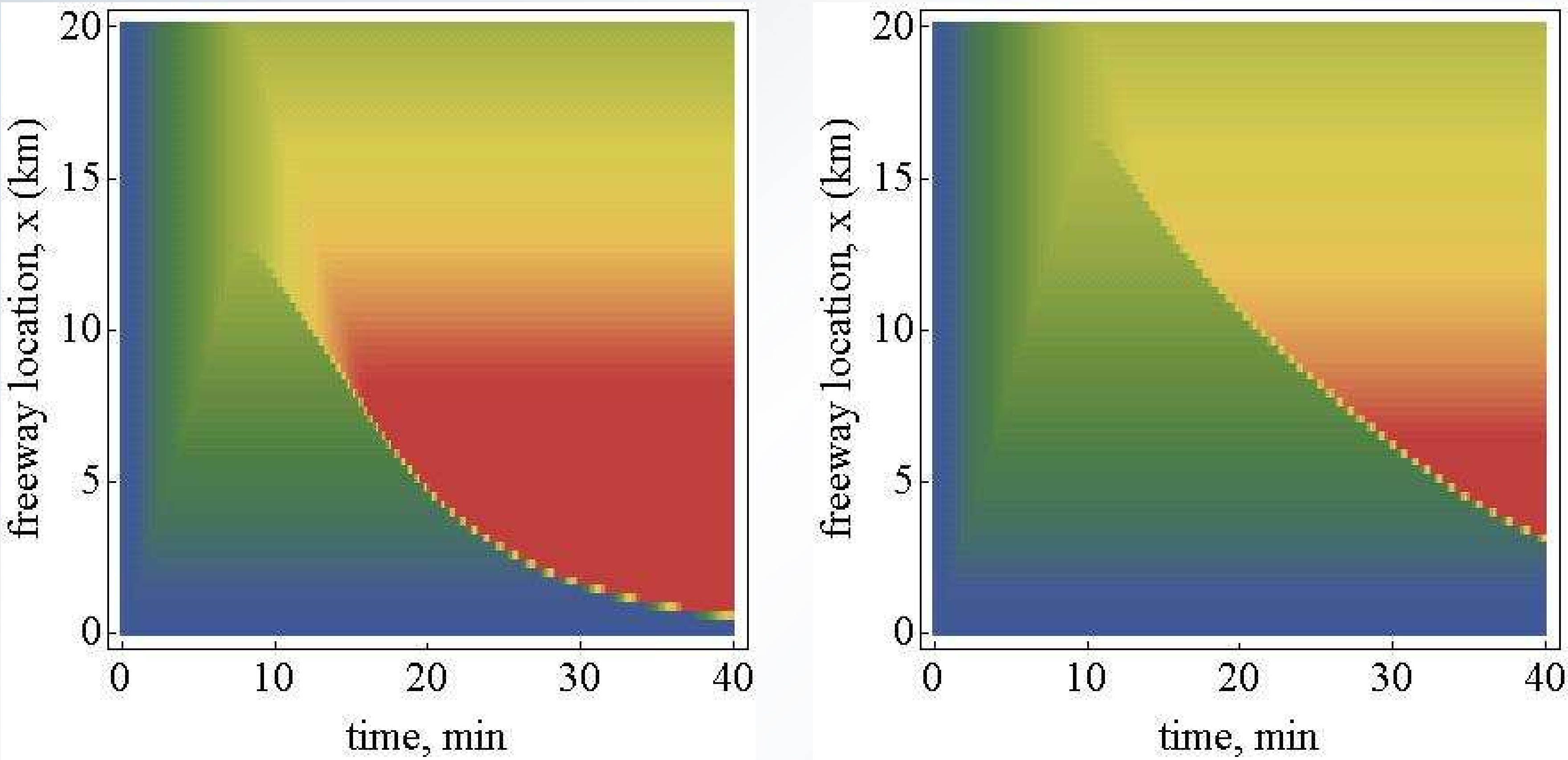
- Time: 15, 16, 17, 18, 19, 20 mins
- Some ramps get heavily congested than others
- Congestion starts around t =15 min simultaneously between points 2 and 3

Density along on-ramps (2)



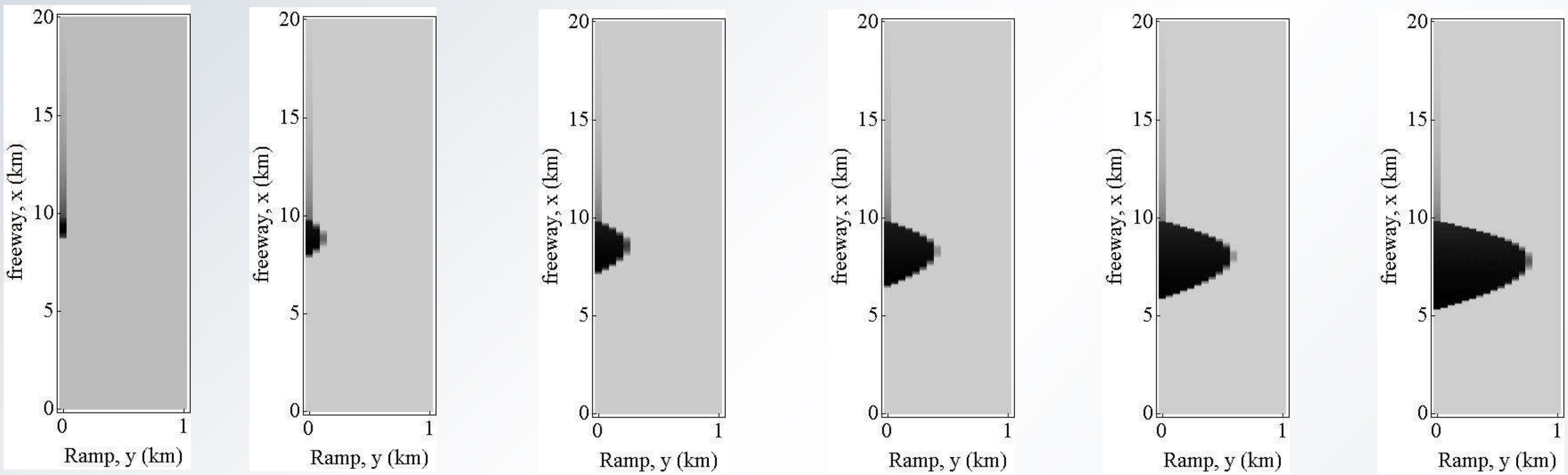
- On-ramp queues propagate upstream
- Longest queue is observed roughly in the midpoint between point 2 and the back of the freeway queue
- On-ramps get congested as the wave passes each of the upstream on-ramps

Uniform Metering

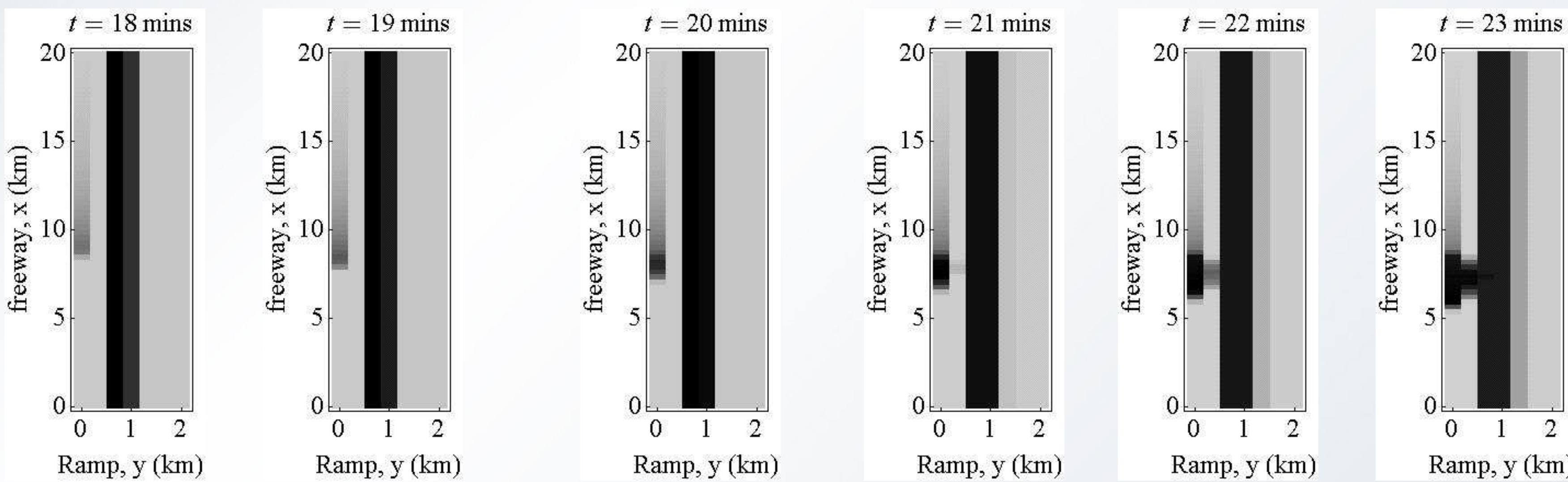


- Metering rate - 950 veh/hr
- Ramp meter - 850 meters upstream of merge

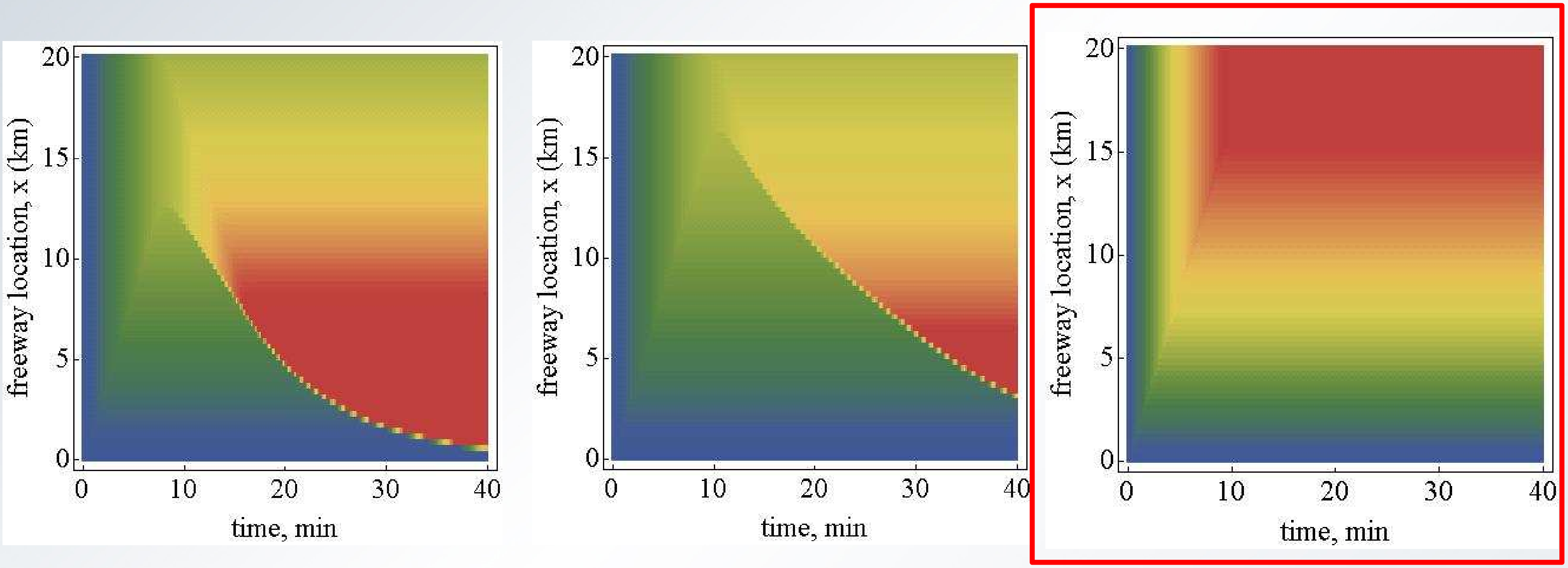
On-ramp densities – Before vs. After



Time: 15, 16, 17, 18, 19, 20 mins

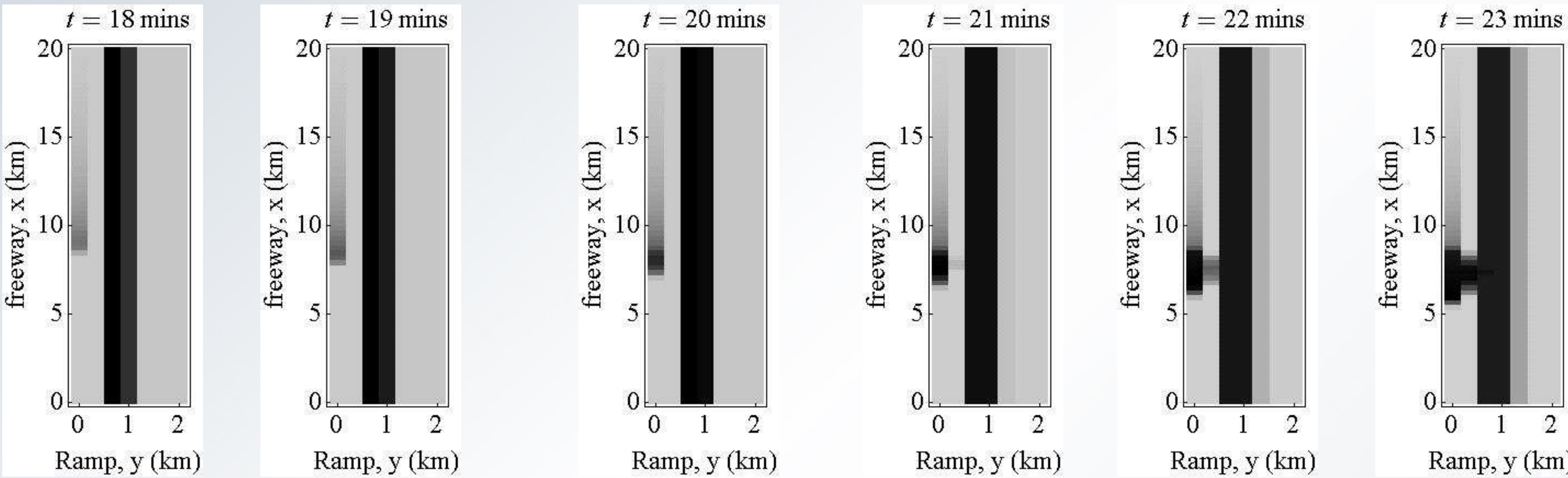


Alternative Strategy

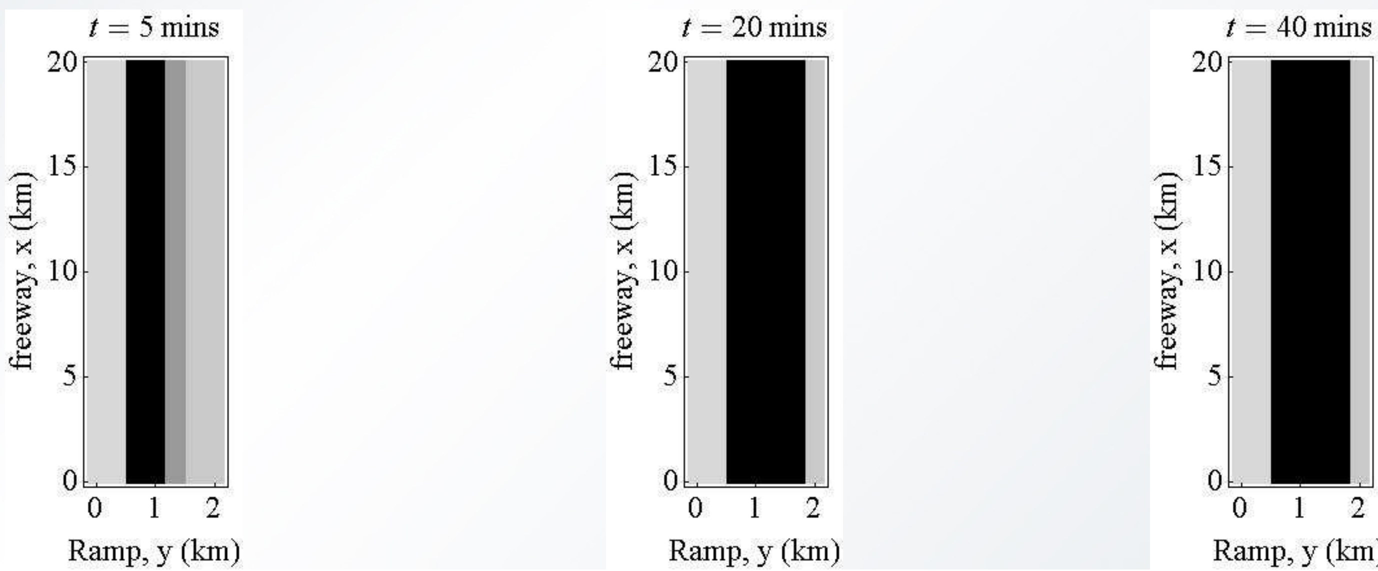


- 750 Veh/hr
- Optimal freeway density with no wave

950 veh/hr vs. 750 veh/hr

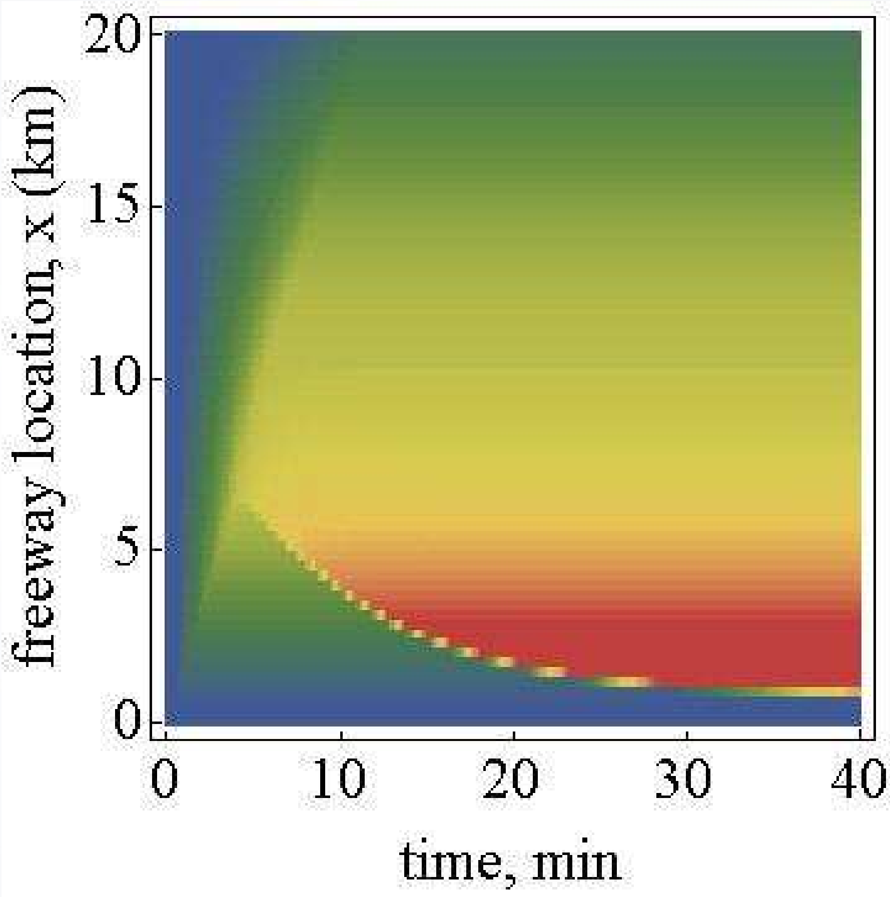


Time: 15, 16, 17, 18, 19, 20 mins

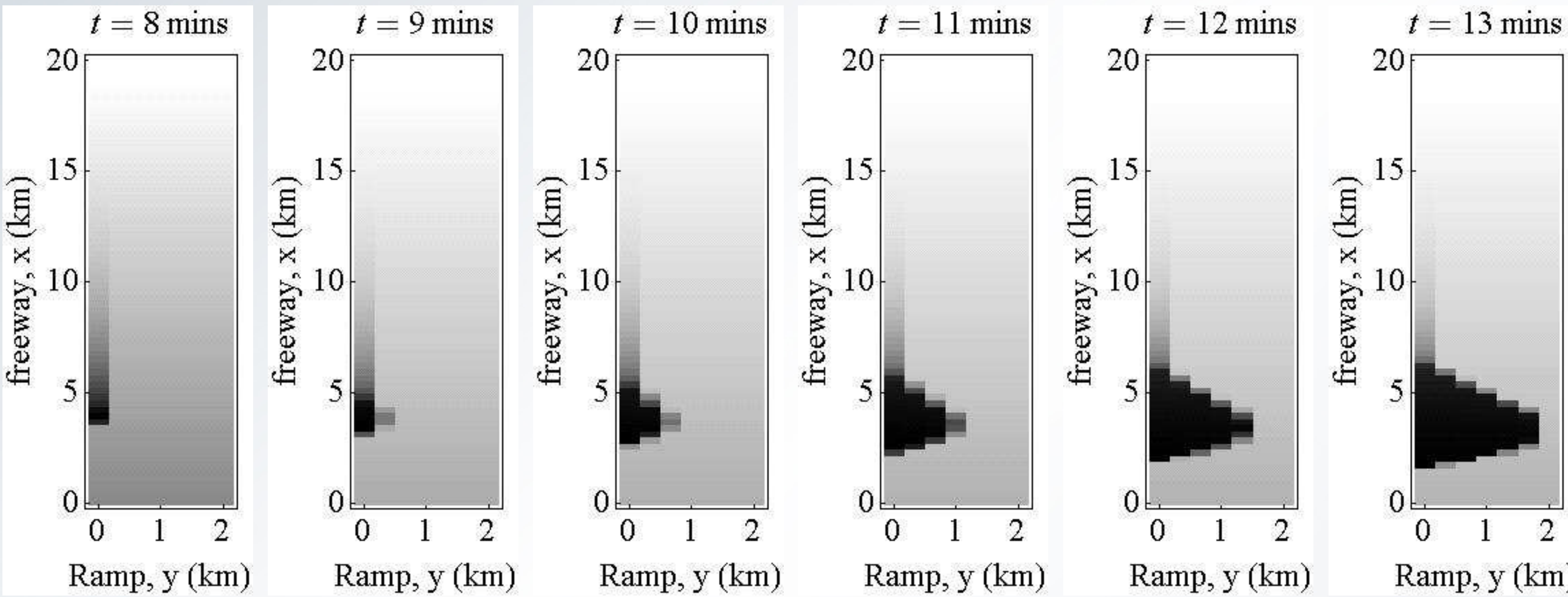


Decreasing on-ramp and Increasing off-ramp demands (morning/evening commute)

- On-ramp demand= 1300*x/Fwy length
- Off-ramp demand = 0.1*x/Fwy length
- The isodensity contours in regions A and C are no longer vertical
- There is a new free-flow region that appears downstream of D1

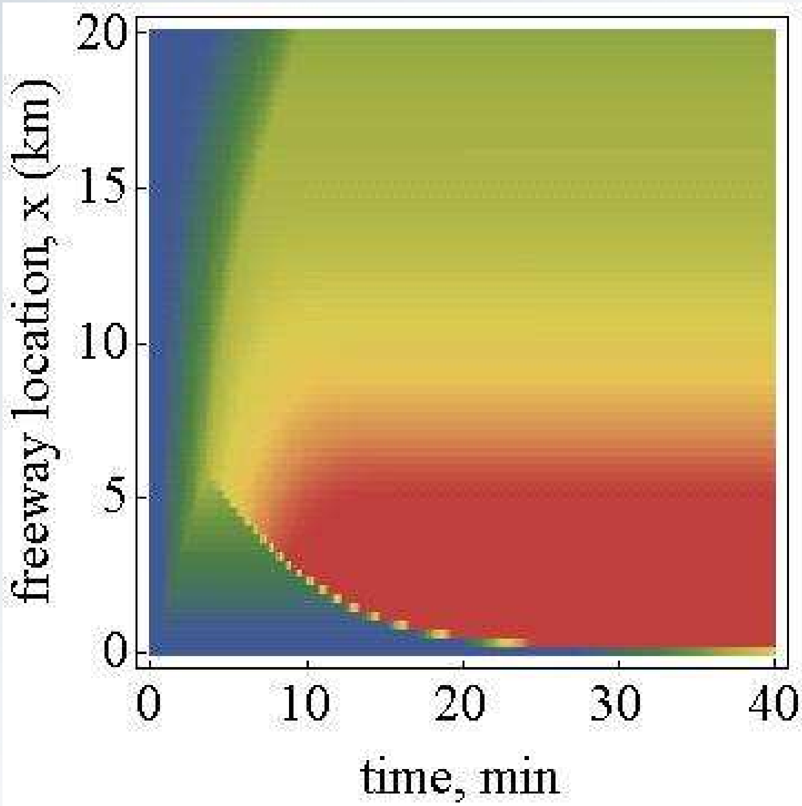


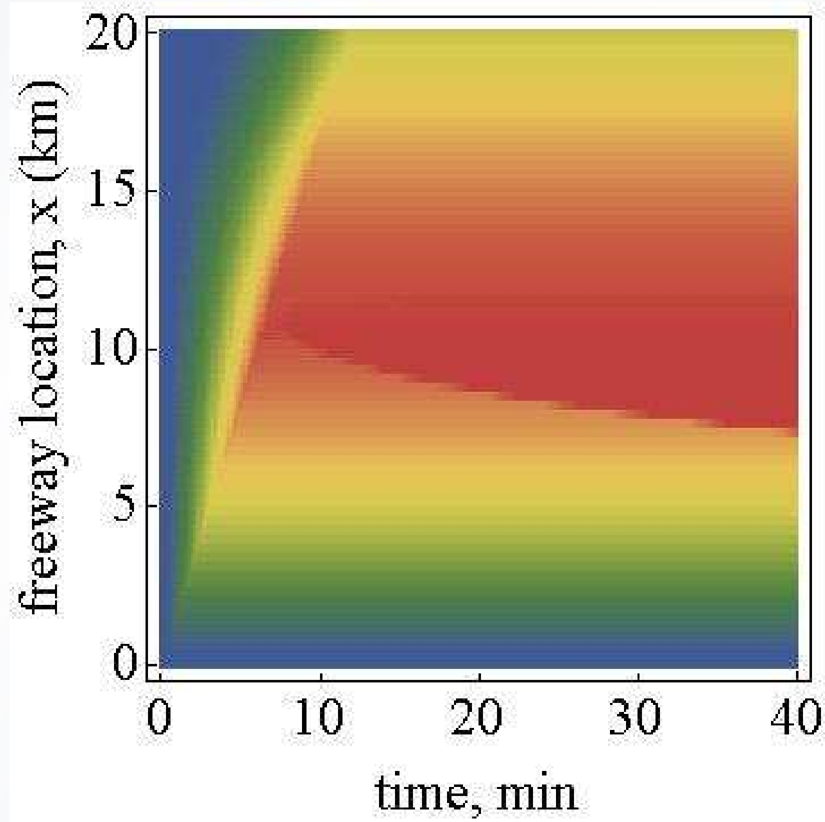
Density along on-ramps



- Queues build upstream since on-ramp demand is high

Metering Strategy





- All ramps with MR = On-demand – 125 veh/hr
- Freeway improves significantly

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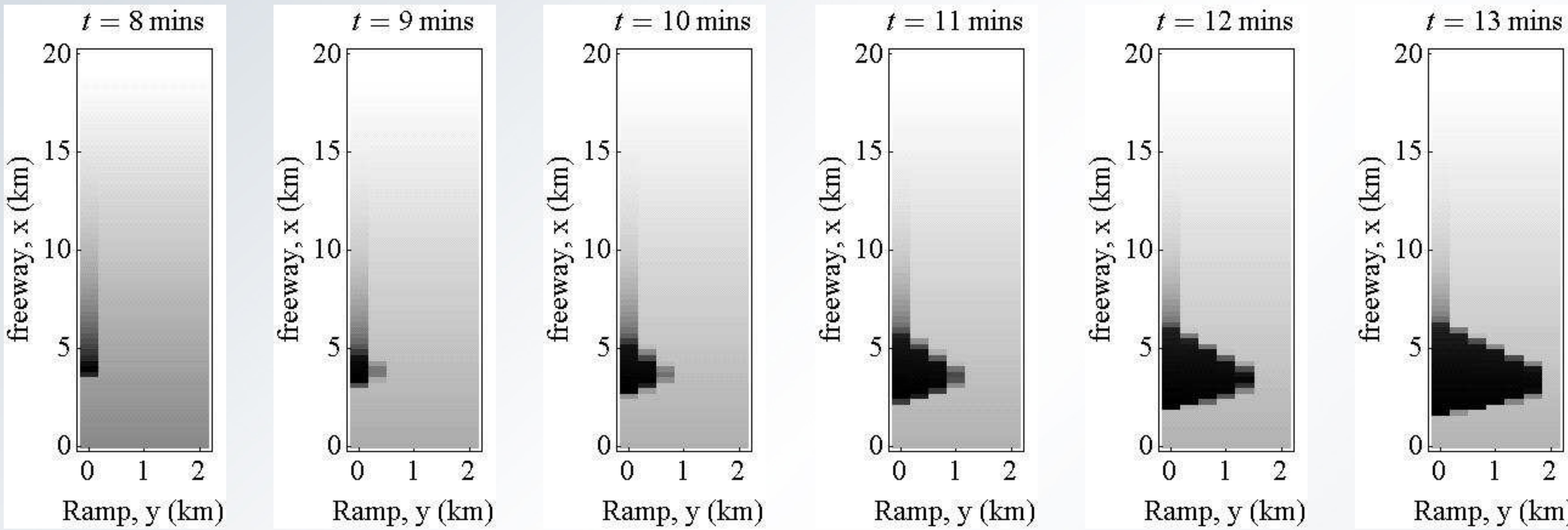
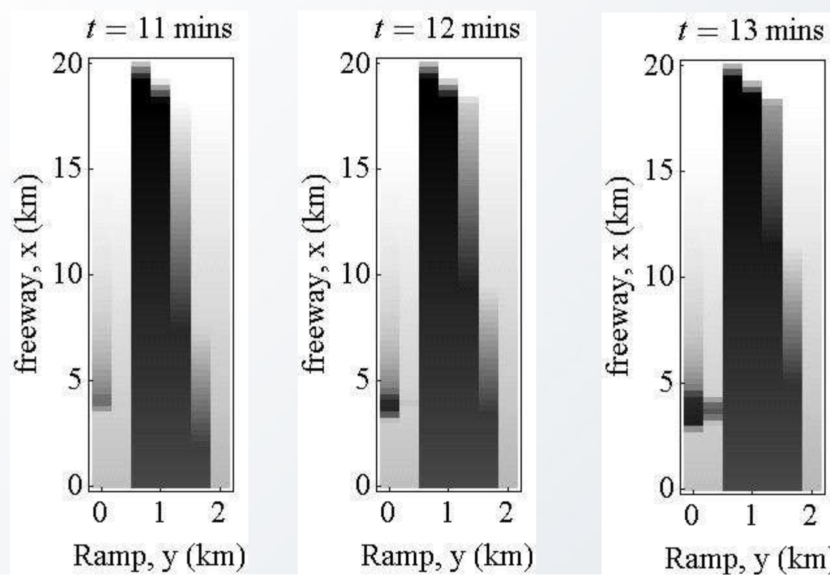
No metering vs. Metering

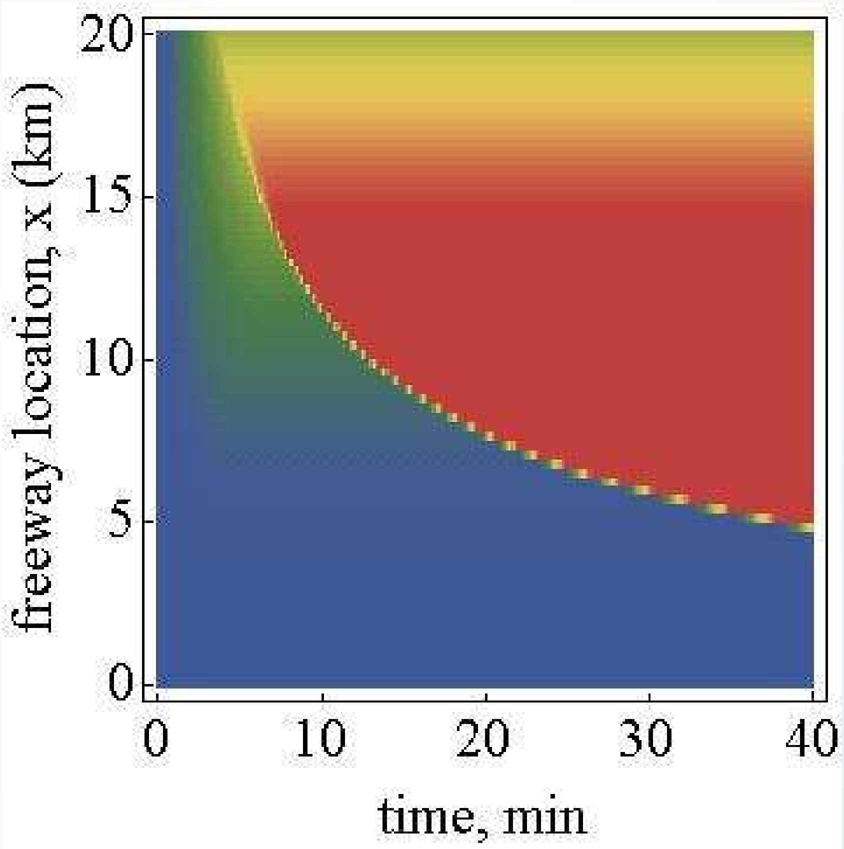


- Queues shifted to on-ramps
- Effectiveness can be measures only by system perspective

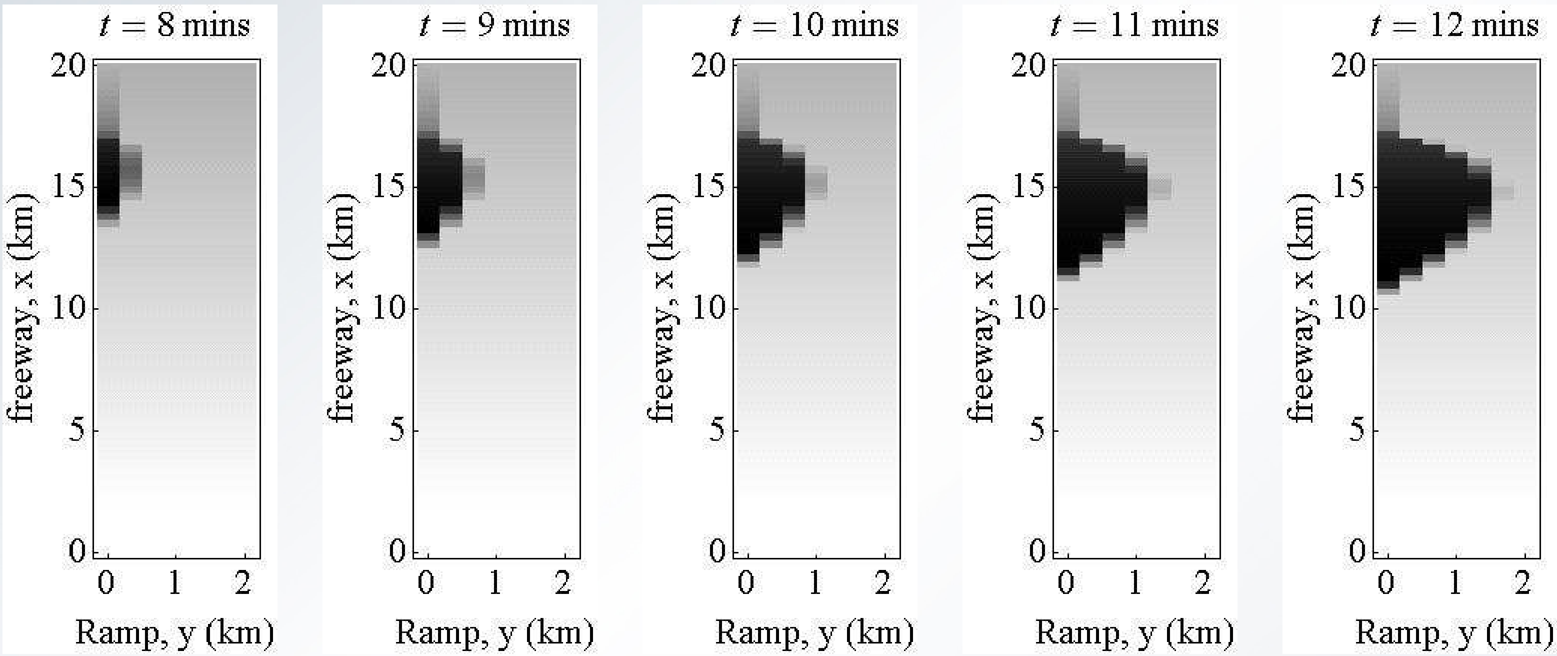


Increasing on-ramp and decreasing off-ramp demands (Fwy-Loop Junction)

- On-ramp demand= 1500*x/Fwy length
- Off-ramp demand = 0.05*x/Fwy length
- Region C tends to disappear (but still exists)
- The interface between regions C and A are either forward moving or backward moving

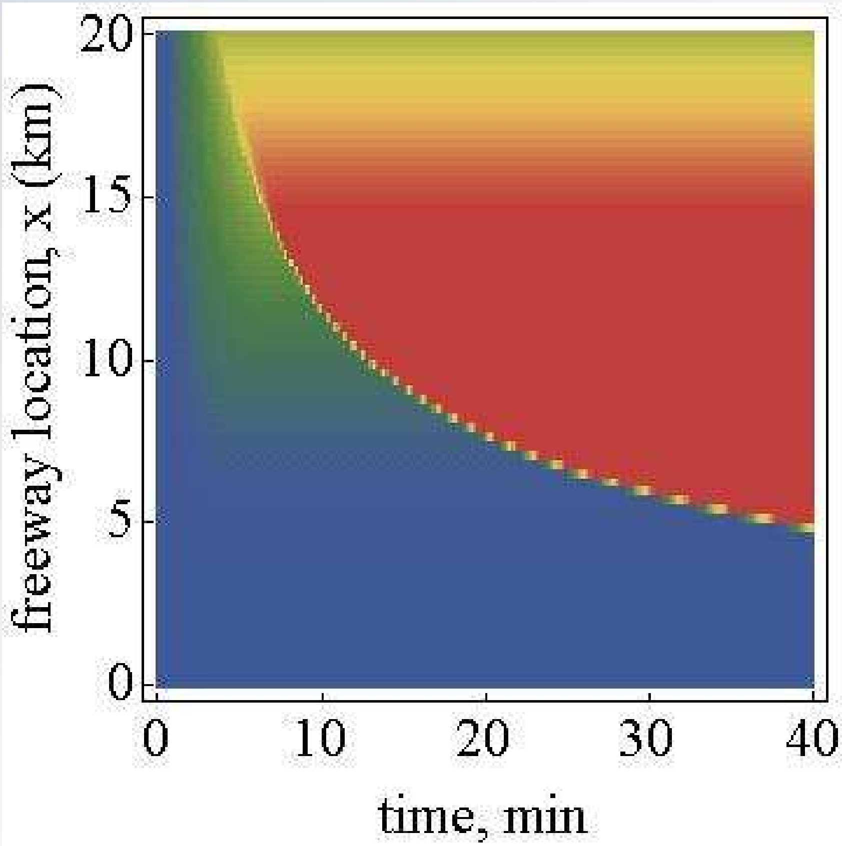


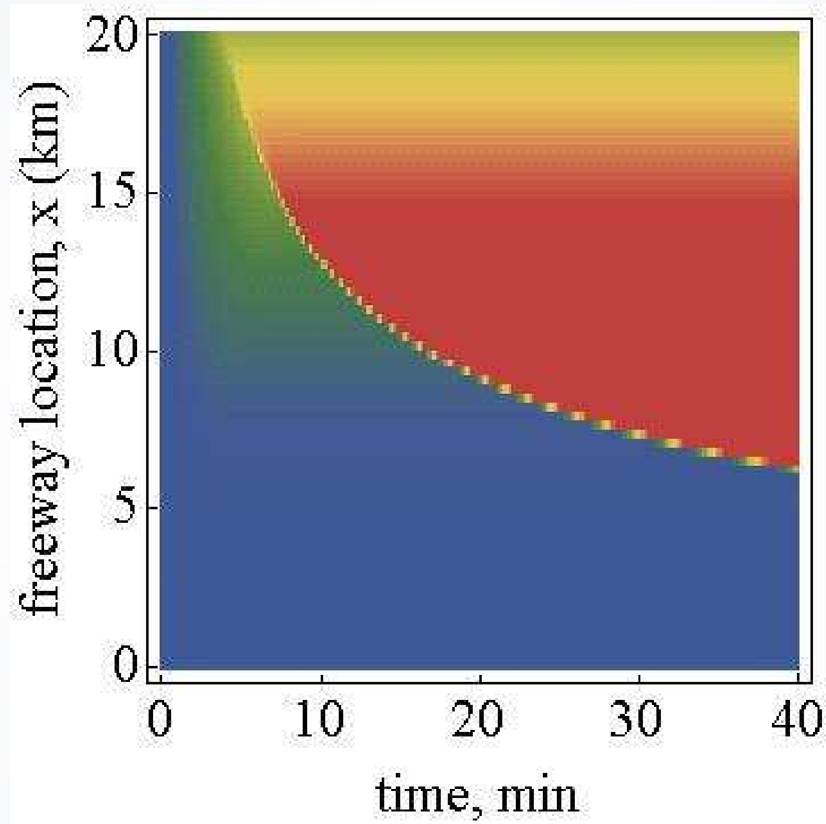
Density along on-ramps



- Queues form downstream since on-ramp demand is high

Metering Strategy

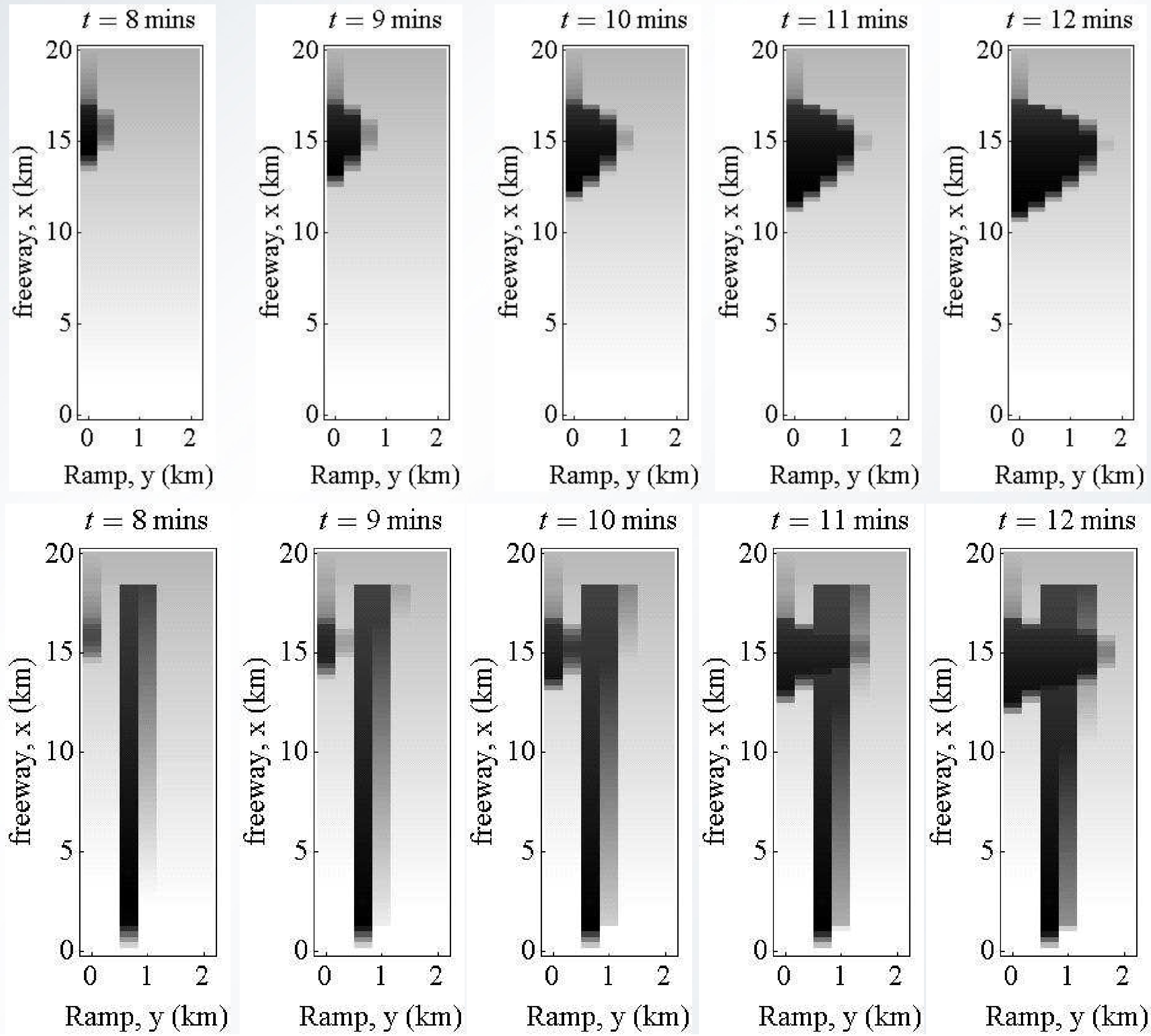




- On-ramp demand – 125 veh/hr
- Freeway density improves slightly

No metering vs. Metering

- Number of ramps congested decreases after metering



Limitations

- Even though gives an exact solution with $w=u$, not realistic
- Results are based on macroscopic congestion characteristics. Need to validate at a microscopic scale
- Difficult to account for complex scenarios with random fluctuations in traffic flows
- Merge geometry, capacity drop, capacity fluctuations, vehicle composition, driver behavior, are not considered in the methodology
- Assumes homogeneous characteristics along/across the roadways. For example, equal lane utilization

Future Direction

- Exact solution for wave speed much smaller than free flow speed will be obtained using Variational theory
- Time-varying demands
- Optimal metering rates using Neural Networks or some other method using system perspective
- Congestion dissipation characteristics
- Validate the results with real-world data and/or microscopic simulations

Thank you

Questions?