12/14/2016

A stochastic modeling of traffic breakdown for freeway merge bottlenecks

Civil and Environmental Engineering

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VSL

Variable Speed Limit

TO PREVENT BREAKDOWN

- Prevent bottleneck activation
- *e.g., Carlson et al. (2010)*

TO INCREASE DISCHARGE RATE

- From moving jams or fixed bottlenecks
- *e.g., Hegyi et al. (2008); Chen et al. (2014)*

Stochastic BN capacity

Main Principle

Speed Limitation ▶ Inflow Regulation ▶ Breakdown prevention

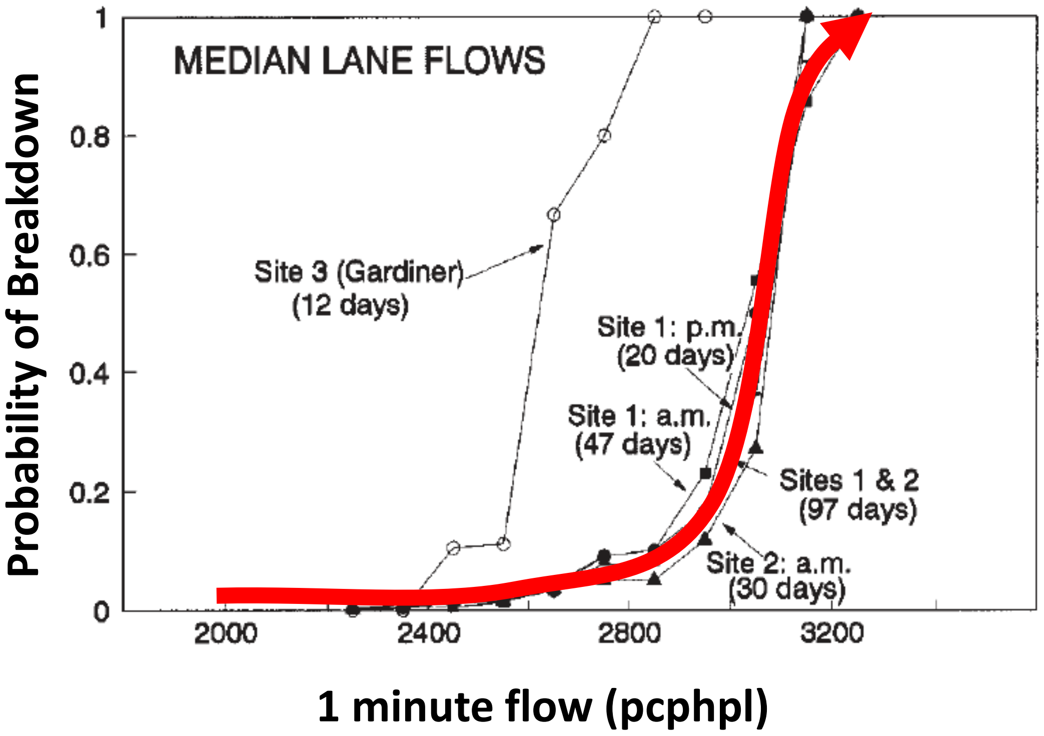
Below bottleneck capacity

& Capacity Drop

STOCHASTIC CAPACITY

Capacity can vary

EMPIRICAL OBSERVATIONS



Persuad et al. (1998)

Elefteriadou (1994), Evans et al. (2001), Son et al. (2004), Brilon et al. (2005), Chen et al. (2014)

PREVIOUS FINDING

- Breakdown probability increases with flow
- It typically has S-shape

LIMITATION

- Mainly focus on flow effect
- Other factors?
- Insight for traffic control?

PROBLEM STATEMENTS

1. Stochastic capacity, but…

- We have a limited understanding of breakdown mechanisms and the effects of various factors

2. VSL can regulate inflow to a bottleneck, but…

- VSL causes controlled-congestion that propagates upstream

3. VSL can prevent traffic breakdown or minimize capacity drop, but…

- Existing strategies do not consider stochastic BN capacity for determining control parameters
- Conservative control → system underutilization

RESEARCH OBJECTIVES

Model, Strategies, Optimization

BREAKDOWN MODEL

- To analyze ***breakdown mechanisms*** and ***effects*** of various factors
- → Offer ***insight*** for traffic control

CONTROL STRATEGIES

- ***CV*** (+VMS): effective for low penetration rate
- ***Proactive***: to minimize breakdown probability
- ***Reactive***: to resolve existing queue / prevent additional breakdown

SYSTEM OPTIMIZATION

- To achieve ***maximum*** delay saving
- Considering ***stochastic capacity*** and control failure probability

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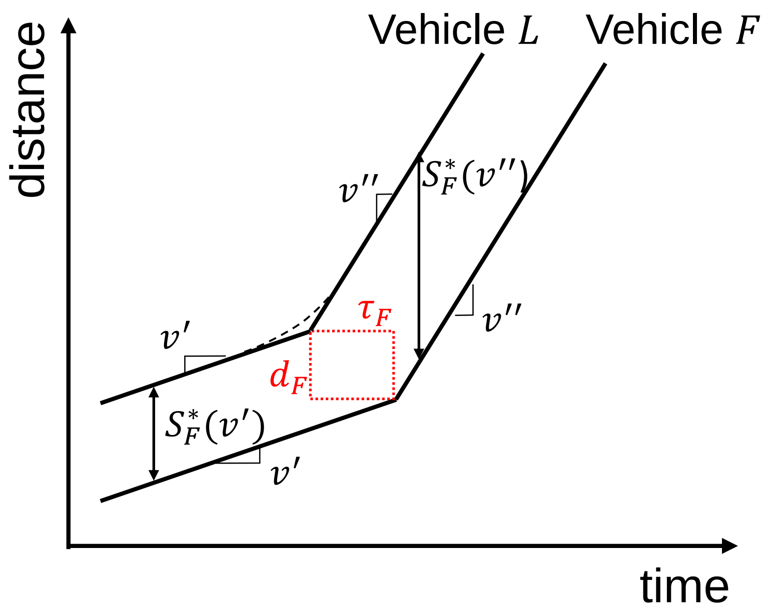
Breakdown Model

DRIVER BEHAVIOR

Newell's Car-Following Model (Newell, 2002)

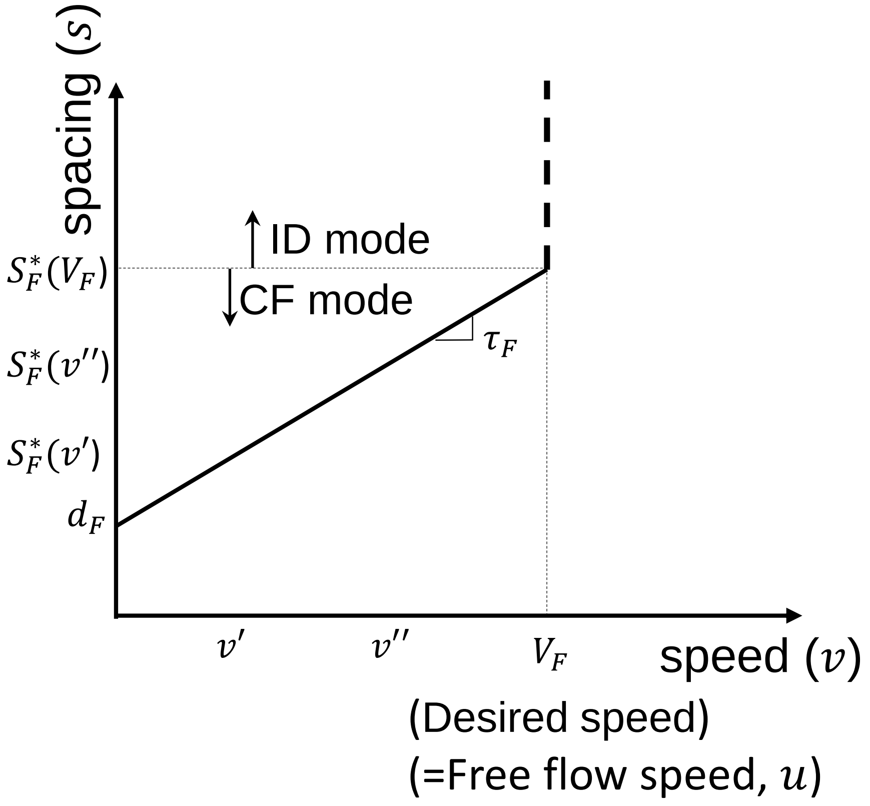
VEHICLE TRAJECTORIES

Same except translation



SPACING AND SPEED

Linear relation

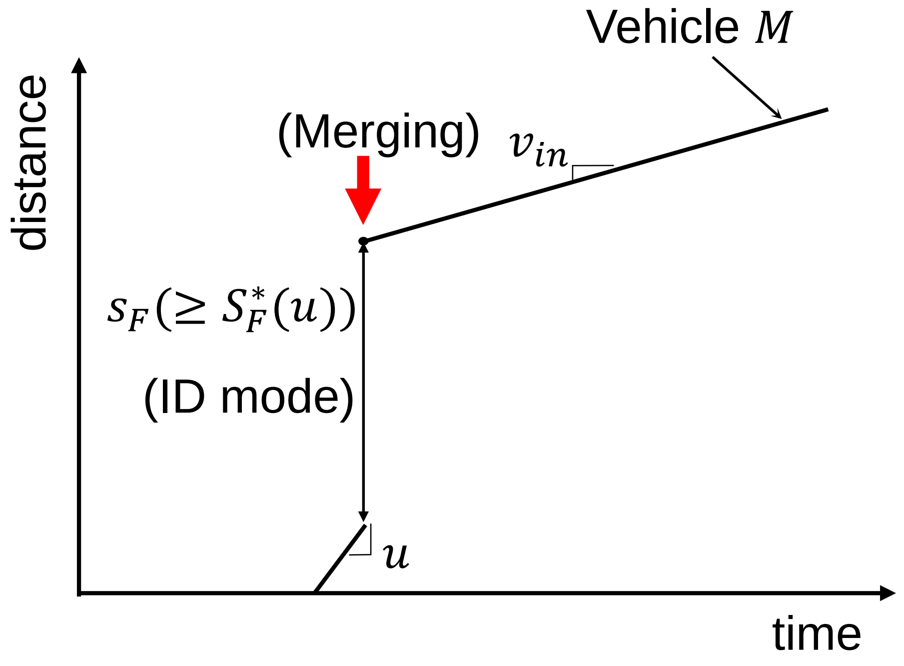


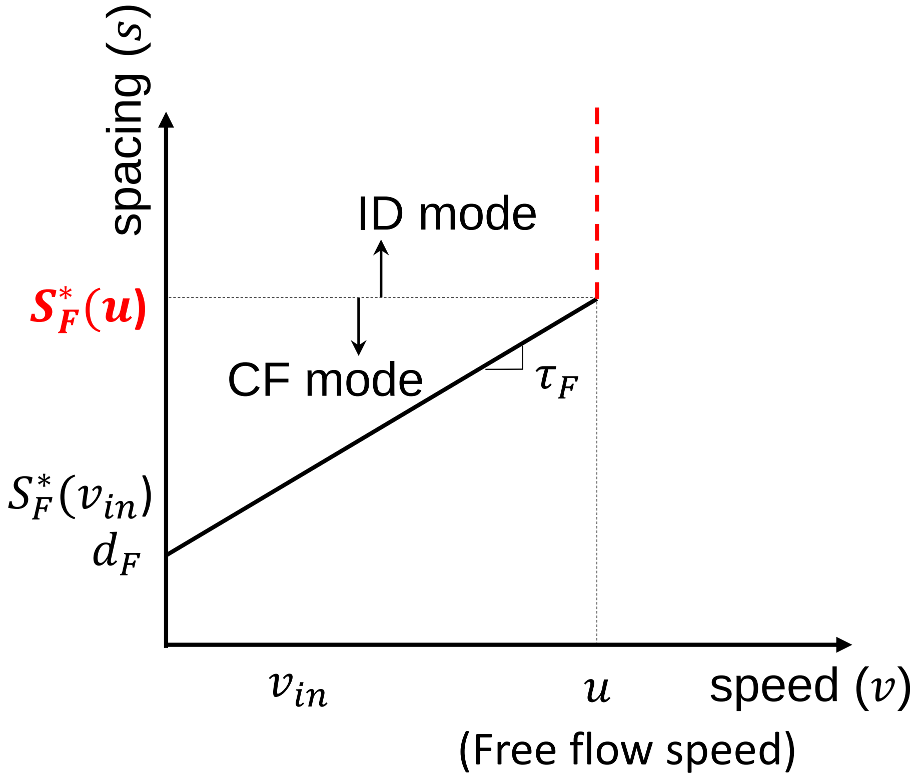
DRIVER BEHAVIOR

Vehicle behavior with merge

CASE 1 : MERGING SPACING (s_F) ≥ DESIRED SPACING ($S_F^*(u)$)

ID mode → CF mode





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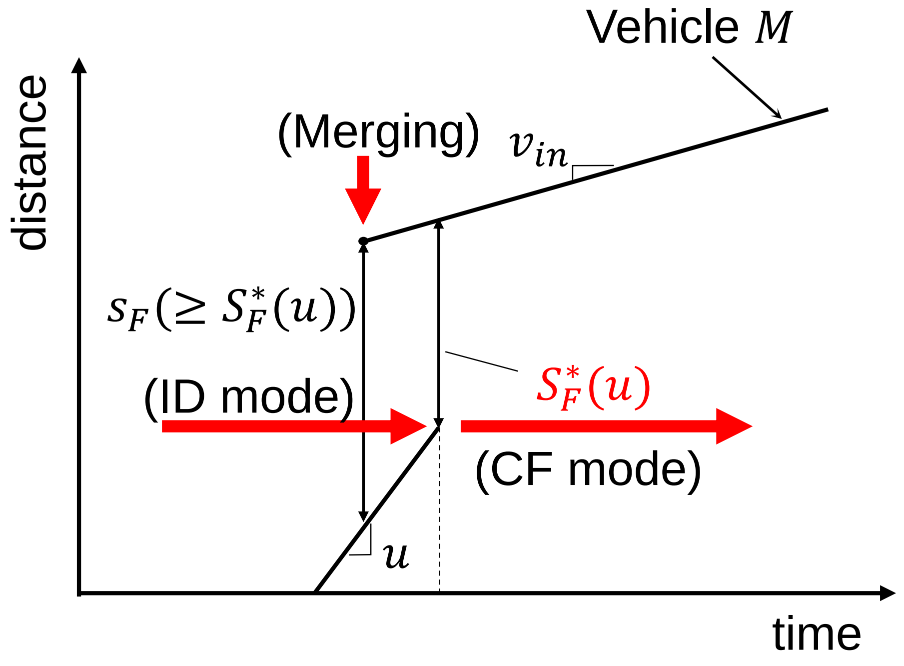

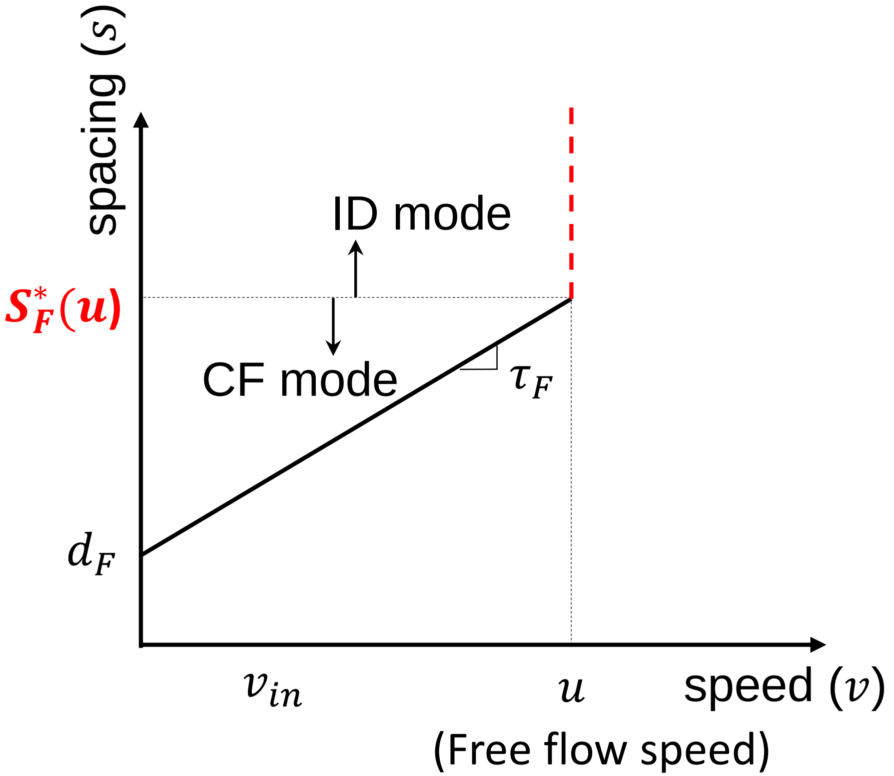

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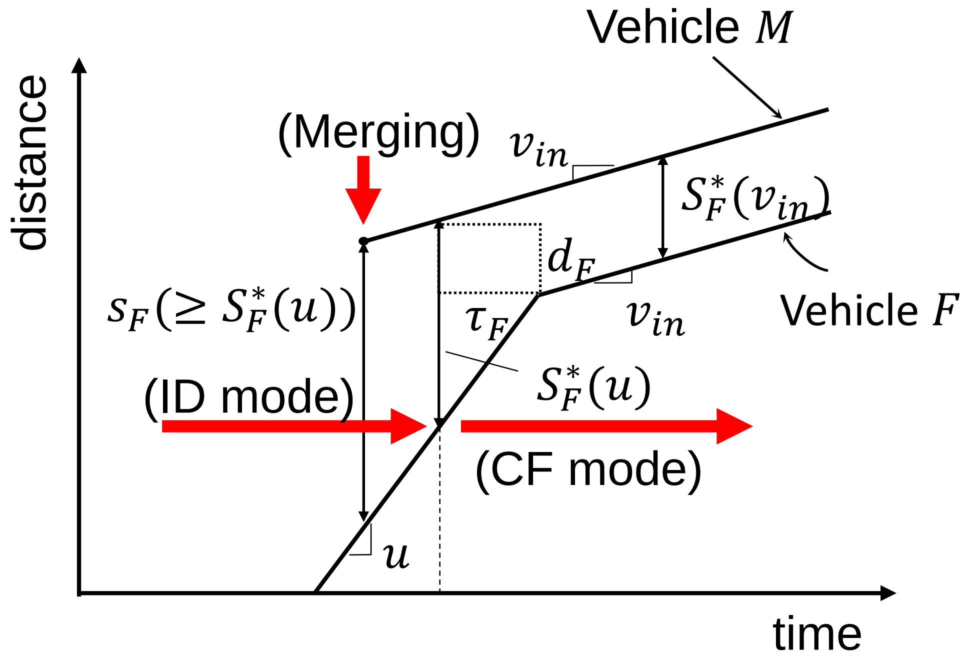
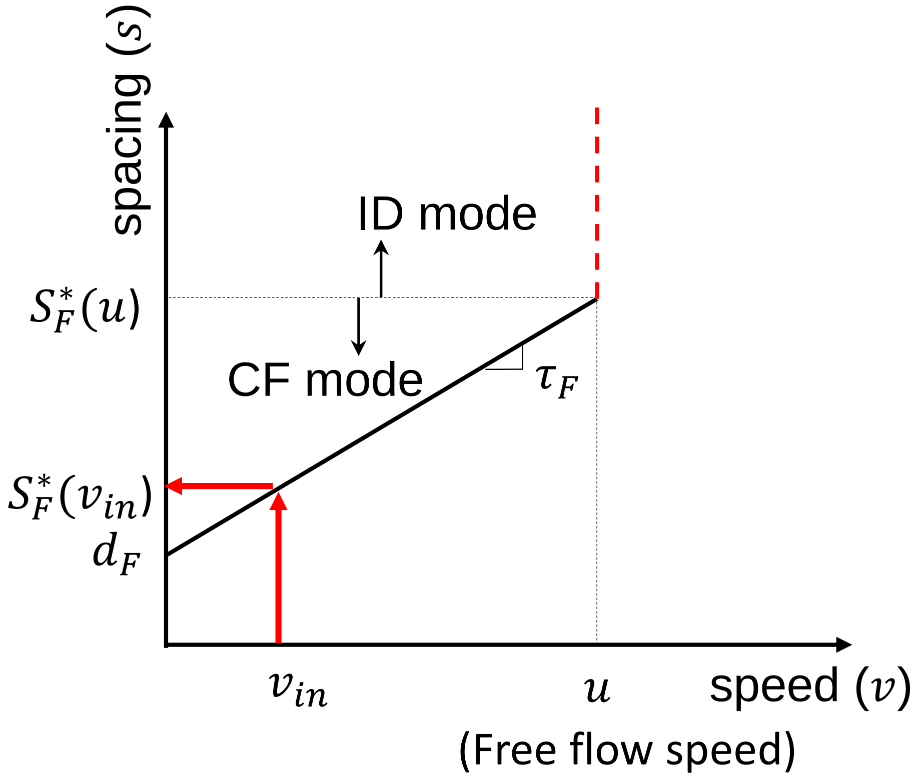


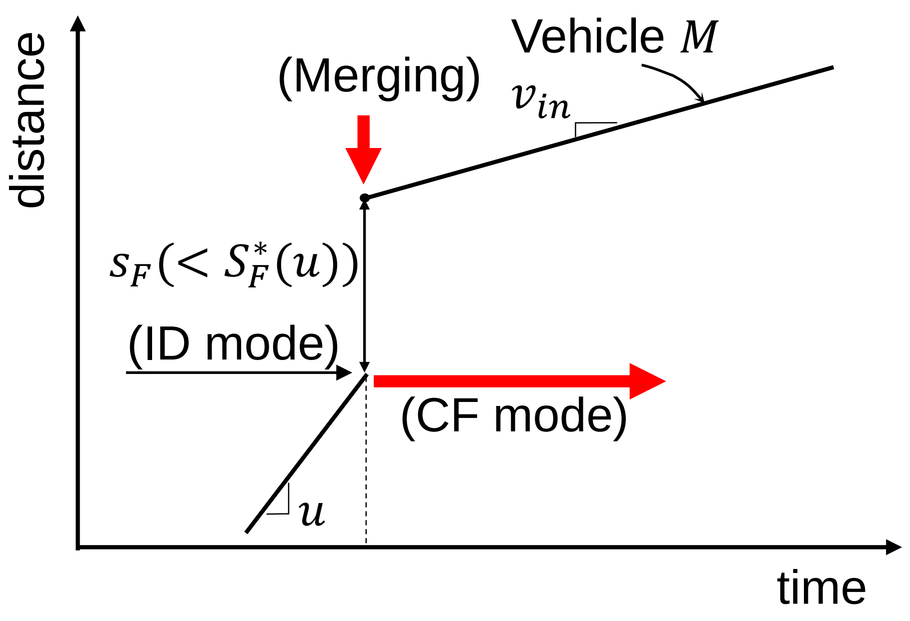


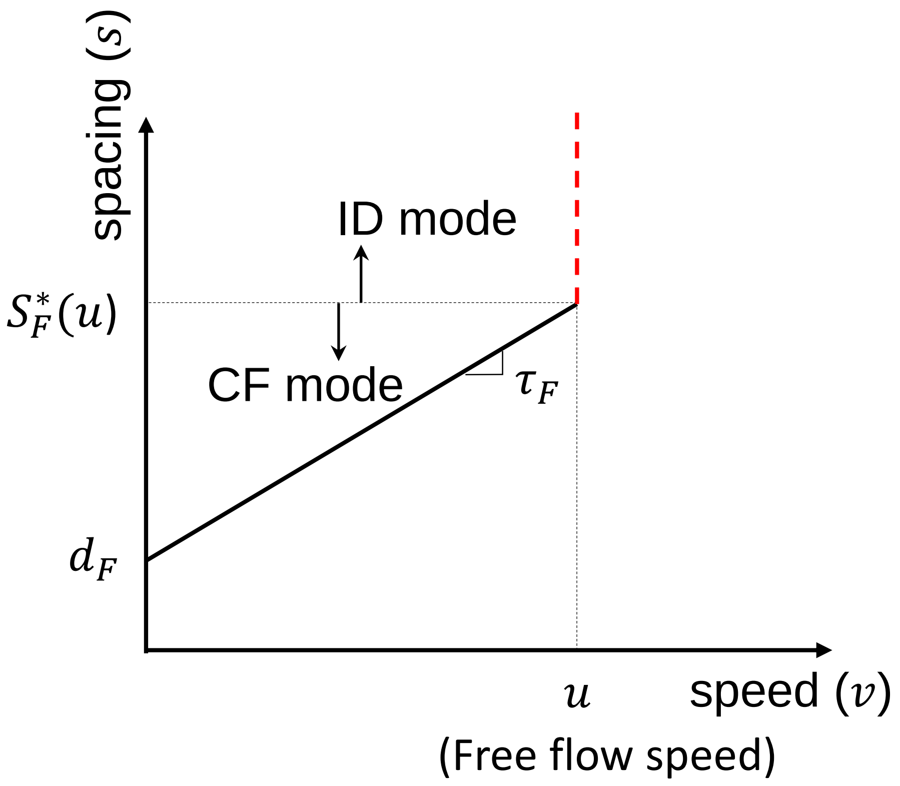
DRIVER BEHAVIOR

Vehicle behavior with merge

CASE 2 : MERGING SPACING (s_F) < DESIRED SPACING ($S_F^*(u)$)

Prompt CF mode





DRIVER BEHAVIOR

Vehicle behavior with merge

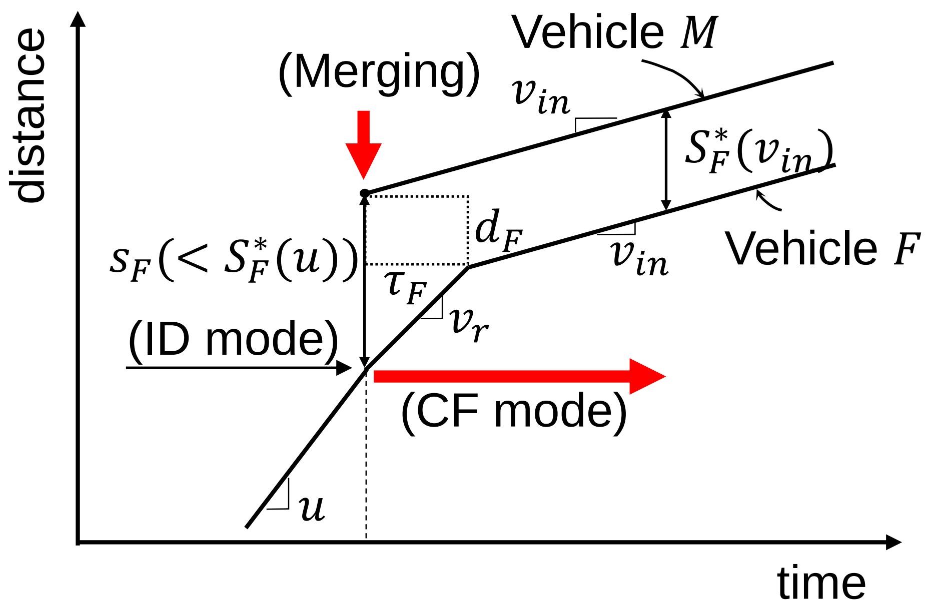
Rule 1

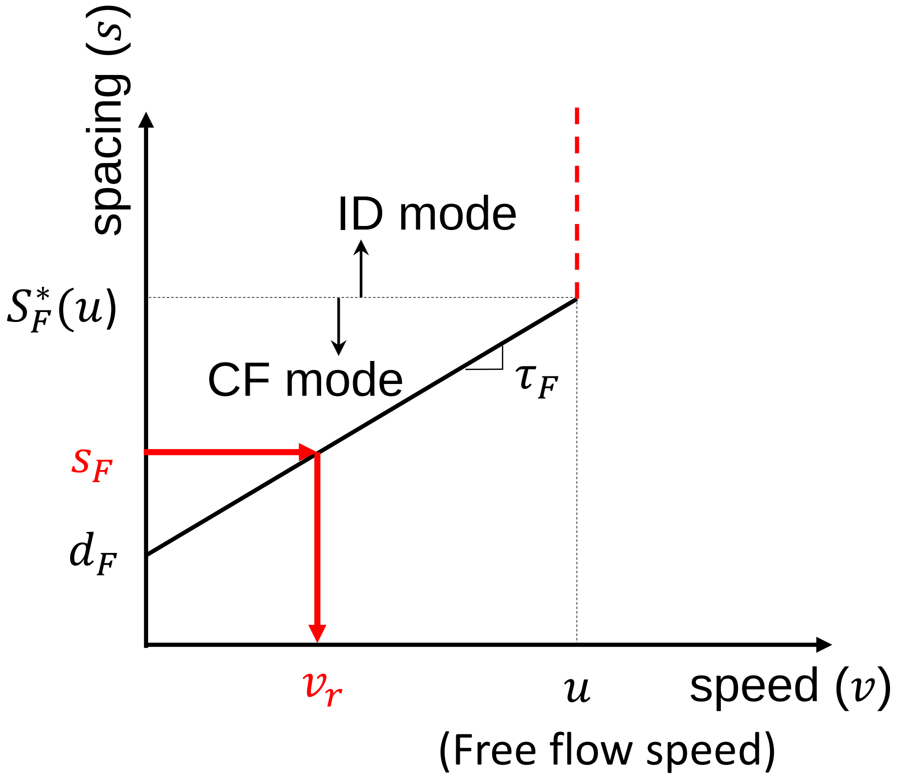
Merging spacing decides the speed

$$v_r = \frac{s_F - d_F}{\tau_F}$$

CASE 2 : MERGING SPACING (s_F) < DESIRED SPACING ($S_F^*(u)$)

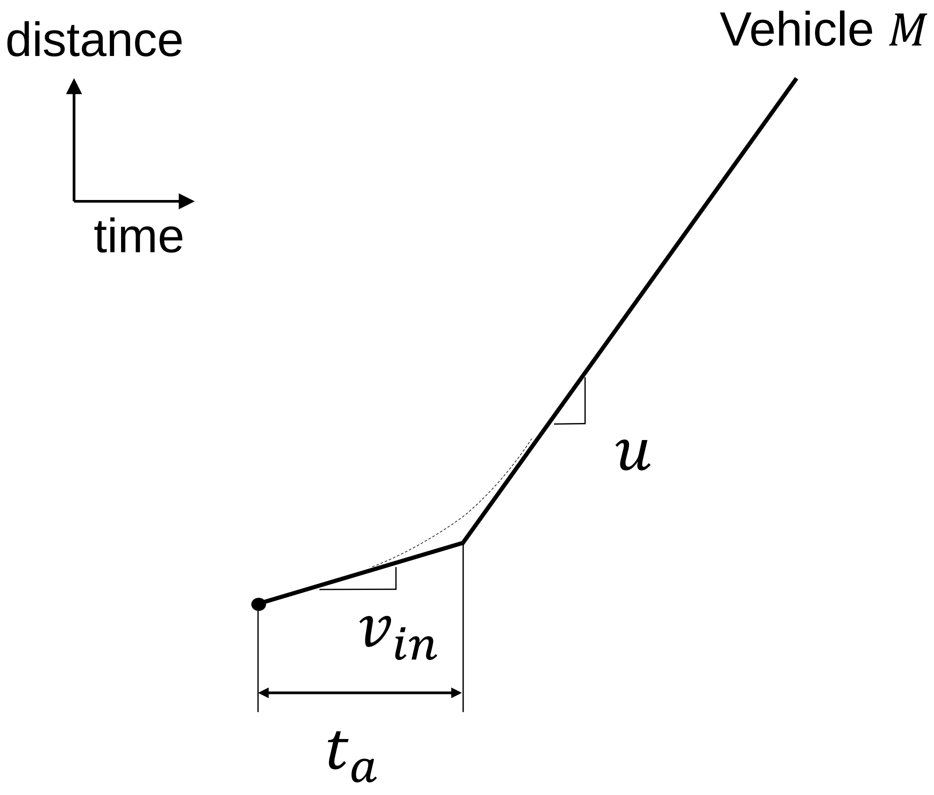
Prompt CF mode





DRIVER BEHAVIOR

Vehicle behavior of merging vehicle



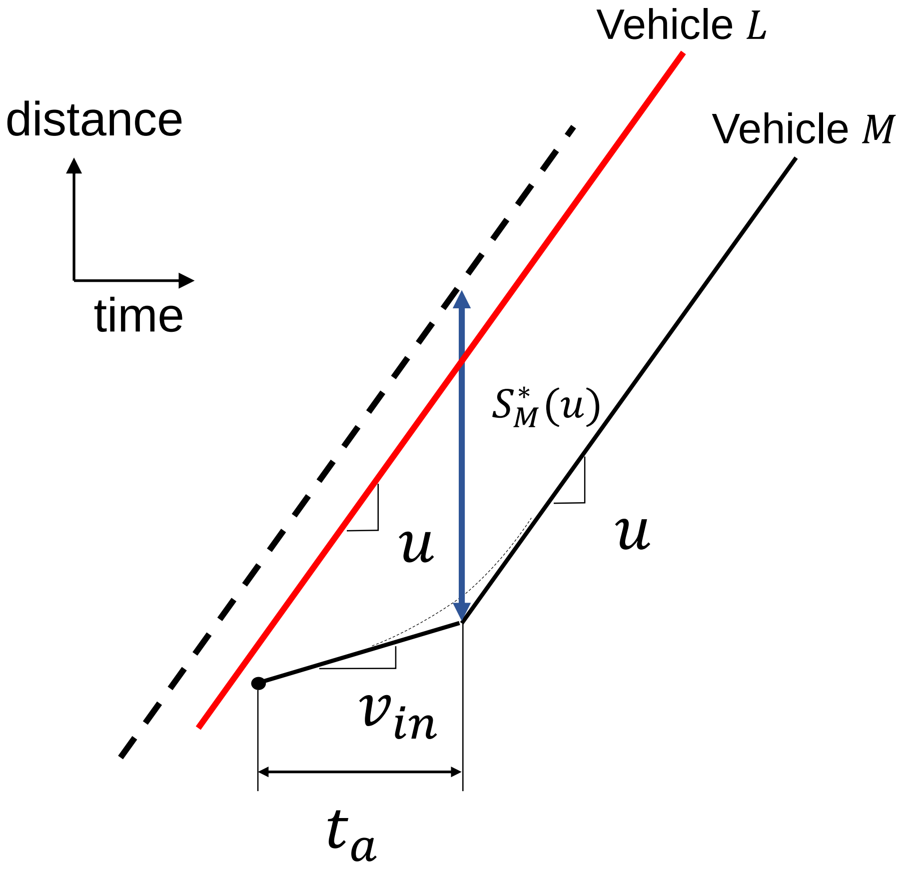
Duration of v_{in} (t_{in})

- *Acceleration time*

$$t_a = \frac{u - v_{in}}{2a}$$

DRIVER BEHAVIOR

Vehicle behavior of merging vehicle



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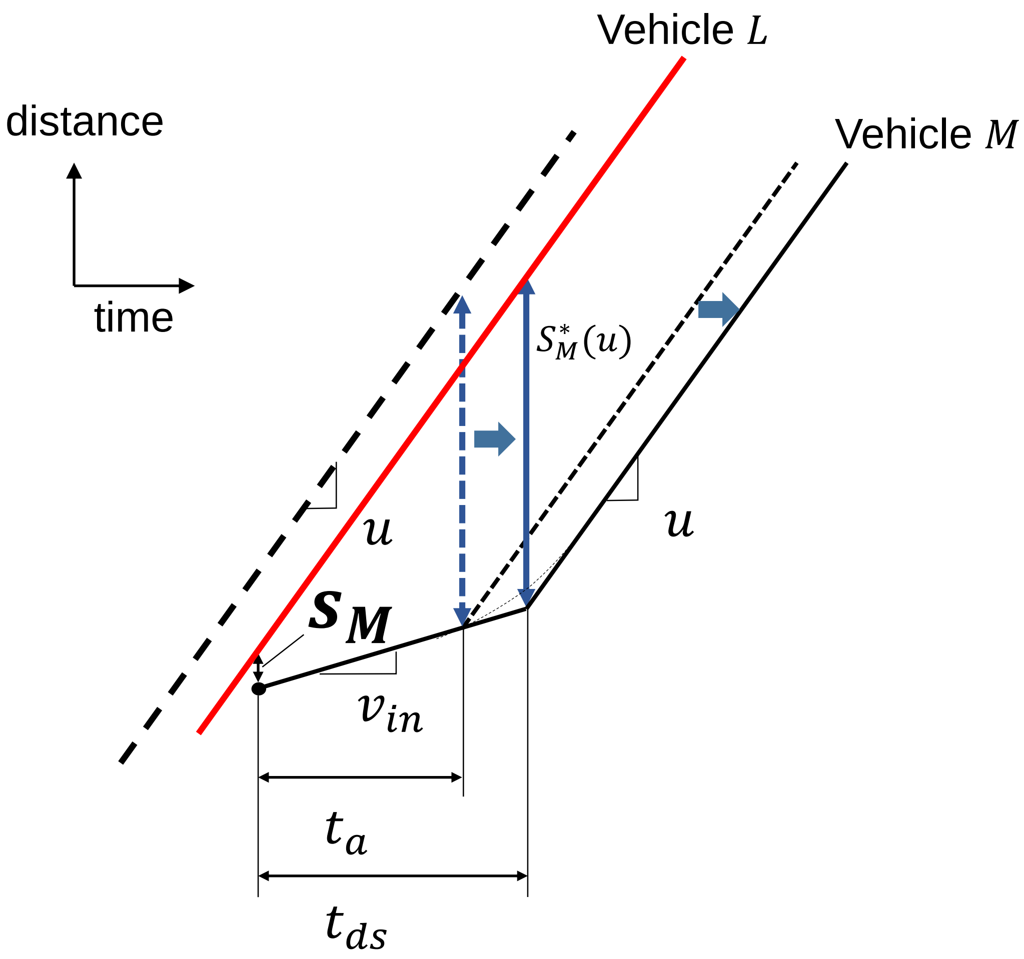


Duration of v_{in} (t_{in})

- *Acceleration time*

$$t_a = \frac{u - v_{in}}{2a}$$

- *Time to reach desired spacing*

$$t_{ds} = \frac{S_M^*(u) - s_M}{u - v_{in}}$$

$$\therefore\ t_{in} = max\ [t_a, t_{ds}]$$

Rule 2

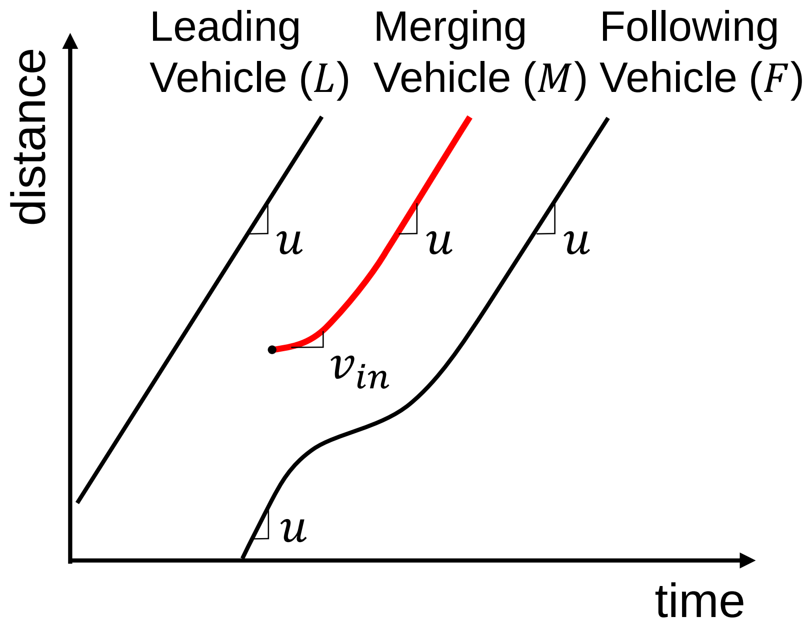
DURATION OF MERGING SPEED

BREAKDOWN PROCESS

Two elements of traffic breakdown

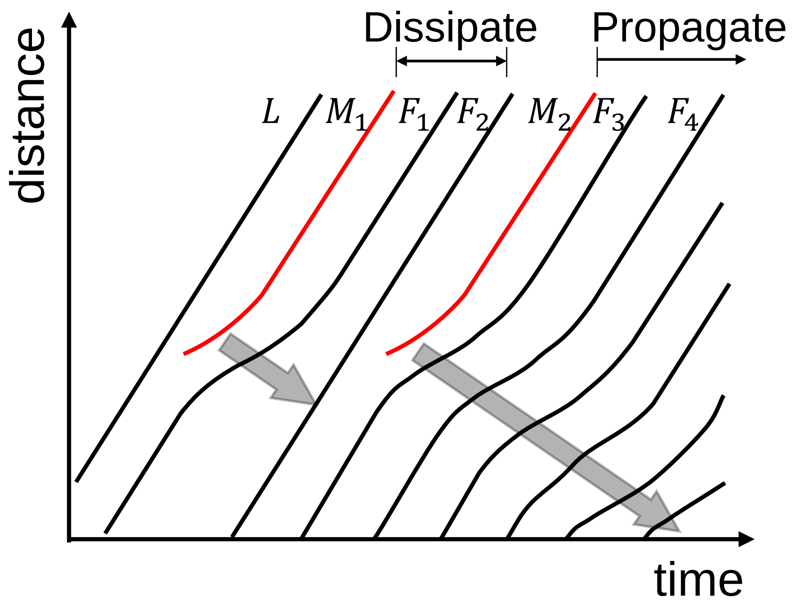
TRIGGER

Speed reduction by merging vehicle



PROPAGATION

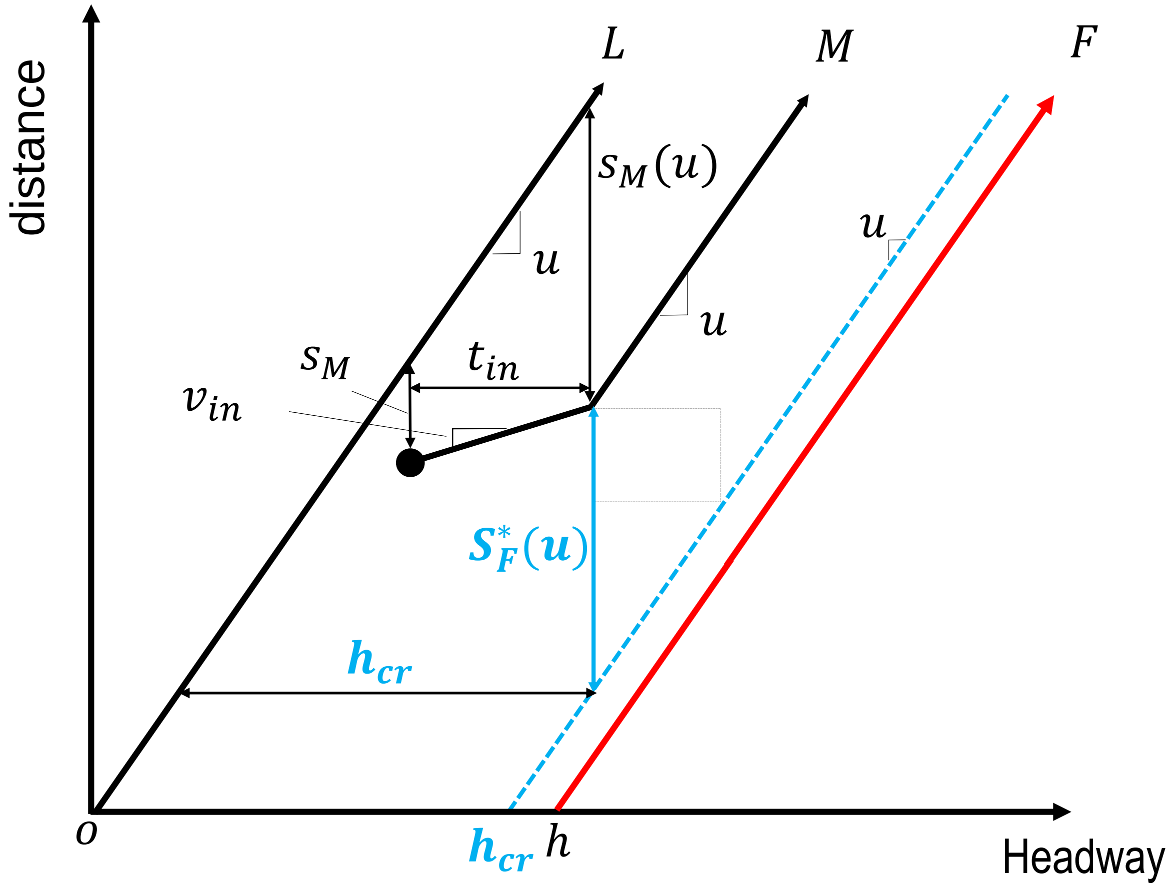
Wide spread congestion



Both Trigger and propagation are necessary to cause traffic breakdown

TRIGGER

Degree of disturbance by merge vehicle



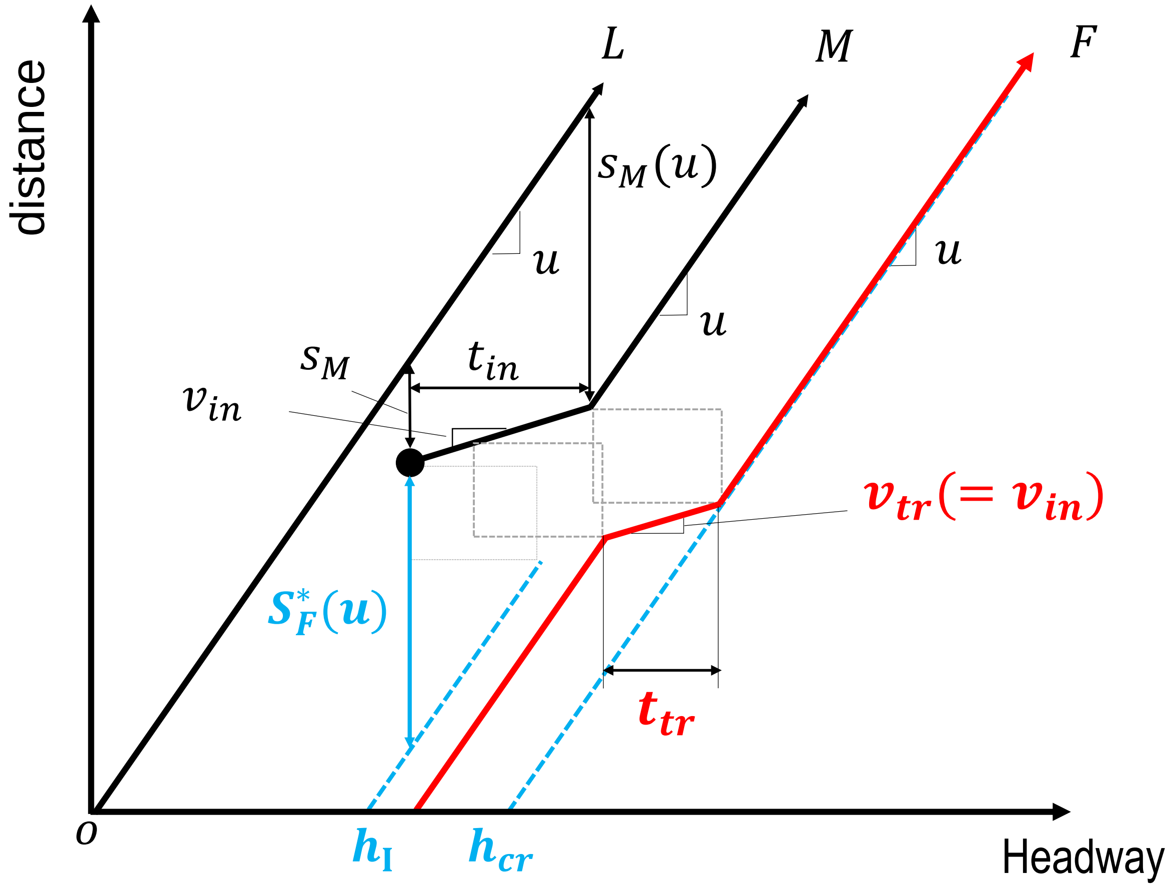
**h: headway between vehicle L and F before merging

NO TRIGGER

- $h > h_{cr}$
  - $h_{cr} = \frac{s_M(u)+S_F^*(u)}{u}$
  - No speed reduction (vehicle F)

TRIGGER

Degree of disturbance by merge vehicle



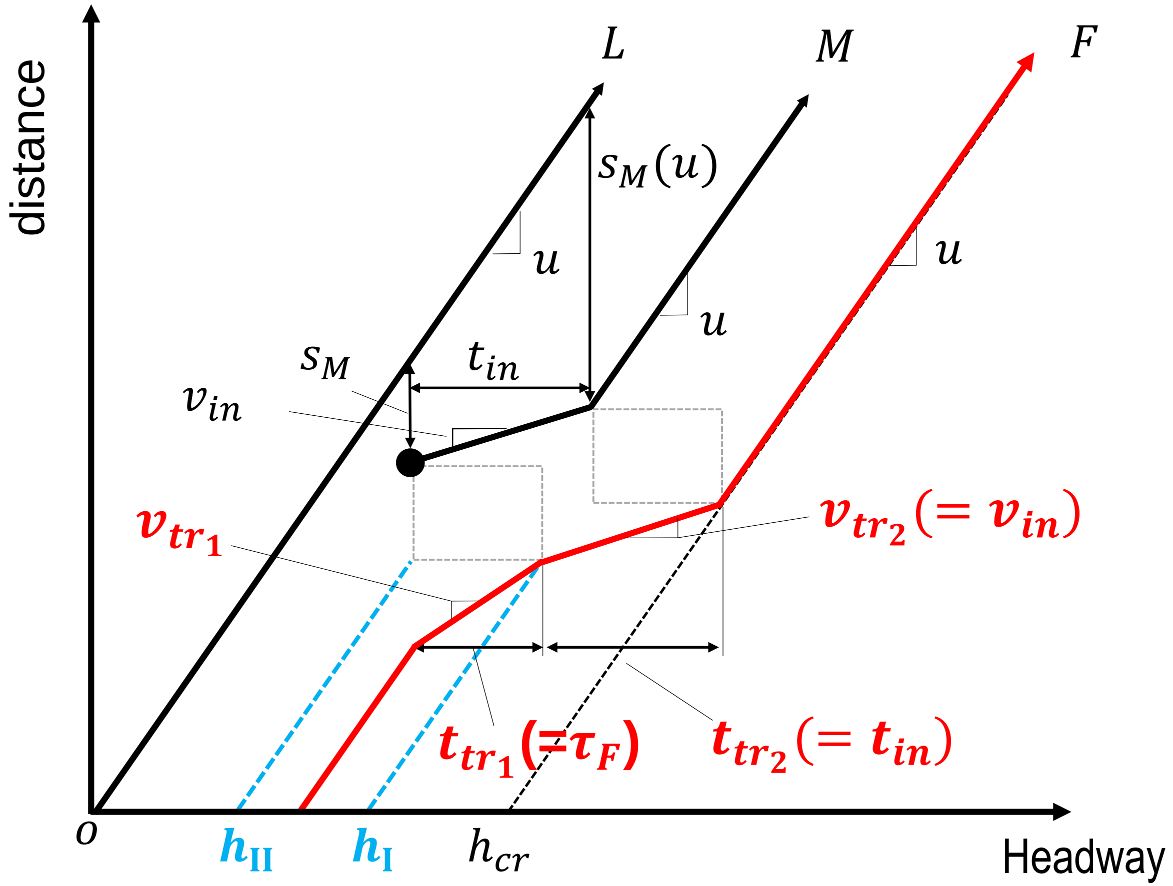
**h: headway between vehicle L and F before merging

TYPE I: MILD

- $h_\mathrm{I} < h \le h_{cr}$
  - $h_\mathrm{I} = \frac{s_M + S_F^*(u)}{u}$
- $v_{tr} = v_{in}$
- $t_{tr} = \frac{h - h_\mathrm{I}}{h_{cr} - h_\mathrm{I}} t_{in}$

TRIGGER

Degree of disturbance by merge vehicle



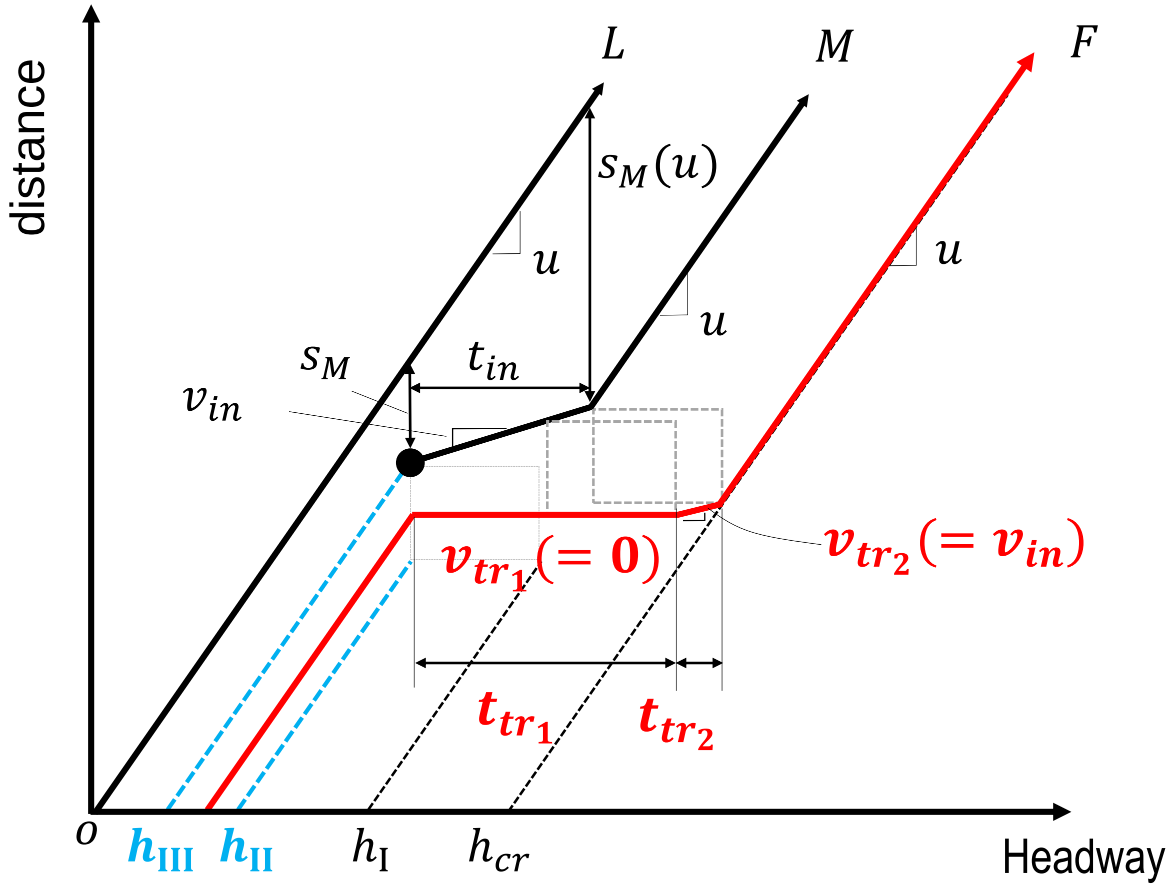
**h: headway between vehicle L and F before merging

TYPE II: MODERATE

- $h_{II} < h \leq h_I$
  - $h_{II} = \frac{s_M + d_F}{u}$
- $t_{tr_1} = \tau_F, t_{tr_2} = t_{in}$
  - $t_{tr} = t_{tr_1} + t_{tr_2}$
- $v_{tr_1} = \frac{(h - h_{II})u}{\tau_F}, v_{tr_2} = v_{in}$
  - $v_{tr} = \frac{t_{tr_1} v_{tr_1} + t_{tr_2} v_{tr_2}}{t_{tr_1} + t_{tr_2}}$

TRIGGER

Degree of disturbance by merge vehicle



**h: headway between vehicle L and F before merging

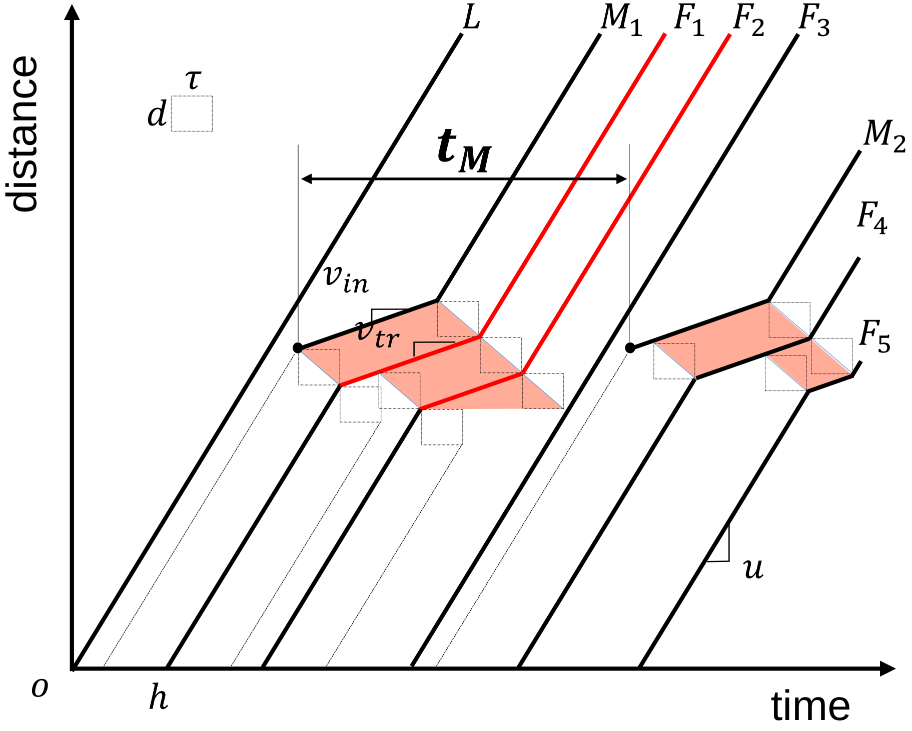
TYPE III: SEVERE

- $h_{III} < h \leq h_{II}$
  - $h_{III} = \frac{s_M}{u}$
- $t_{tr_1} = \frac{d_F - S_F}{v_{in}} + \tau_F,$

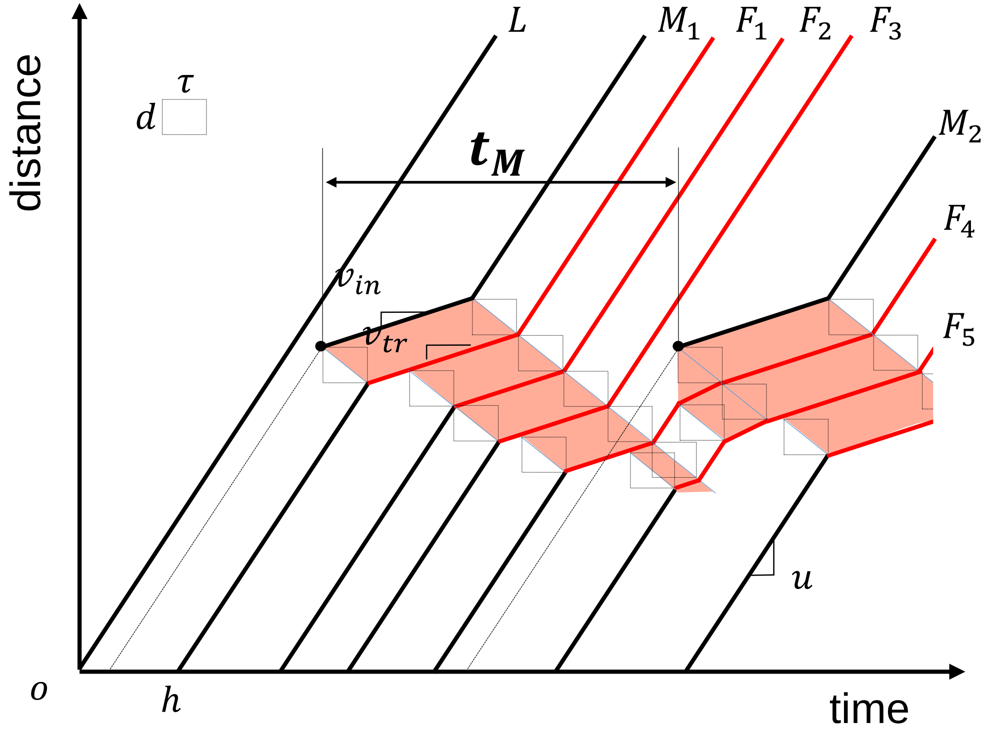
  $t_{tr_2} = t_{in} + \tau_F - t_{tr_1}$
  - $t_{tr} = t_{tr_1} + t_{tr_2}$
- $v_{tr_1} = 0 \, , v_{tr_2} = v_{in}$
  - $v_{tr} = \frac{t_{tr_1} v_{tr_1} + t_{tr_2} v_{tr_2}}{t_{tr_1} + t_{tr_2}}$

PROPAGATION

Persistence of disturbance until next merging vehicle



<Not propagation>

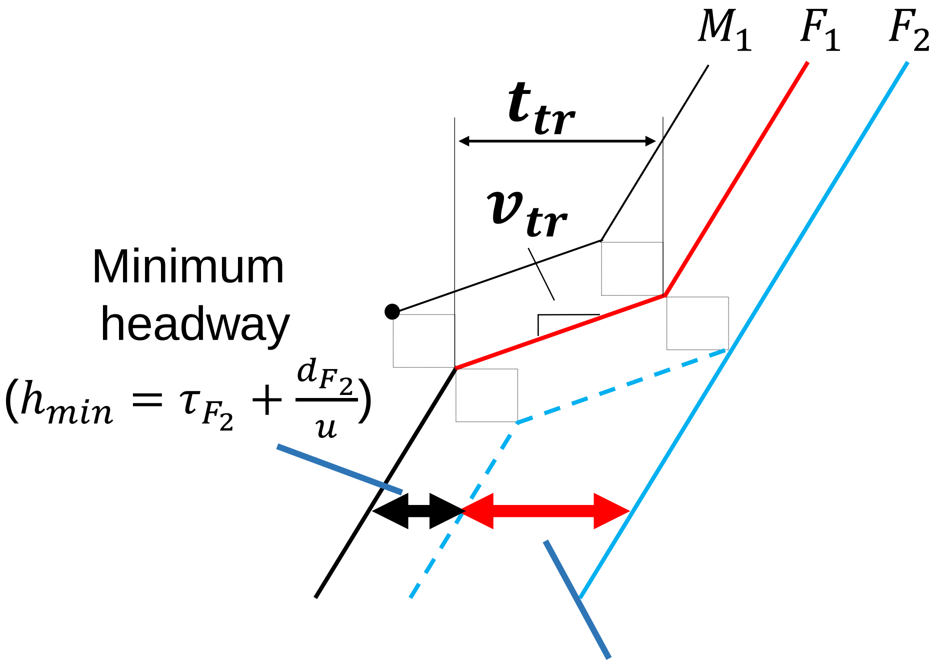


<Propagation>

"Disturbance will cumulate over time / lead to widespread congestion"

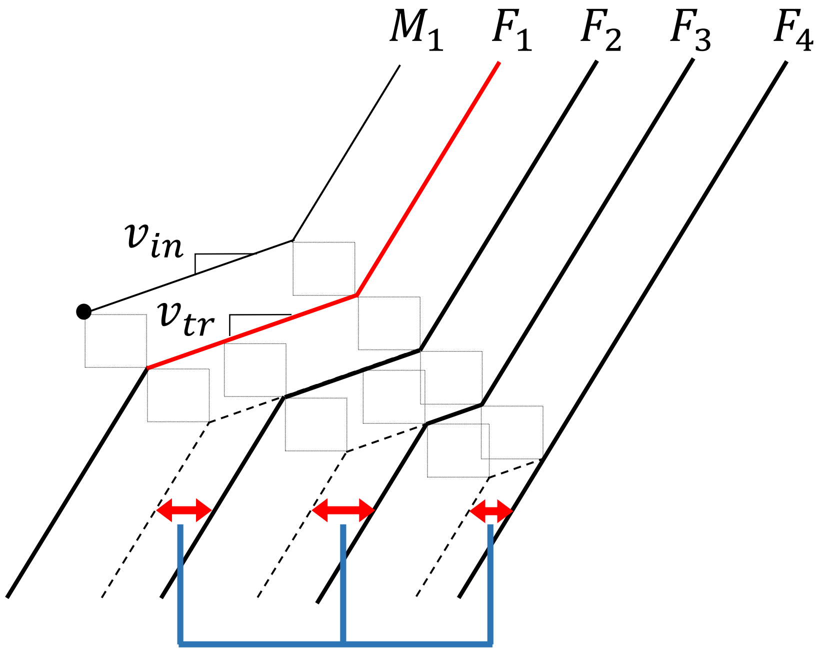
PROPAGATION

To resolve triggered disturbance



Critical buffer time (B_{cr})

>



Sum of Buffer headway (during t_M)

** Buffer headway of vehicle i (b_i)*

$$b_i = h_i - \frac{S_i^*(u)}{u} = h_i - \left(\tau_i + \frac{d_i}{u}\right)$$

PROPAGATION

Probability calculation

Probability of propagation

$$p(PR) = p\left(\sum_{i=1}^{n} b_i < B_{cr}\right)$$

Definition of buffer headway →

$$= p\left(\sum_{i=1}^{n}\left[h_i - \left(\tau_i + \frac{d_i}{u}\right)\right] < B_{cr}\right)$$

$$b_i = h_i - \left(\tau_i + \frac{d_i}{u}\right)$$

$$= p\left(\sum_{i=1}^{n} h_i < B_{cr} + \sum_{i=1}^{n}\left(\tau_i + \frac{d_i}{u}\right)\right)$$

Divide by n →

$$= p\left(E(h) < \frac{B_{cr}}{n} + \left(E(\tau) + \frac{E(d)}{u}\right)\right)$$

$$B(h) = \frac{B_{cr}}{n} + \left(E(\tau) + \frac{E(d)}{u}\right)$$ →

$$= p\big(E(h) < B(h)\big)$$

Central limit theorem →

$$= p\left(Z < \frac{B(h) - \mu_h}{\sigma_h/\sqrt{n}}\right)$$

Z-score (standard normal distribution)

BREAKDOWN PROBABILITY

Integrating of Trigger and Propagation

BREAKDOWN = "TRIGGER" AND "PROPAGATION"

$$p(BD) = \sum_{i=\mathrm{I}}^{\mathrm{III}} p(Type\ i\ trigger) \times p(Propagation|Type\ i\ trigger)$$

(Probability of breakdown)

$$= \sum_{i=\mathrm{I}}^{\mathrm{III}} \int_{a_i}^{b_i} p(h)\,dh \times \frac{\int_{a_i}^{b_i} p(h)\,p(PR|h)dh}{\int_{a_i}^{b_i} p(h)\,dh}$$

$$= \sum_{i=\mathrm{I}}^{\mathrm{III}} \int_{a_i}^{b_i} p(h)\,p(PR|h)dh \qquad = \int_{\boldsymbol{h}_{\mathrm{III}}}^{\boldsymbol{h}_{cr}} \boldsymbol{p(h)p(PR|h)dh}$$

Model Properties

And breakdown mechanism

MODEL PROPERTIES

Understand Breakdown Mechanisms → Insight for Control

Breakdown probability decreases with

1) Low flow rate (mainline, merging)
2) High merging speed
3) Low deviation of headway
4) Small τ (aggressive driver)

MODEL PROPERTIES

Effects of Headway Distribution (Deviation)

3 scenarios of headway distribution

- Same mean, different deviations

  (i) Exponential distribution: $\sigma_h = \mu_h$

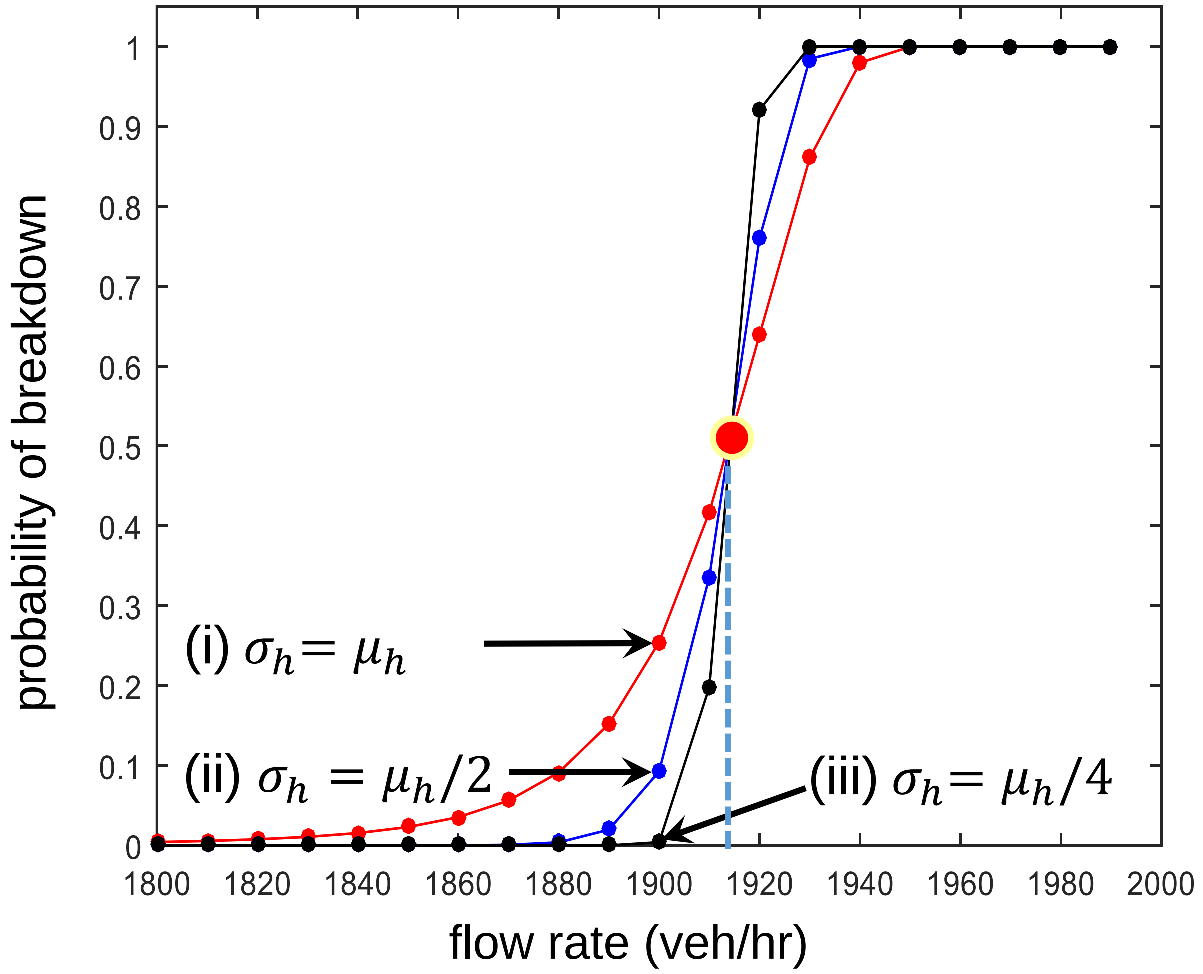
  (ii) Gamma distribution: $\sigma_h = \mu_h/2$

  (iii) Gamma distribution: $\sigma_h = \mu_h/4$

MECHANISM

✓ **Small headway deviation**

→ Low propagation → Low breakdown (Before critical flow)



Proactive VSL Control

1. INTRODUCTION
2. BREAKDOWN MODEL
3. MODEL PROPERTIES
4. PROACTIVE CONTROL
5. CONCLUSION

PROACTIVE VSL CONTROL

Headway Adjustment Area

OBJECTIVES

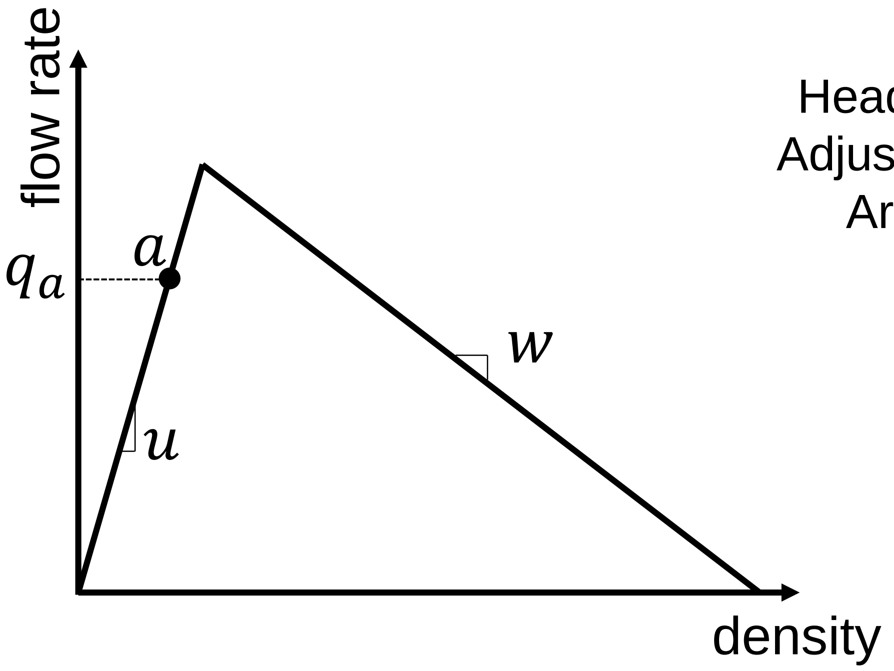
- To achieve uniform headways in free flow state
- Not to generate controlled congestion that propagates upstream

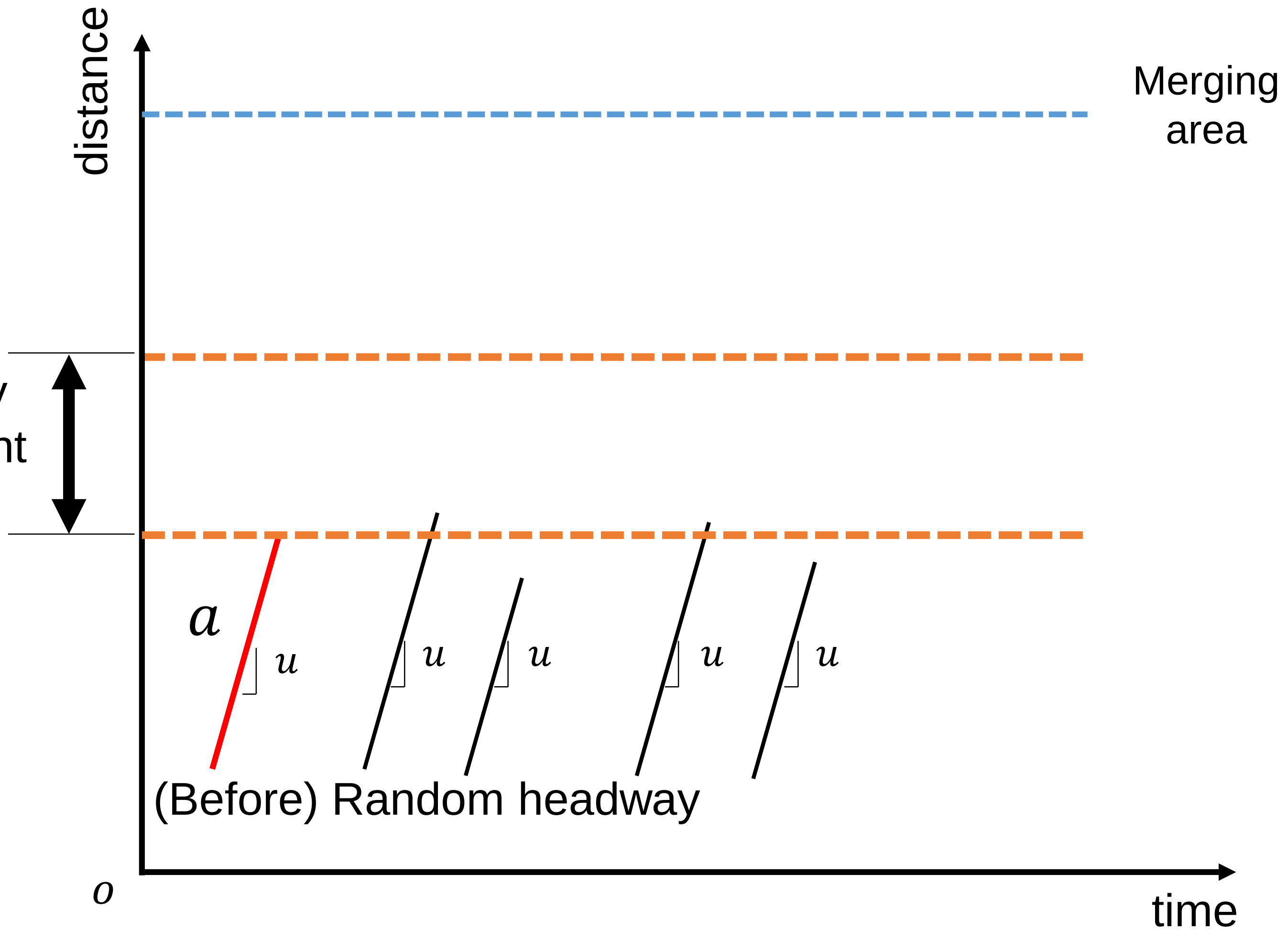
MEANS

- Temporary deceleration of CV
- Combination with VMS control

PROACTIVE VSL CONTROL

Control Procedure





PROACTIVE VSL CONTROL

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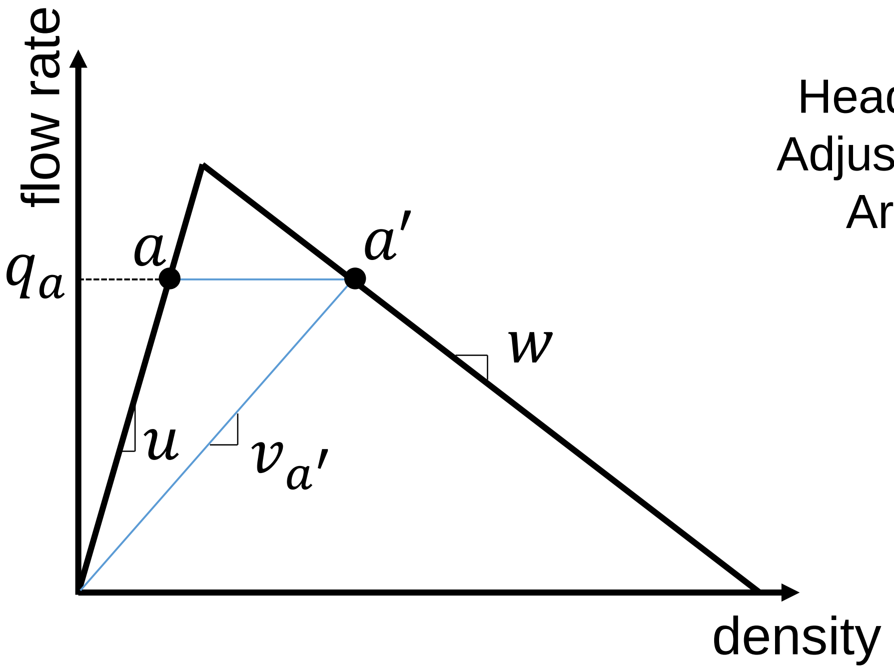
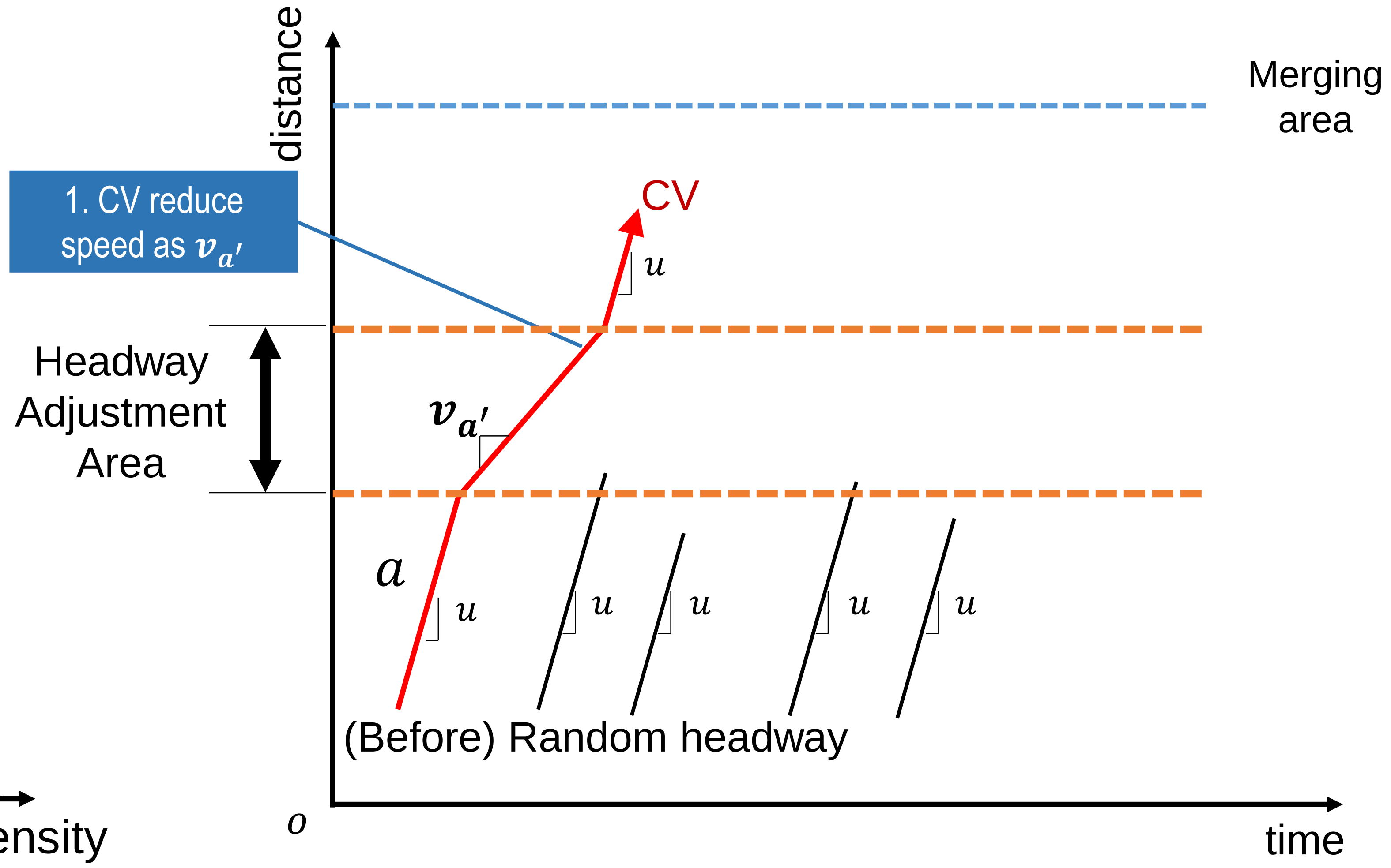
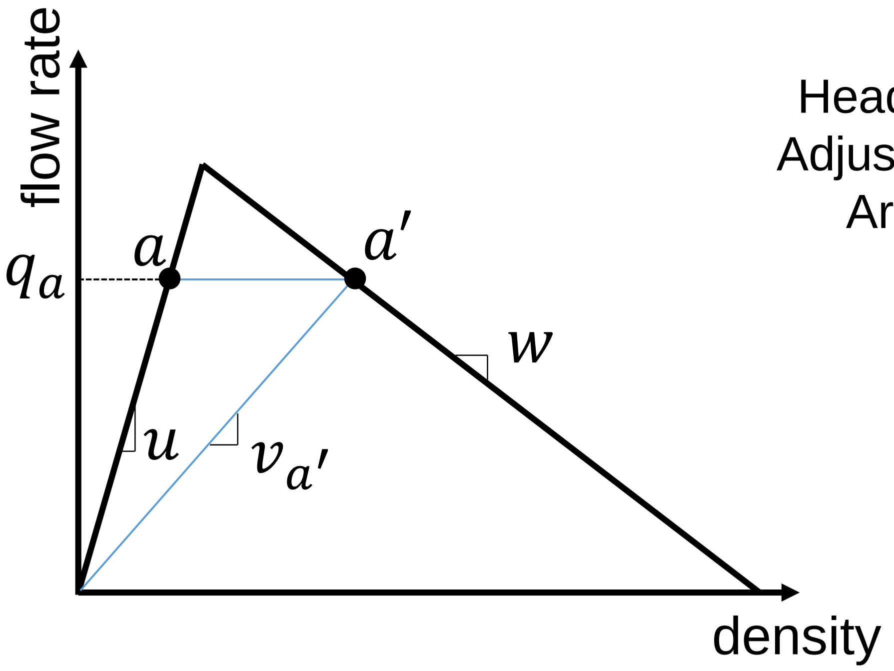
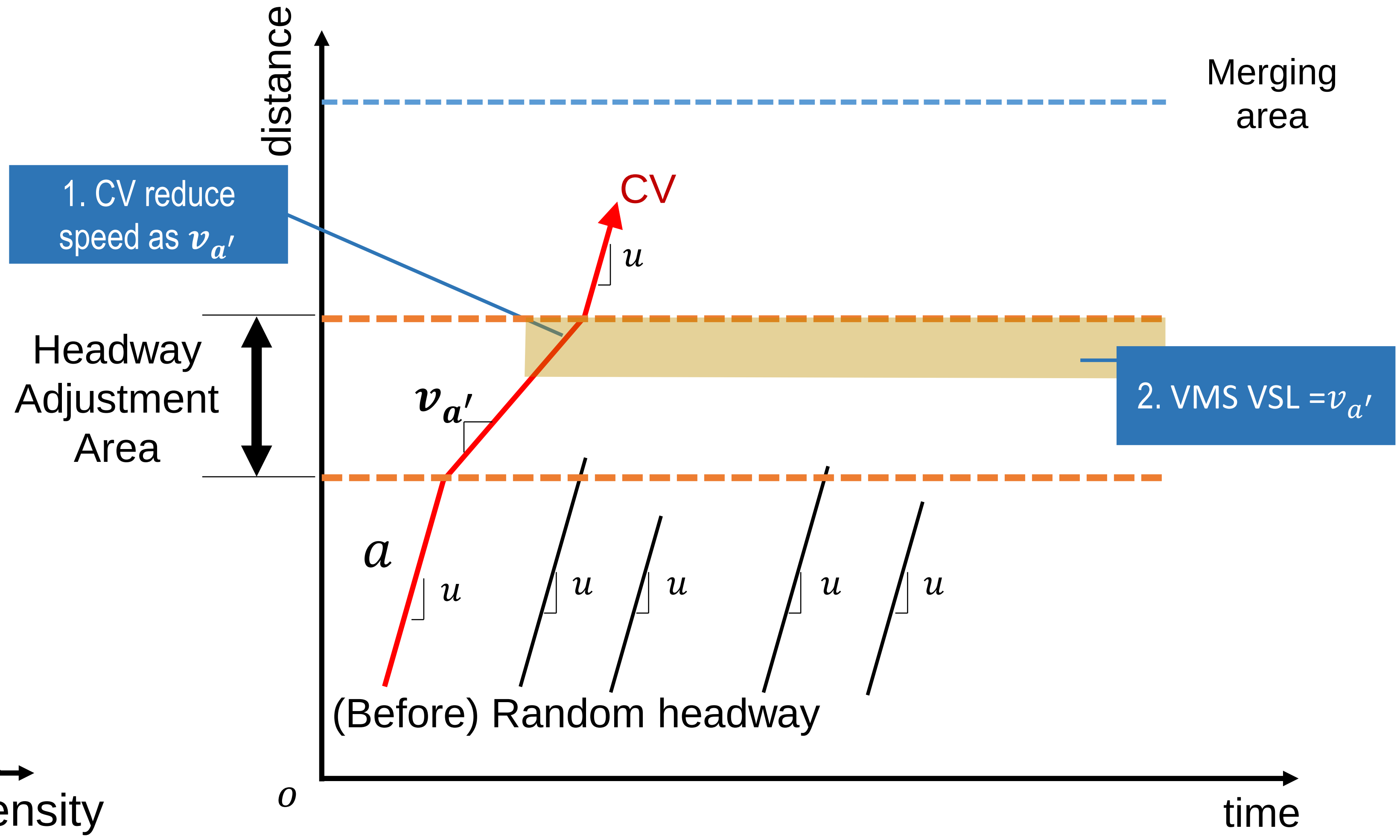




PROACTIVE VSL CONTROL

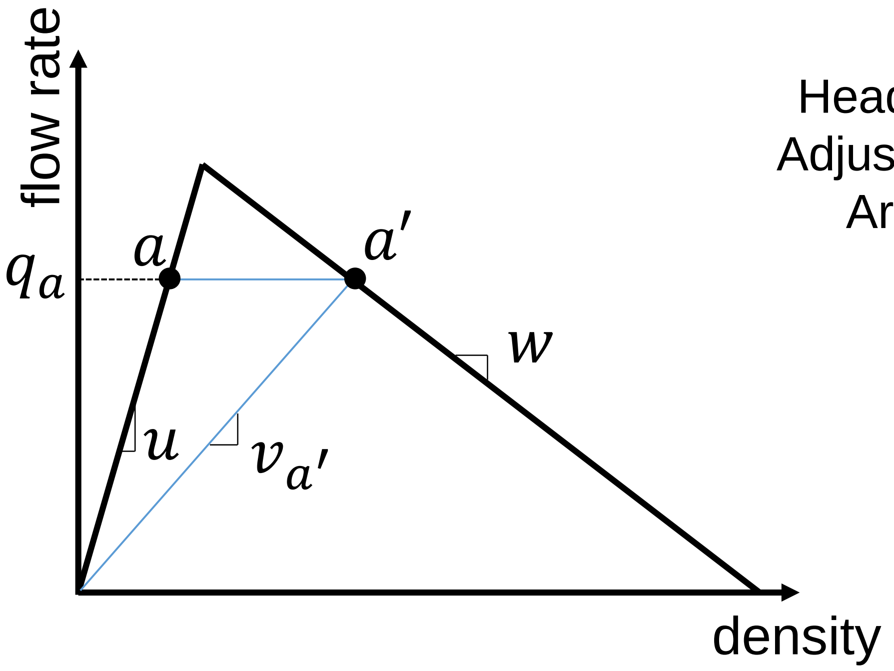
Control Procedure

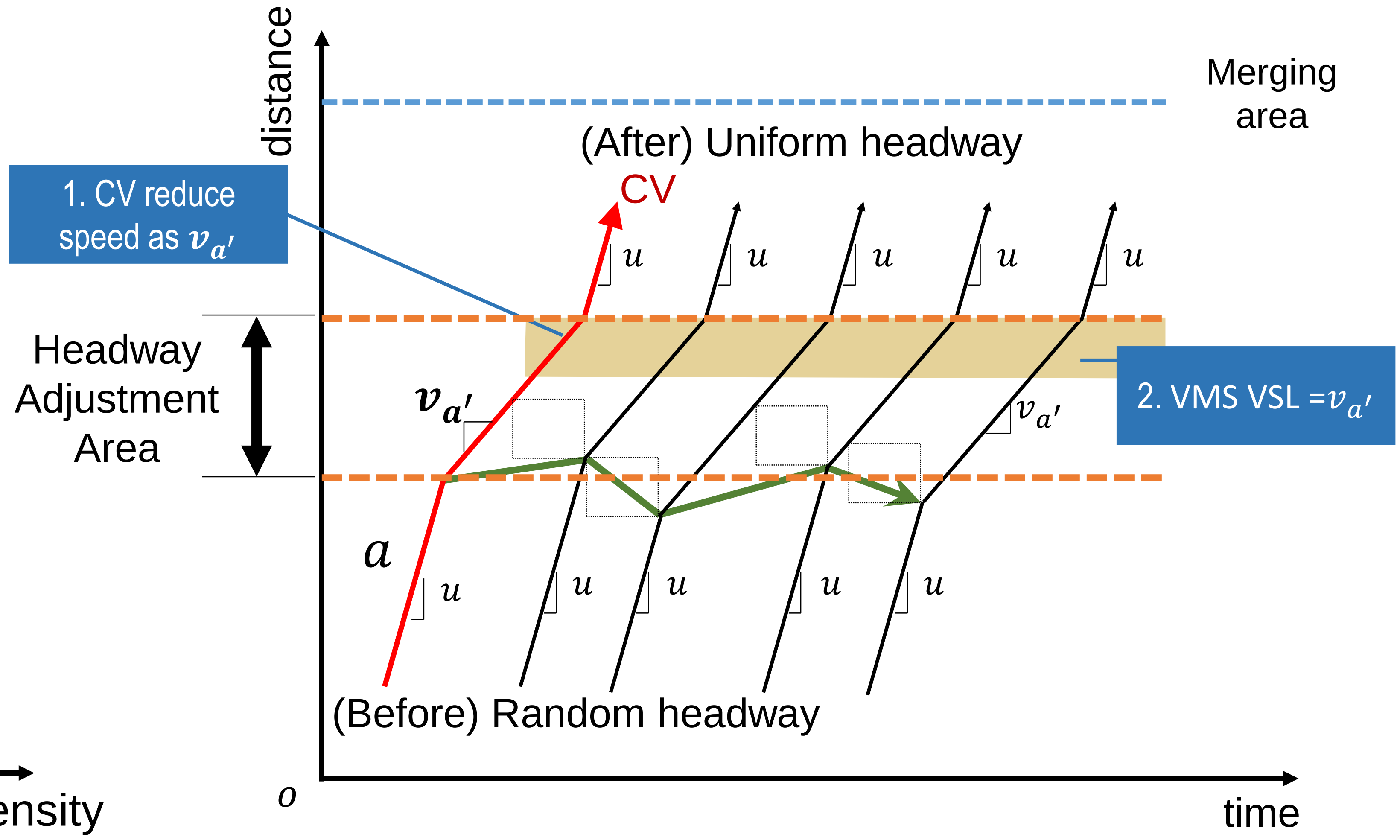




PROACTIVE VSL CONTROL

Control Procedure





Conclusions

And Future works

CONCLUSIONS / CONTRIBUTIONS

BREAKDOWN MODEL

- Better describes the ***mechanisms*** of traffic breakdown
- Obtain ***insight*** for traffic control: small headway deviation

PROACTIVE CONTROL

- ***Harmonize vehicle headways*** using CV (CAV) and VMS
- Decrease breakdown probability ***without*** controlled-congestion propagating upstream

LIMITATIONS / FUTURE WORKS

Multilane and Autonomous Vehicle

MULTILANE ISSUE

- ***Breakdown model:*** Following vehicles can change lanes
- ***Traffic control:*** Vehicle might change lanes to avoid speed reduction

↓

- ***Model*** Consider probability of LC
- ***Low CV*** Additional control by VMS
- ***High CV*** Simultaneous control of multiple CVs in different lanes


Thank You!
Source: U.S.DOT

CAPACITY DROP

Discharge rate from bottleneck diminishes after onset of congestion

Authors (Year)	Type	Capacity Drop
Edie (1961)	Tunnel	**-12.5 %**
Banks (1991)	On-ramp	**-3.0~-10.0 %**
Hall and Agyemang-Duah (1991)	On-ramp	**-5.0~-6.0 %**
Cassidy and Bertini (1999)	On-ramp On-ramp	**-8.0~-9.0 %** **-4.0~-10.0 %**
Bertini and Leal (2005)	Lane drop	**-10.0 %**

STOCHASTIC CAPACITY

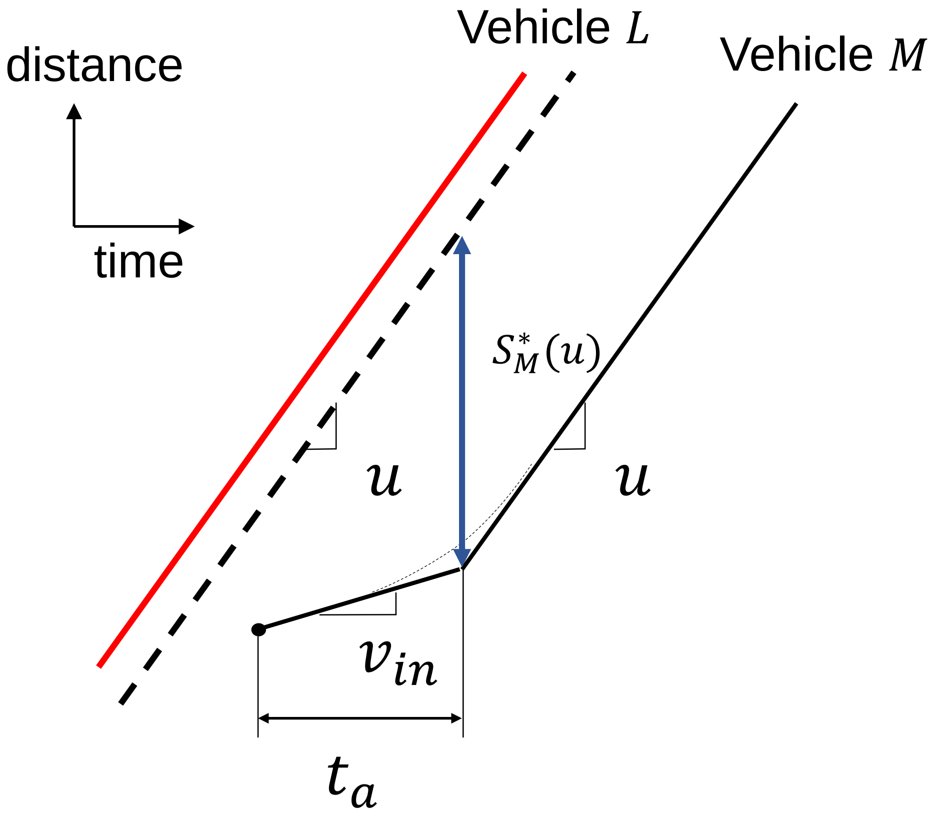
Capacity can vary

MECHANISM

- Elefteriadou (1994): Effect of merging flow rate (by Breakdown process)
- Evans et al. (2001): Effect of mainline flow (by Markov Chains)
- **Son et al. (2004): Effect of merging vehicle (by Wave propagation model)**
- X. Chen et al. (2014): Effect of merging vehicle (by Queueing theory)

DRIVER BEHAVIOR

Vehicle behavior of merging vehicle



Duration of v_{in} (t_{in})

- *Acceleration time*

$$t_a = \frac{u - v_{in}}{2a}$$

TRIGGER

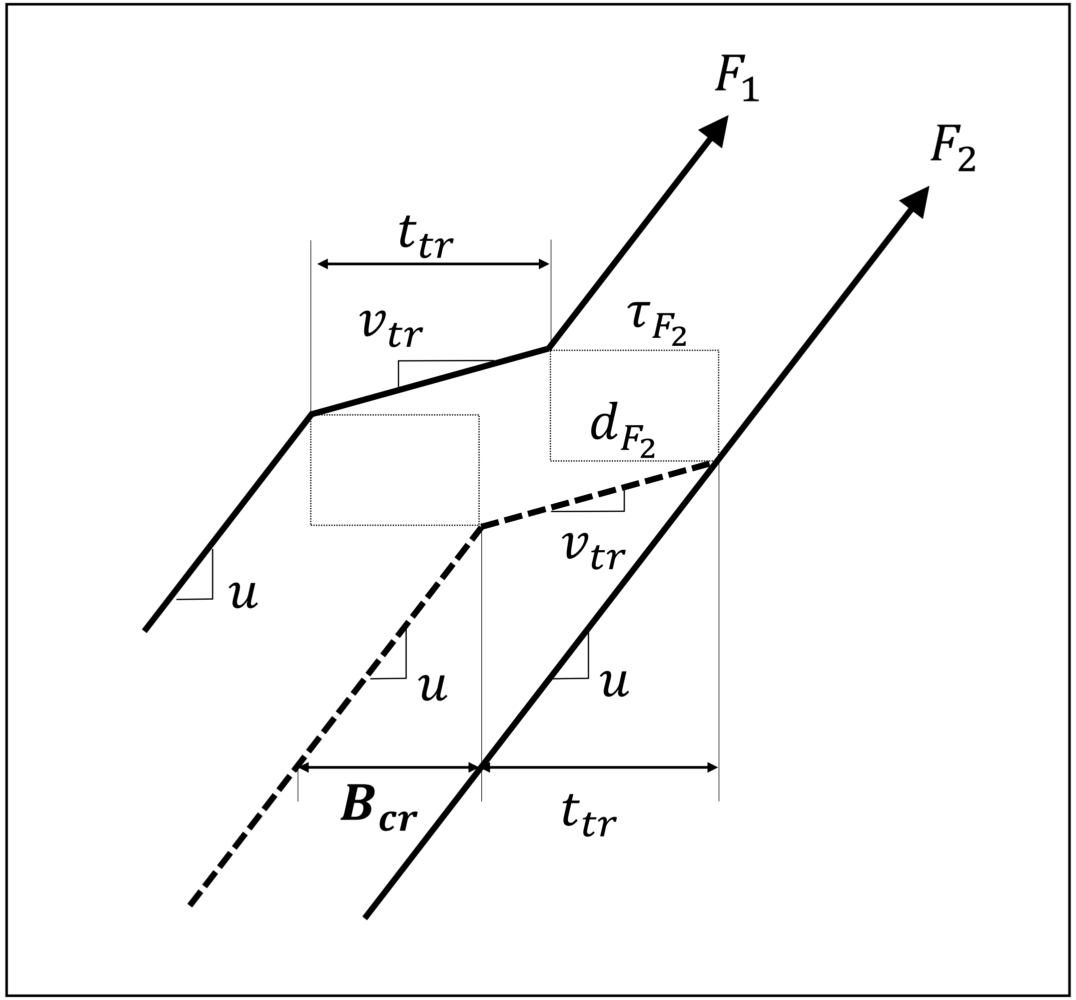
Degree of disturbance by merge vehicle

Trigger Type	Range of h $(a_i < h < b_i)$	v_{tr}		t_{tr}	
		v_{tr_1}	v_{tr_2}	t_{tr_1}	t_{tr_2}
No trigger	$h > h_{cr}$	-		-	
I	$h_{\mathrm{I}} < h \leq h_{cr}$	v_{in}		$\frac{h - h_{\mathrm{I}}}{h_{cr} - h_{\mathrm{I}}} t_{in}$	
II	$h_{\mathrm{II}} < h \leq h_{\mathrm{I}}$	$\frac{(h - h_{\mathrm{II}})u}{\tau_F}$	v_{in}	τ_F	t_{in}
III	$h_{\mathrm{III}} < h \leq h_{\mathrm{II}}$	0	v_{in}	$\frac{d_F - (h - h_{\mathrm{III}})u}{v_{in}} + \tau_F$	$t_{in} + \tau_F - t_{tr_1}$

***The magnitude of trigger depends on headway, h, between leading and following vehicle.**

PROPAGATION

Probability calculation



Probability of propagation

$$p(PR) = p(\sum_{i=1}^{n} b_i < B_{cr})$$

PROPAGATION PROBABILITY.

- n: *vehicle number during merging interval,* t_M

$$n = qt_M$$

- b_i: *buffer headway of vehicle* i

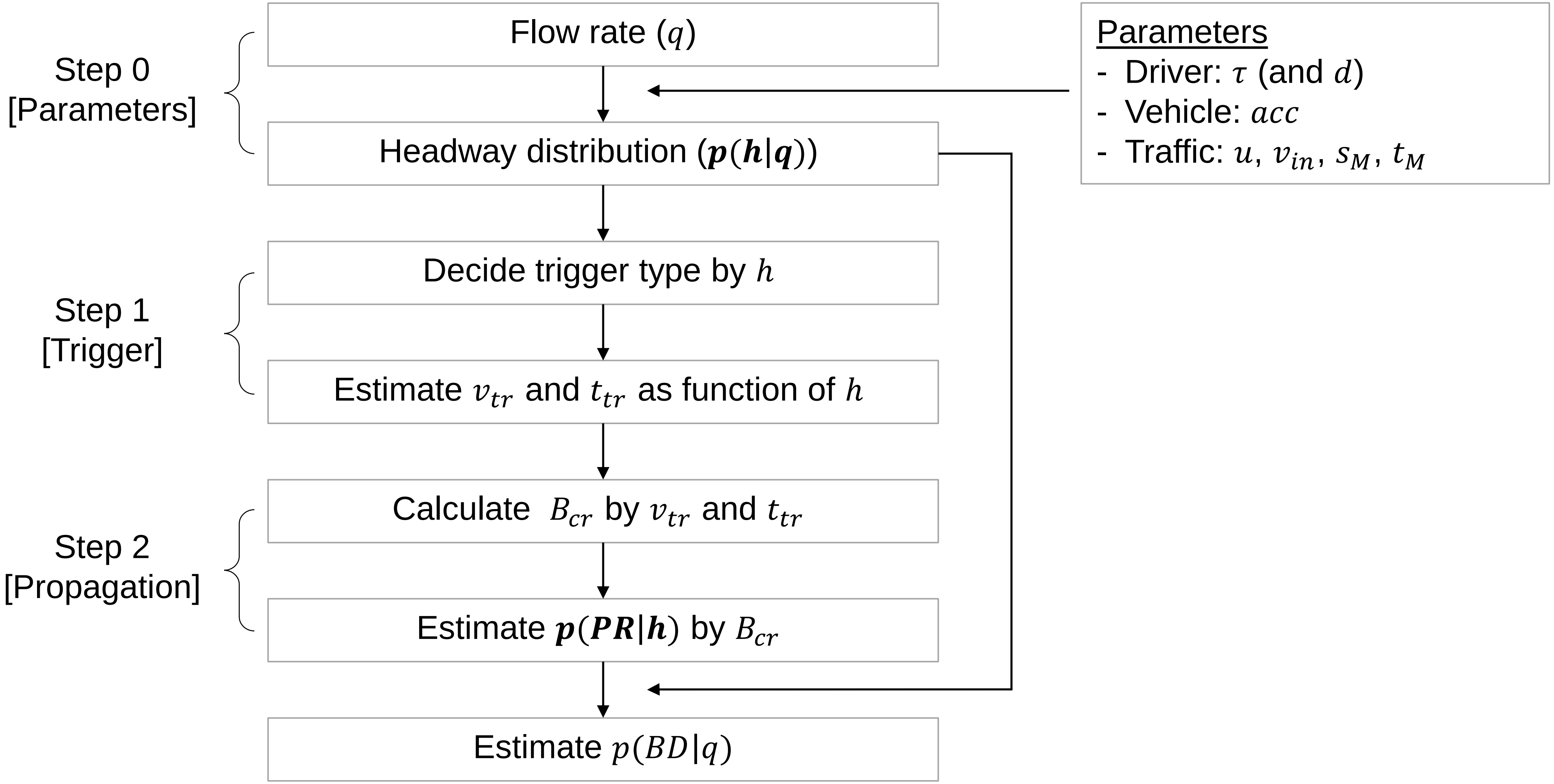
$$b_i = h_i - \frac{S_i^*(u)}{u} = h_i - \left(\tau_i + \frac{d_i}{u}\right)$$

- B_{cr}: *Critical buffer time*

$$B_{cr} = t_{tr}\left(1 - \frac{v_{tr}}{u}\right)$$

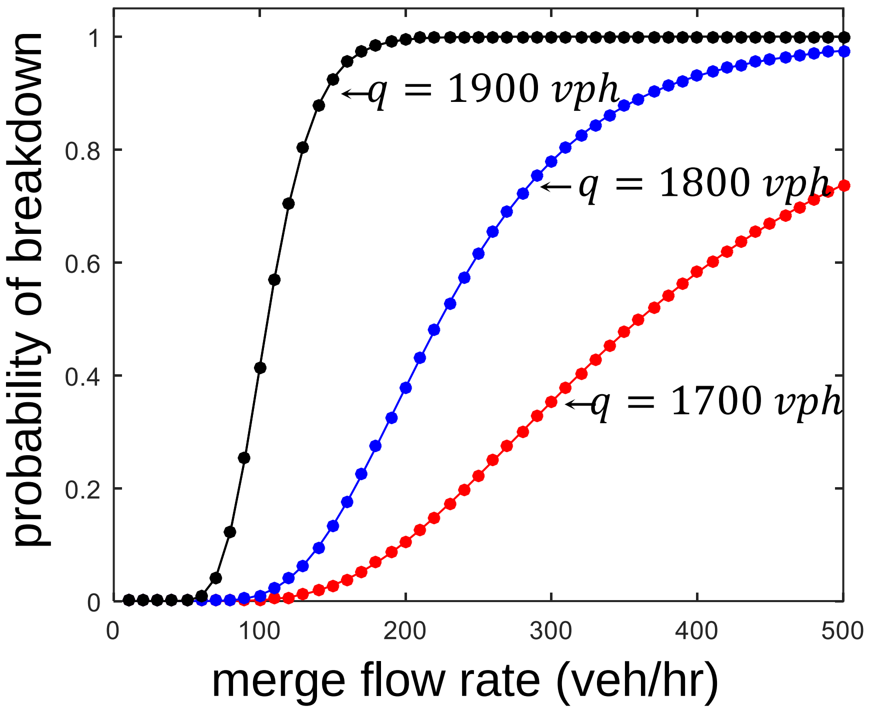
BREAKDOWN PROBABILITY

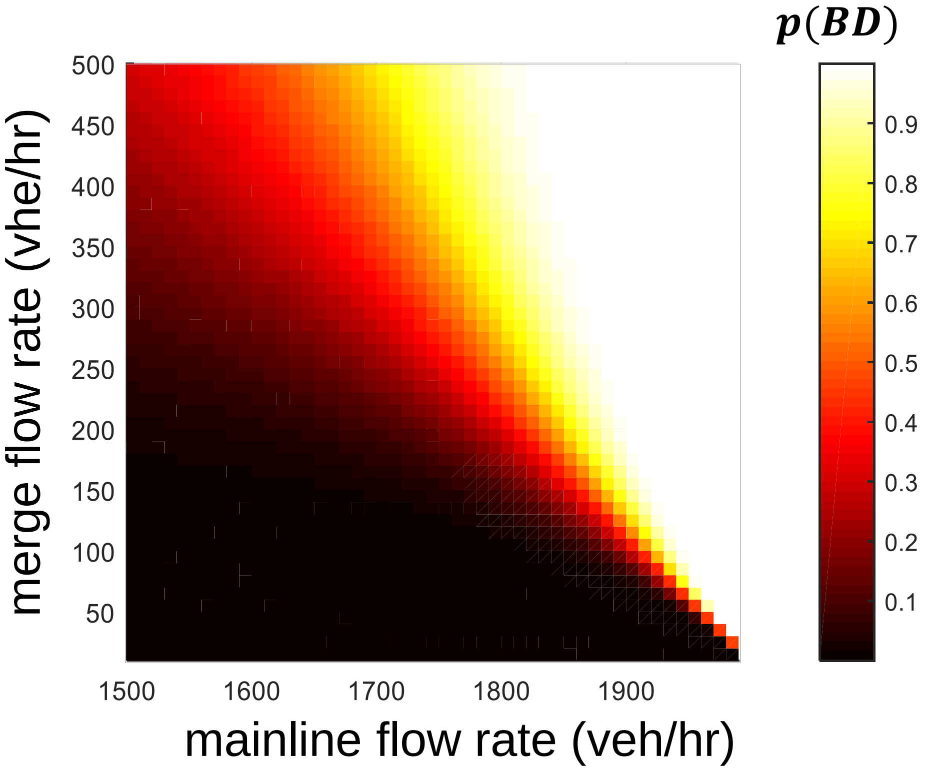
Process Summary



MODEL PROPERTIES

Effects of Flow rate





MECHANISM

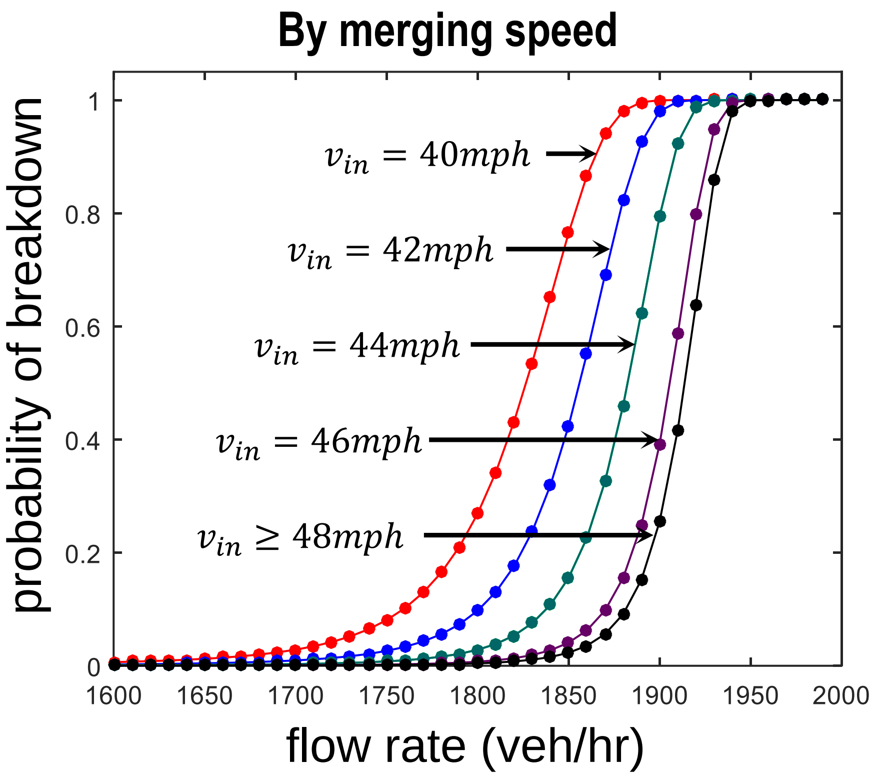
(Smaller buffer headway)

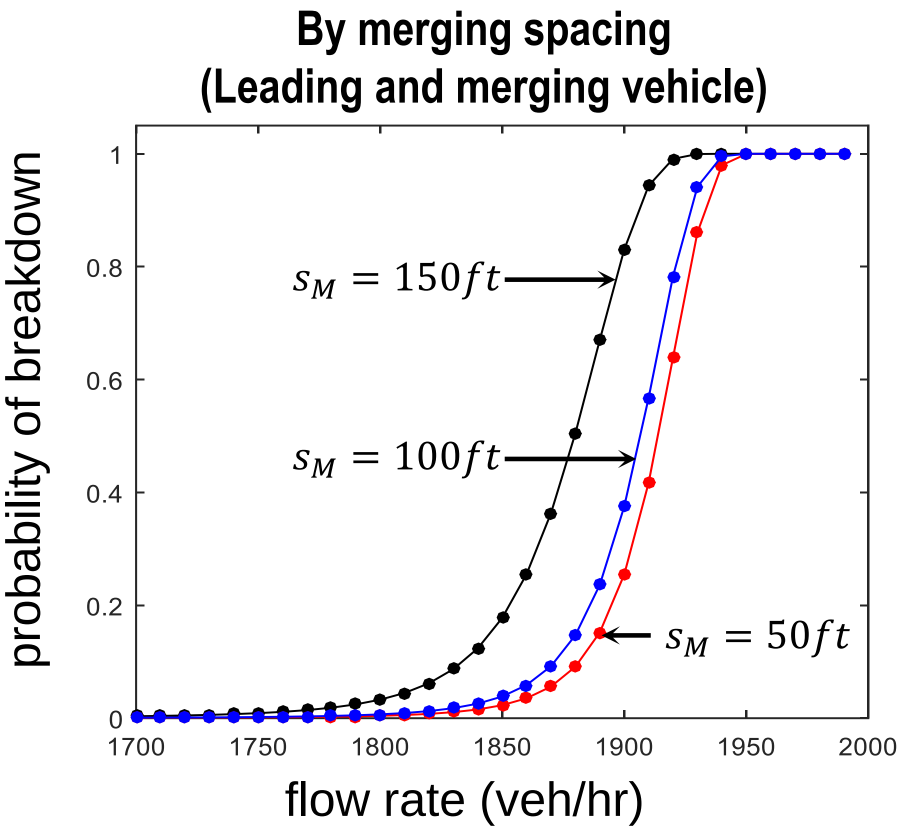
- ✓ Higher mainline flow → Severe trigger, Higher prob. propagation → Higher prob. breakdown
- ✓ Higher merge flow rate → Higher prob. propagation → Higher prob. breakdown

(Shorter merging interval → Fewer vehicles to resolve disturbance)

MODEL PROPERTIES

Effects of Merging behavior





MECHANISM

- ✓ High merging speed → Mild trigger → Low breakdown
- ✓ Small merging spacing (close to leading vehicle) → Mild trigger → Low breakdown

MODEL PROPERTIES

Effects of Driver Characteristics

Effect of Driver characteristic (τ)

- Trigger (magnitude of v_{tr} and t_{tr}) is affected by τ_F
- Propagation is affected by $E(\tau)$

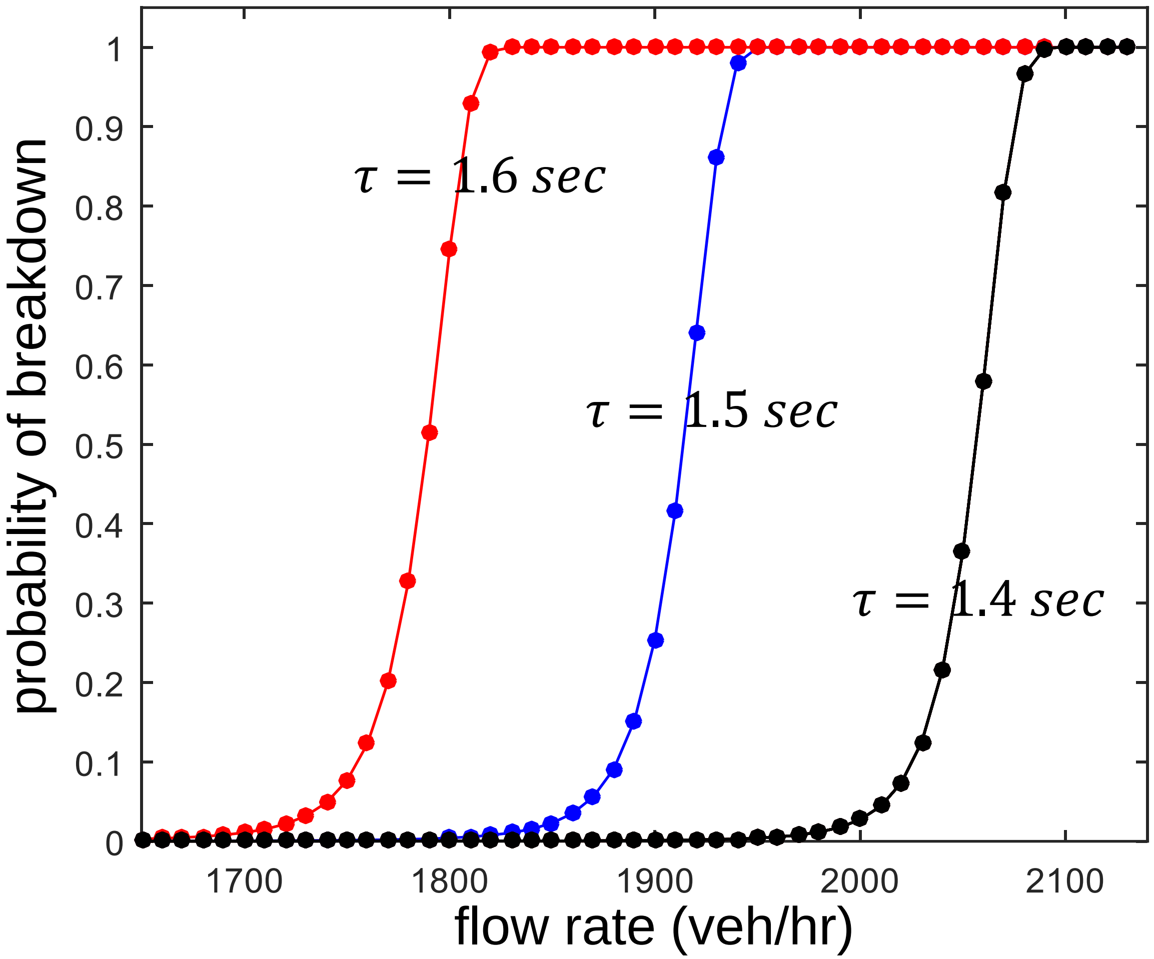
MECHANISM

✓ Small $E(\tau)$ (aggressive driver)

→ Mild trigger, Low prob. propagation

→ Low breakdown

Effects of $E(\tau)$



INSIGHTS FOR TRAFFIC CONTROL

Contribution

Understand Breakdown Mechanisms → Insights for Control

Breakdown probability decrease with

1) Low flow rate (mainline, merging) ➔ *Demand & traffic management*
2) High merging speed ➔ *Geometric design*
3) Low deviation of headway ➔ *Controllable (proactive control)*
4) Low τ (aggressive driver) ➔ *Connected automated vehicle*

PROACTIVE VSL CONTROL

Contribution

Decrease Breakdown Probability without Propagated Congestion

Discuss for VMS

- Required at low CV penetration to control regular vehicles

⬇

- Phase-out with CV penetration increasing

ONGOING WORKS

Model Validation

Parameters		From
Free flow speed	u	Trajectory or Historical data (free flow state)
Wave speed	w	Trajectory or Literature
Headway distribution	$p(h)$	Trajectory or Detector data
Average tau	$E(\tau)$	Trajectory or Literature
Merge flow rate	q_M	Historical data
Merge headway distribution	$p(t_M)$	Trajectory data
Merge speed	v_{in}	Trajectory data
Acceleration rate	a	Trajectory data
Merge spacing	s_M	Trajectory data

STOCHASTIC BREAKDOWN MODEL

Results / Features

- Develop model to link microscopic behavior to breakdown probability
- Increases with flow rate (S-shape)

  → Consistent with previous result
- General model to incorporate other factors as well as flow rate

  (→ Next Chapter)