

CIVE 440

Traffic Engineering and Simulation – Traffic Flow Theory



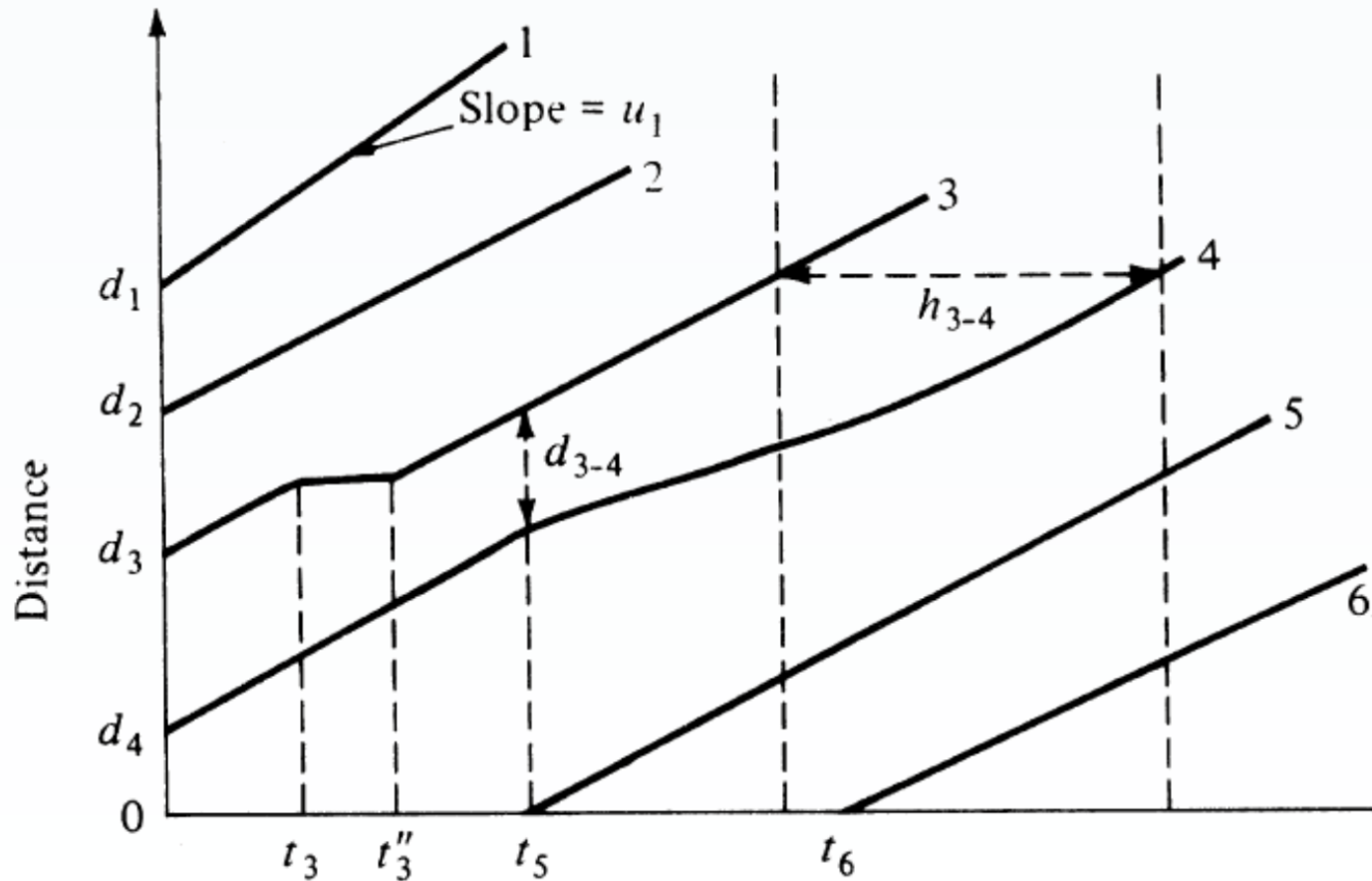
McGill

Faculty of Engineering

Department of Civil Engineering and Applied Mechanics

Fall 2016

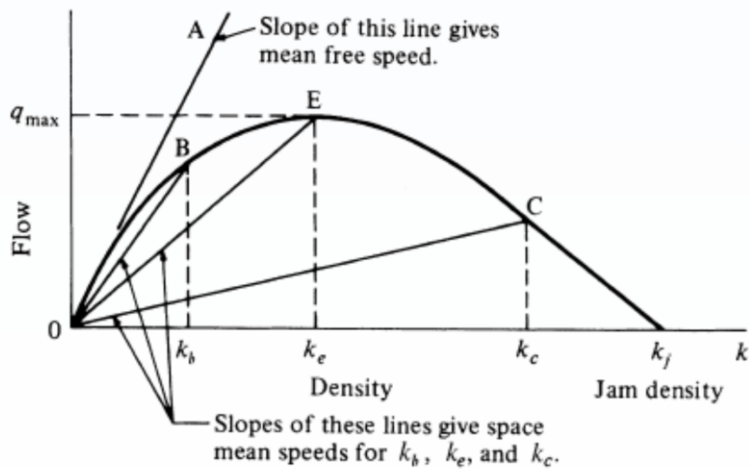
TIME SPACE DIAGRAM



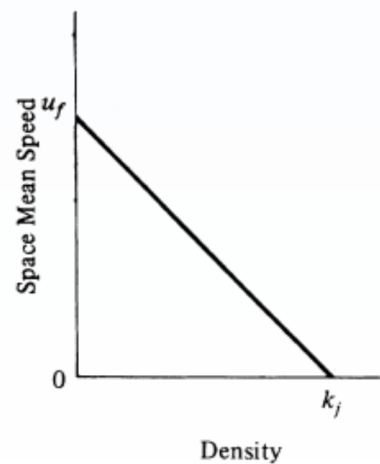
MACROSCOPIC TRAFFIC FLOW

Recall, we have macroscopic flow measures:

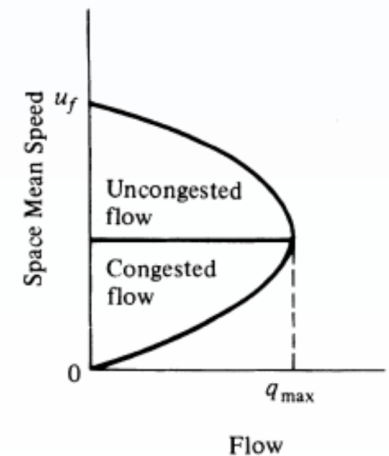
- Flow q (veh/h)
- Density k (veh/km)
- [Aggregated] speed v (km/h)



(a) Flow versus density



(b) Space mean speed versus density



(c) Space mean speed versus volume

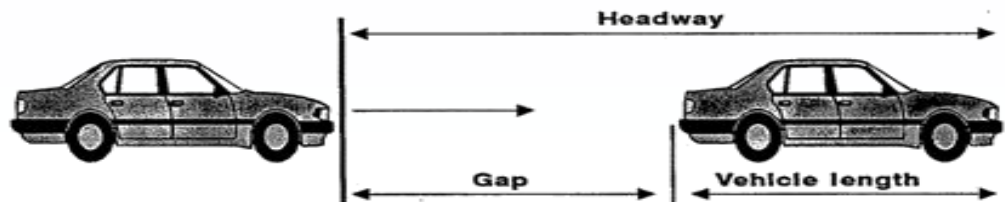
MICROSCOPIC TRAFFIC FLOW

But we also have microscopic flow measures:

- Headway h (s) / spacing s (m)
- Gap g (s) / clearance c (m)
- [Instantaneous] speed v (km/h)

$$\bar{s} = \frac{\text{distance}}{n} \approx \frac{1}{k}$$

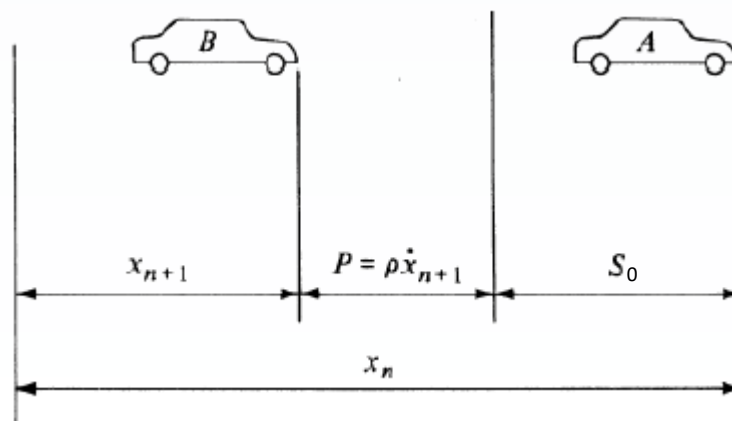
$$\bar{h} = \frac{\text{time}}{n} \approx \frac{1}{q}$$



CAR FOLLOWING

Consider two vehicles A and B on a single lane of highway (see figure)

- Let us denote n th vehicle as the lead vehicle (A) and $(n + 1)$ as the following vehicle (B)
- We denote the position of n (A) and $n + 1$ (B) with x_n and x_{n+1} respectively

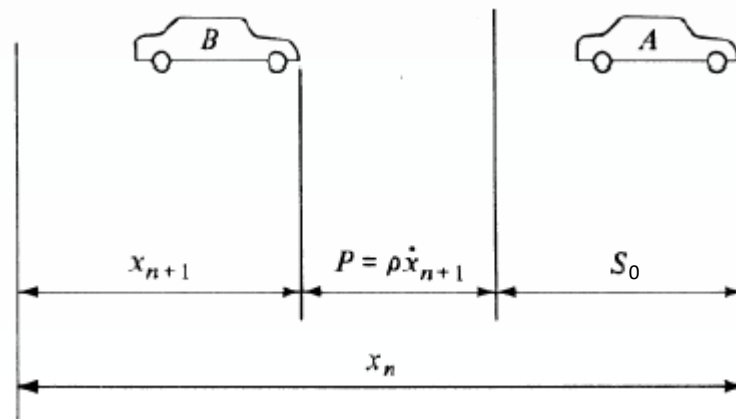


Driver $n + 1$ (B) will try to maintain a *desired* following distance of P behind the spacing S_0 of vehicle n (A).

$$P = \rho \dot{x}_{n+1}$$

where $\rho =$ factor of proportionality (speed-distance)

$\dot{x}_{n+1} =$ speed of the $(n + 1)$ th vehicle

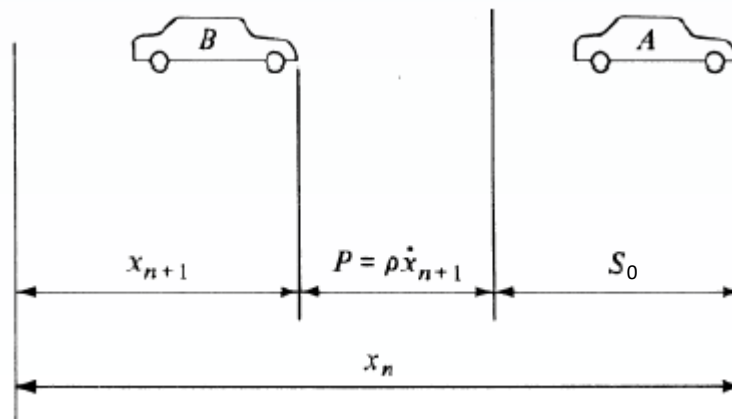


The spacing S_0 is the spacing between vehicles at rest (minimum spacing for safety/maneuverability when stationary). The ordinary spacing s is thus:

$$S = x_n - x_{n+1} = \rho \dot{x}_{n+1} + S_0$$

Differentiating for acceleration:

$$\ddot{x}_{n+1} = \frac{\dot{x}_n - \dot{x}_{n+1}}{\rho}$$

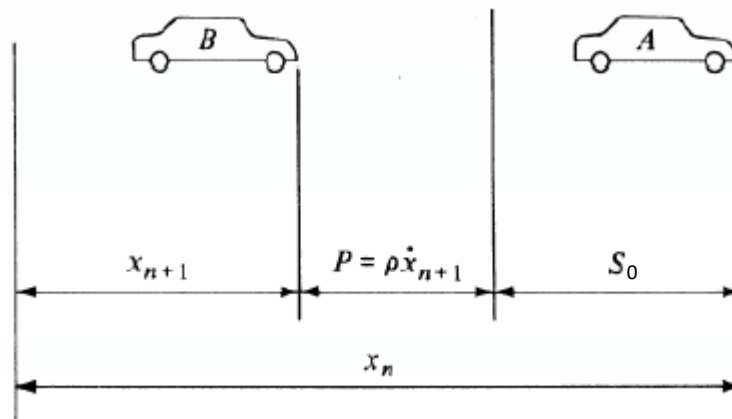


x_{n+1}'' represents the acceleration response to the changes in n th vehicle.

- However, in reality there is a driver time lag T for this response (i.e. reaction time)

$$x_{n+1}''(t + T) = \lambda(x_n'(t) - x_{n+1}'(t))$$

where $\lambda = \frac{1}{\rho}$ inverse of proportionality, a.k.a. sensitivity



λ can also be modeled using:

$$\lambda = \frac{ax_{n+1}^{\dot{m}}(t + T)}{(x_n(t) - x_{n+1}(t))^{\iota}}$$

a , m and ι are model coefficients.

$$x_{n+1}^{\ddot{}}(t + T) = \frac{ax_{n+1}^{\dot{m}}(t + T)}{(x_n(t) - x_{n+1}(t))^{\iota}} (x_n^{\dot{}}(t) - x_{n+1}^{\dot{}}(t))$$

The above equation can be used to determine the velocity, flow, and density of a traffic stream in steady state. Solve for acceleration, then integrate for speed and position!

Using $m = 0$ and $\iota = 1$:

$$\lambda = \frac{a}{x_n(t) - x_{n+1}(t)}$$

$$x_{n+1}^{\ddot{}}(t + T) = \frac{a(x_n^{\dot{}}(t) - x_{n+1}^{\dot{}}(t))}{x_n(t) - x_{n+1}(t)}$$

Integrate...

$$x_{n+1}^{\dot{}}(t + T) = a \ln(x_n(t) - x_{n+1}(t)) + C$$

Assuming steady state (behaviour of individuals = behaviour of mean)...

$$v = a \ln\left(\frac{1}{k}\right) + C$$

Recall the speed-density relationship:

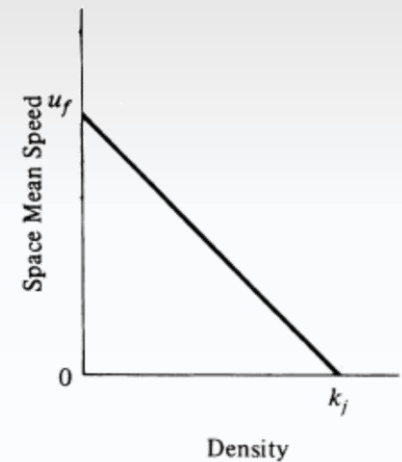
$$0 = a \ln \left(\frac{1}{k_j} \right) + C$$

$$C = -a \ln \left(\frac{1}{k_j} \right)$$

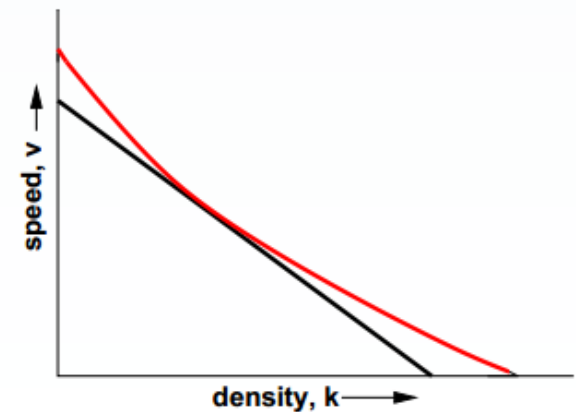
Substituting C back into the model:

$$v = v_0 \ln \left(\frac{k_j}{k} \right)$$

This is **Greenberg's** model!



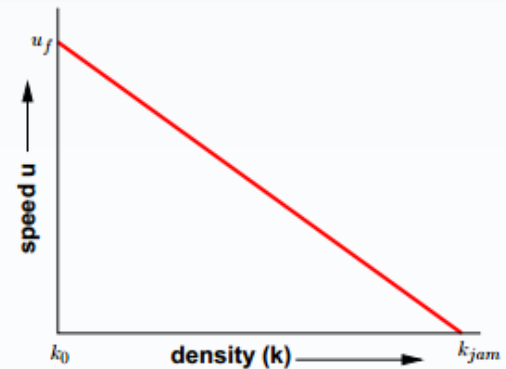
(b) Space mean speed versus density



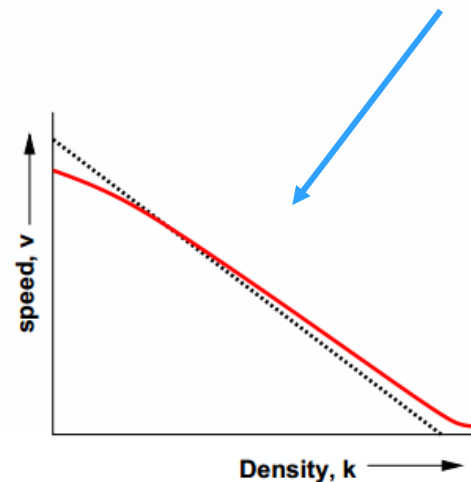
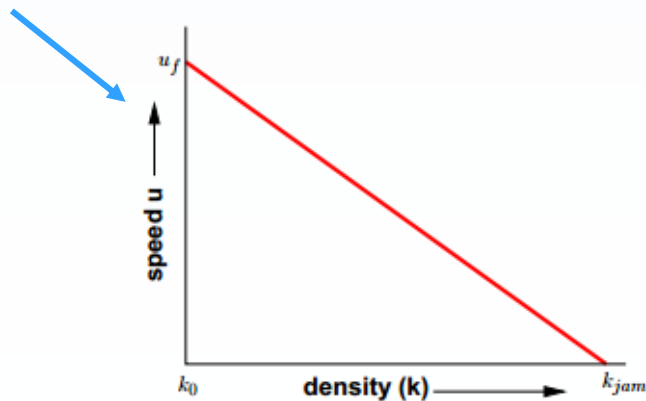
Using $m = 0$ and $\iota = 2$ you obtain **Greenshield's** model.

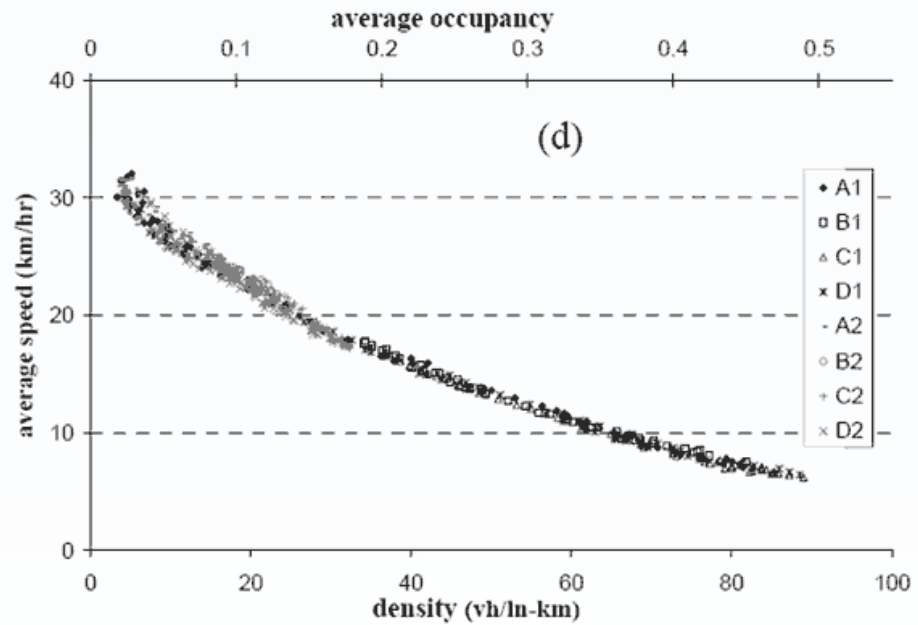
$$v = v_f \left(1 - \frac{k}{k_j} \right)$$

$$(k_o = \frac{1}{2} k_j, v_o = \frac{1}{2} v_f)$$



There are many more models including **Underwood's** and **Pipe's generalised** model.





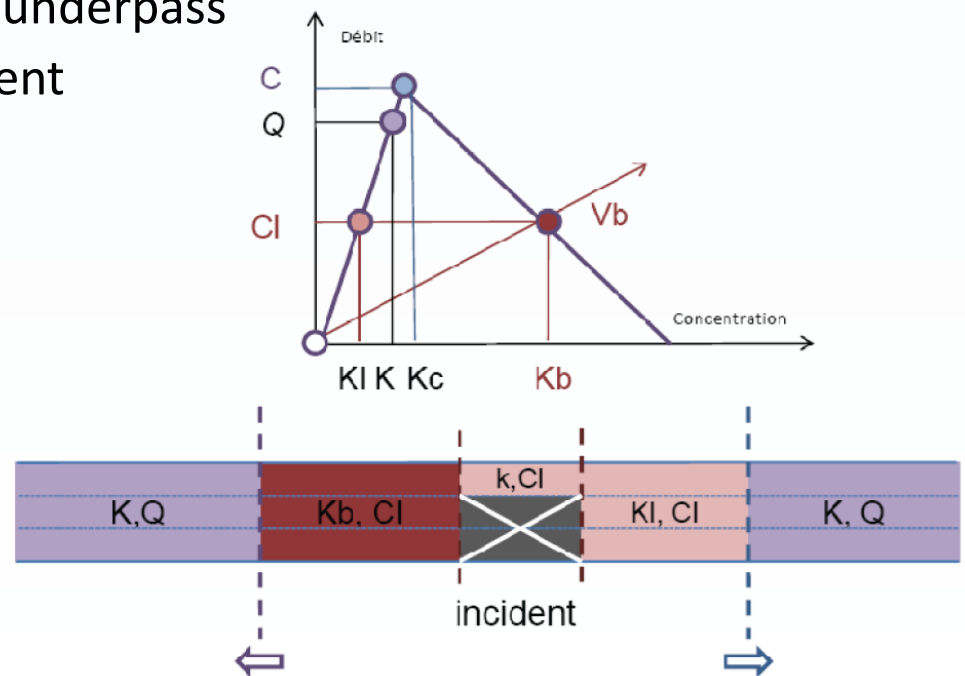
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SHOCKWAVES

Consider the case of two contiguous sections of highway with different capacities.

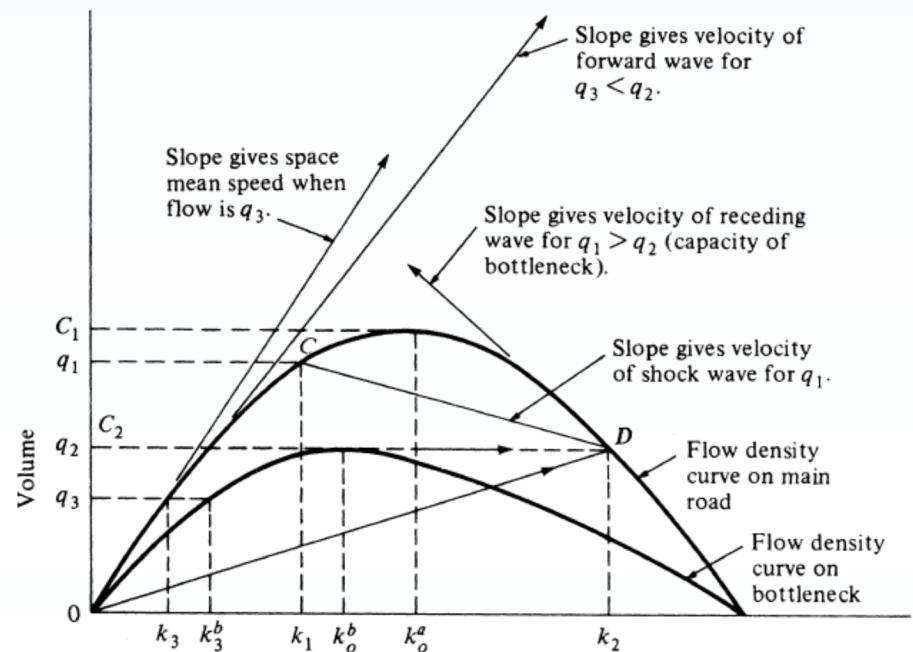
- This may be due to
 - an old, narrow bridge or underpass
 - or perhaps a traffic incident

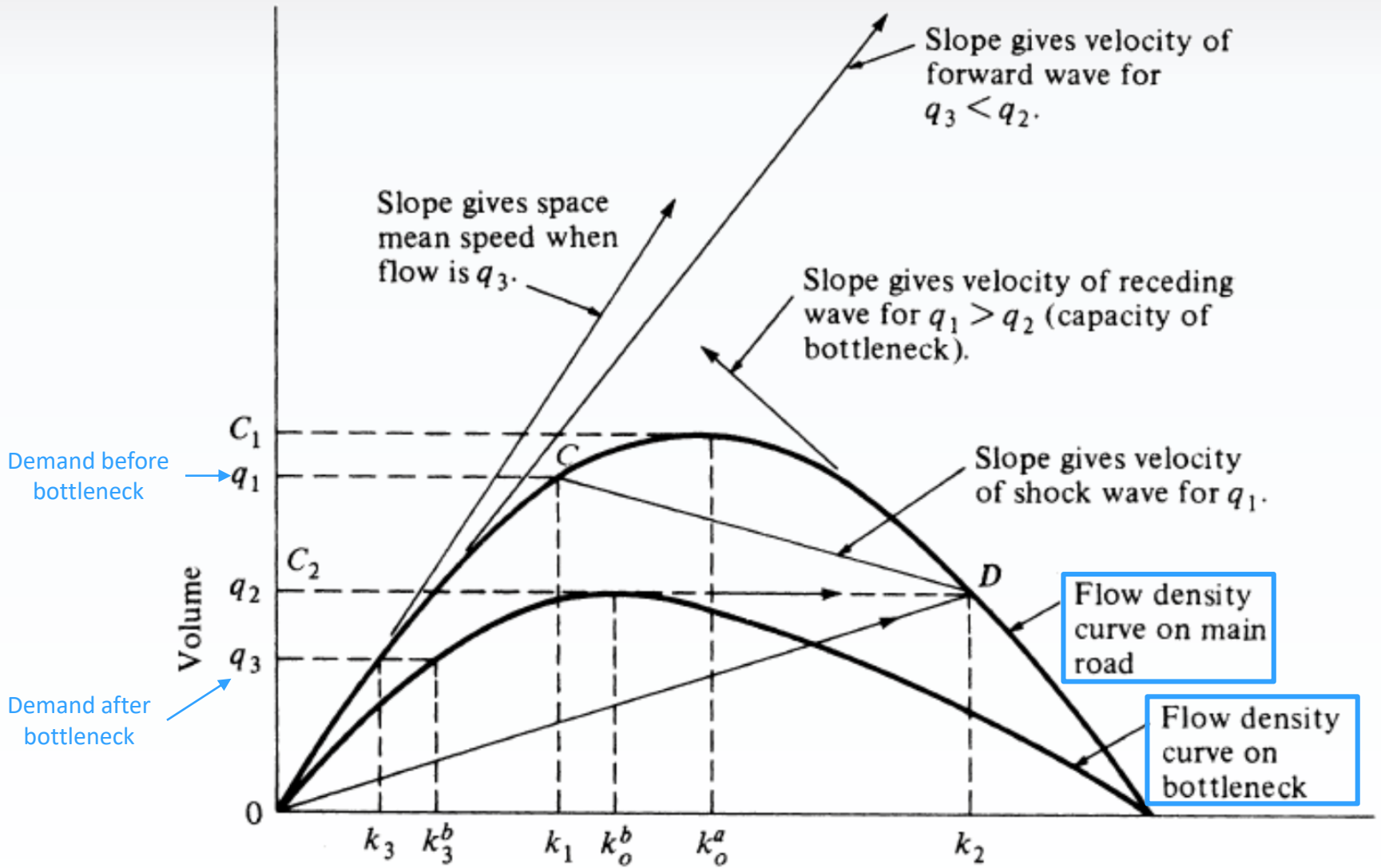
What happens?



A slowing down of incoming vehicles is formed.

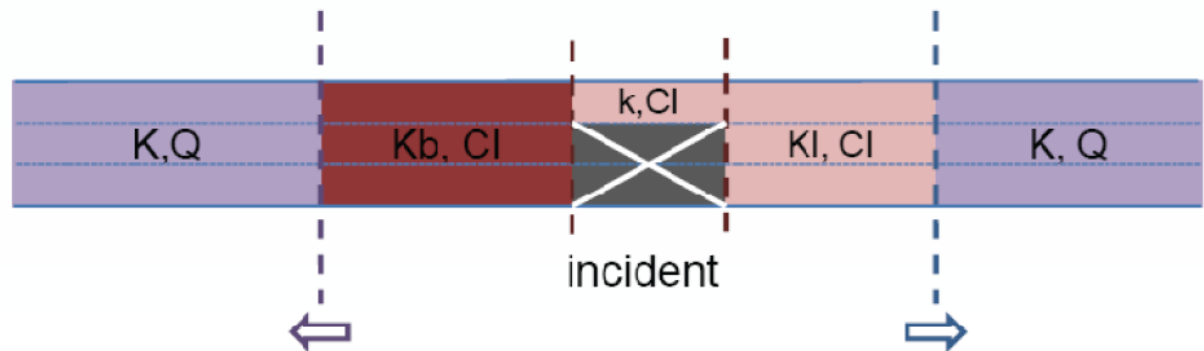
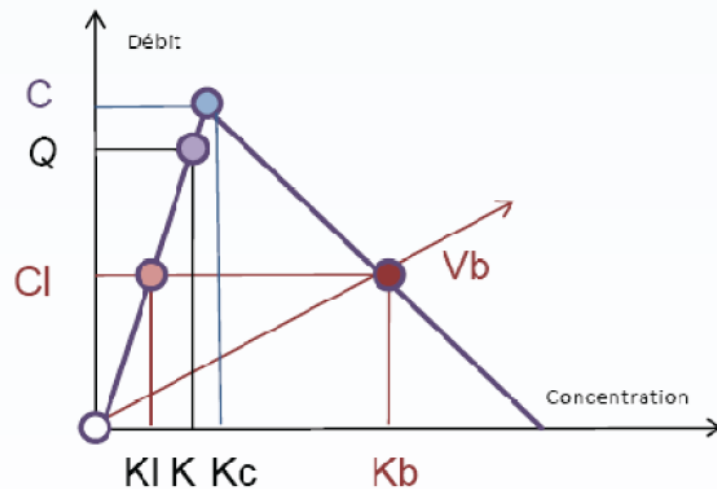
- This is the primary source of all ordinary highway congestion experienced.
- A shockwave propagates upstream where vehicles transition from **free-flow** to a **congested state**.
- So long as $Q_D > Q_C$ ($C1 > C2$), the wave will continue to propagate backwards as the length of the queue increases.
- Q_D will sooner or later decrease as drivers choose alternate routes or trip times.
 - Alternatively, Q_C may increase if corrective action is taken.





You may also notice a forward shockwave where the road ahead of the bottleneck is relatively empty.

- The capacity is typically larger than the inputs can possibly provide in the bottleneck downstream zone (by definition).
- $Q_D < Q_C$ ($C2 < C3$)



SHOCKWAVE TYPES

Frontal stationary:

- are formed when the capacity suddenly reduces to zero or at the source of the bottleneck
- for example, at a signalized intersection, the red signal indicates that traffic on the approach or set of lanes cannot move across the intersection.

Backwards forming shockwave:

- are formed when the capacity is reduced below the demand flow rate resulting in the formation of a queue upstream of the bottleneck.
- the shock wave moves upstream from the bottleneck, creating a queue.

SHOCKWAVE TYPES

Forwards moving shockwave:

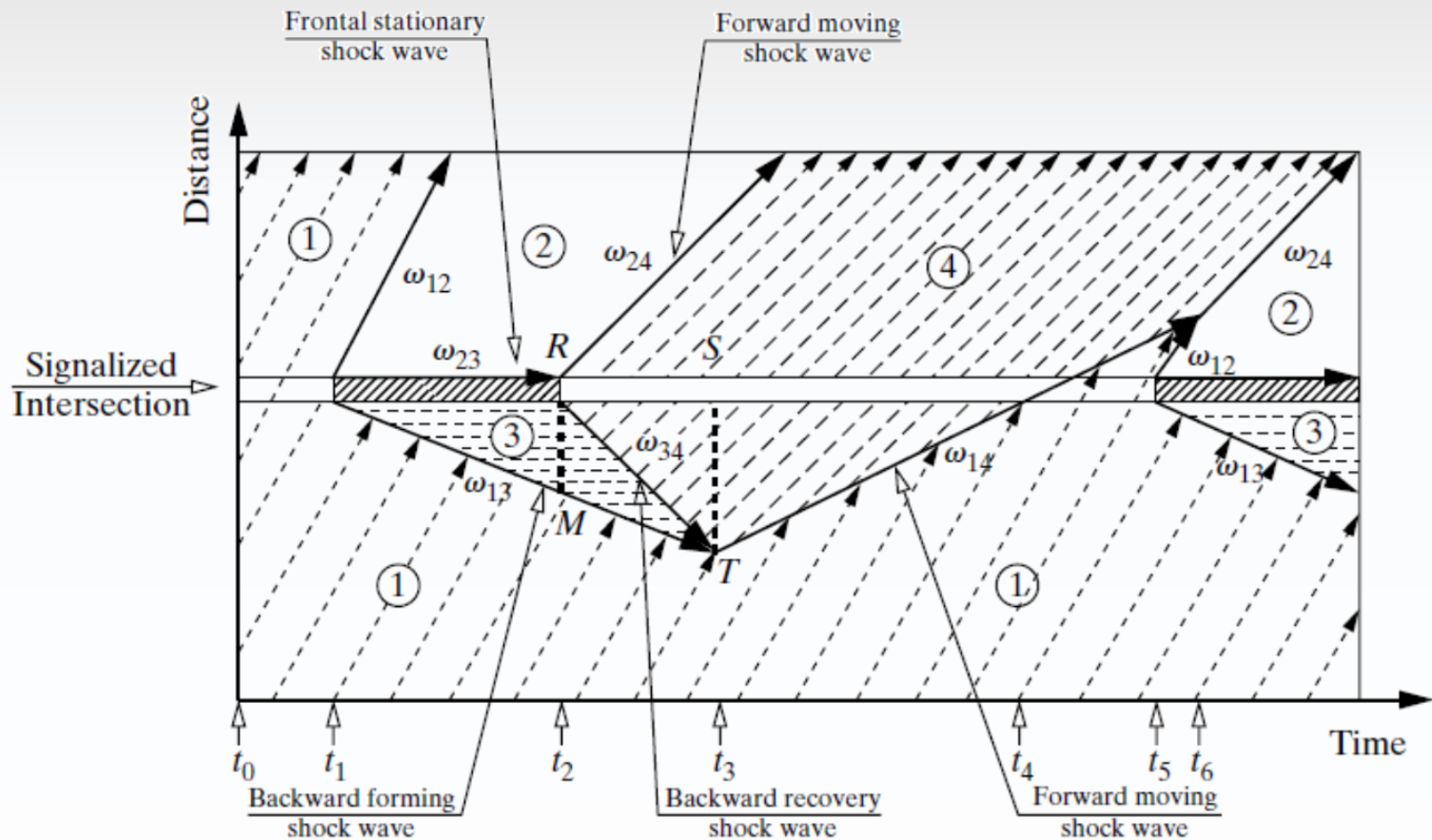
- are usually formed when a capacity suddenly decreases or demand suddenly increases.
- this is the propagation of the new traffic state downstream of a bottleneck.

Note that queues always incorporate two of the above shockwaves at either end of the queue.

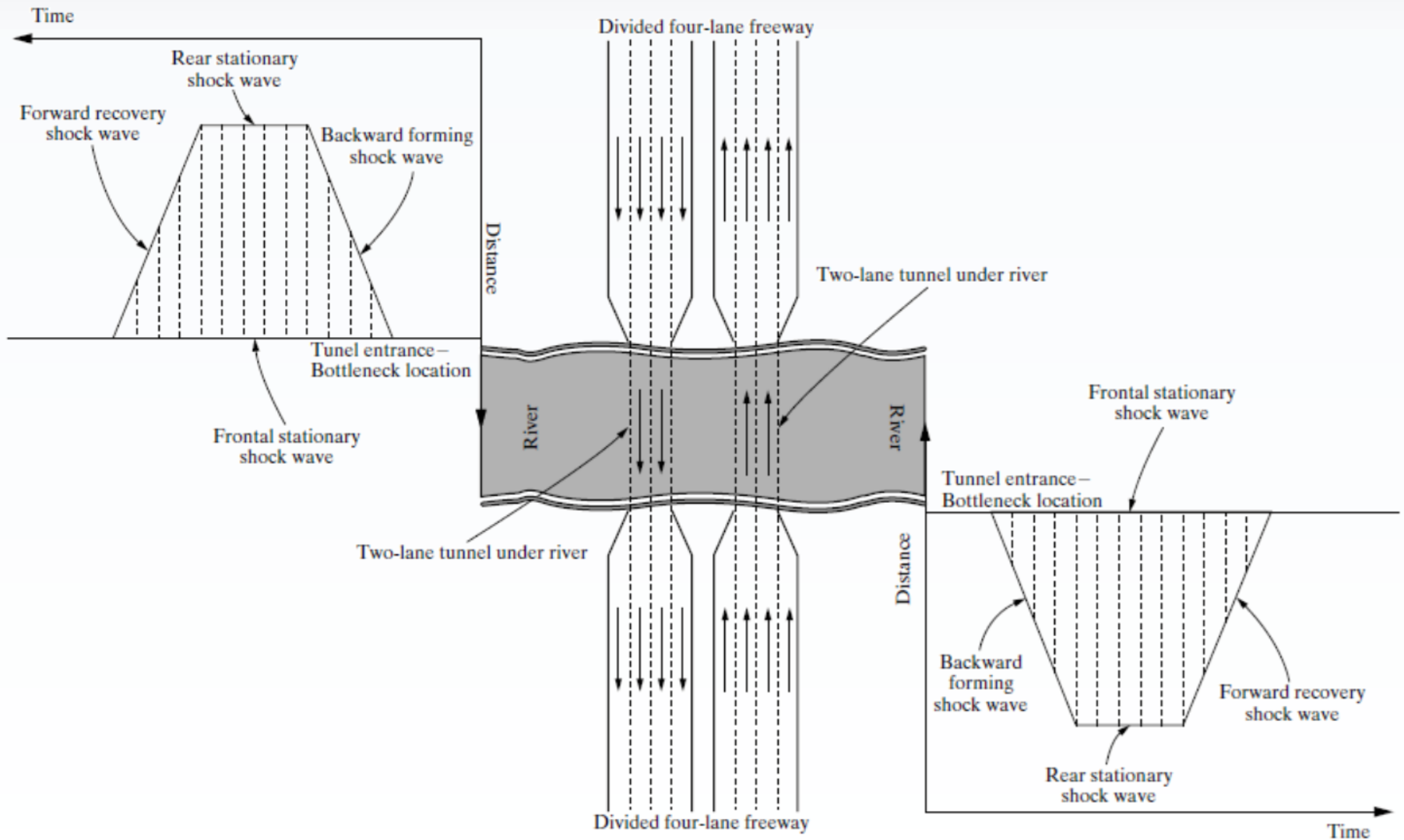
- A new pair of shockwaves is formed every time demand or capacity changes.

Also note that some bottlenecks are not stationary

- E.g. slow moving truck hogging lanes.



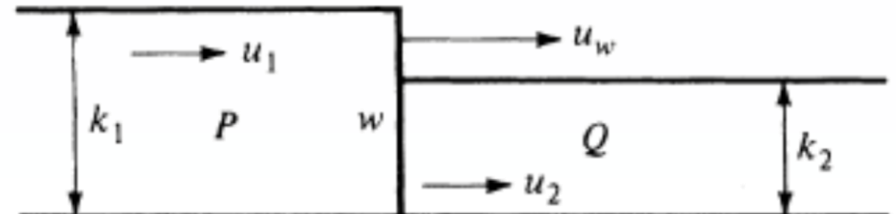
- Section 1 – free flow traffic
- Section 2 – no traffic
- Section 3 – stopped traffic behind stop light
- Section 4 – flow at capacity



SHOCKWAVE VELOCITY

Consider the scenario where the **shockwave w** is traversing from state 1 (u_1, k_1) to state 2 (u_2, k_2) with a velocity of u_w .

- The vehicles moving from state 1 to state 2 are the same, but the capacities on either side differ.
- Let's consider N_1 and N_2 as the volume of vehicles moving in these states – using conservation of flow.
- $N_1 = q_1 t$ and $N_2 = q_2 t ; N_1 = N_2$
- Relative speed of vehicles in 1 (just upstream of shockwave) = $u_2 - u_w$
- Similarly, $u_2 - u_w$



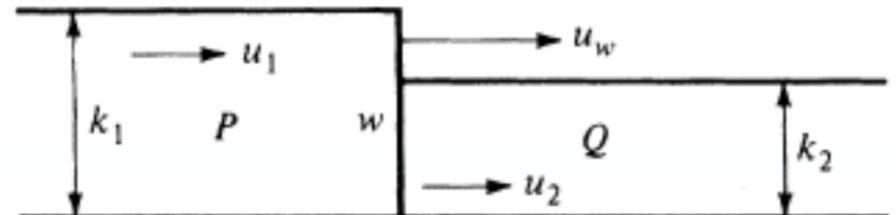
$$q_1 t = q_2 t$$

$$(u_1 - u_w)k_1 = (u_2 - u_w)k_2$$

$$u_w(k_2 - k_1) = q_2 - q_1$$

Rearrange:

$$u_w = \frac{q_2 - q_1}{k_2 - k_1}$$



In the specific case of traffic lights with corresponding regions (i.e. uniform, unsaturated flow):

Maximum queue length:

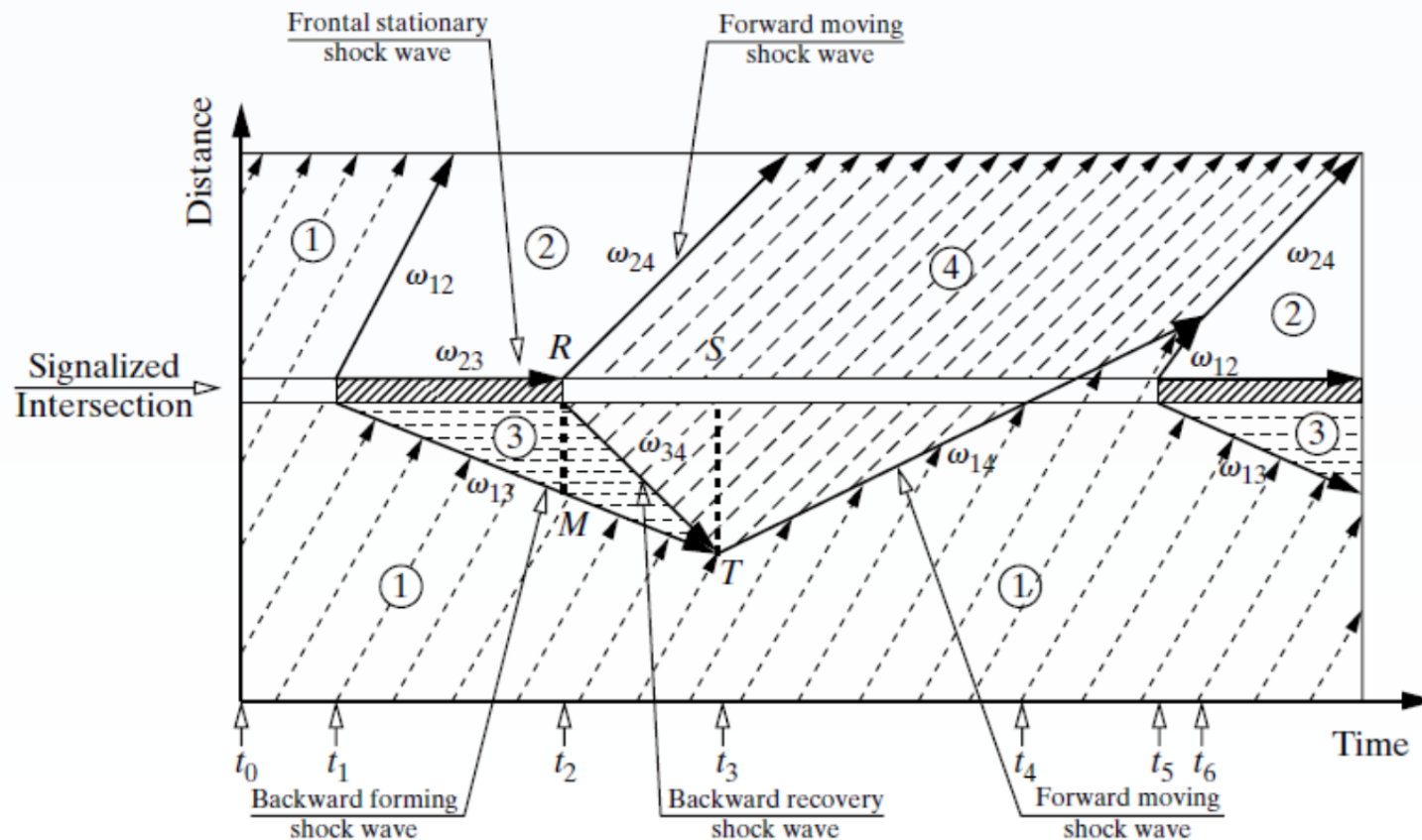
$$ST = \frac{r \omega_{34} \omega_{13}}{(\omega_{34} - \omega_{13})}$$

Queue dissipation time from start of green:

$$RS = \frac{r \omega_{13}}{(\omega_{34} - \omega_{13})}$$

EXAMPLE

Calculate the shockwave speeds in this example.



EXAMPLE

The southbound approach of a signalized intersection carries a flow of 1000 veh/h/ln at a velocity of 80 km/h. The duration of the red signal indication for this approach is 15 sec. If the saturation flow is 2000 veh/h/ln with a density of 46.875 veh/km/ln, the jam density is 93.75 veh/km/ln, determine the following:

- **a.** The length of the queue at the end of the red phase.
- **b.** The maximum queue length.
- **c.** The time it takes for the queue to dissipate after the end of the red indication.

SHOCKWAVE SOURCES

Lane closure/removal:

- Incident (temporary)
- Bridge (permanent) or other form of urban bottleneck



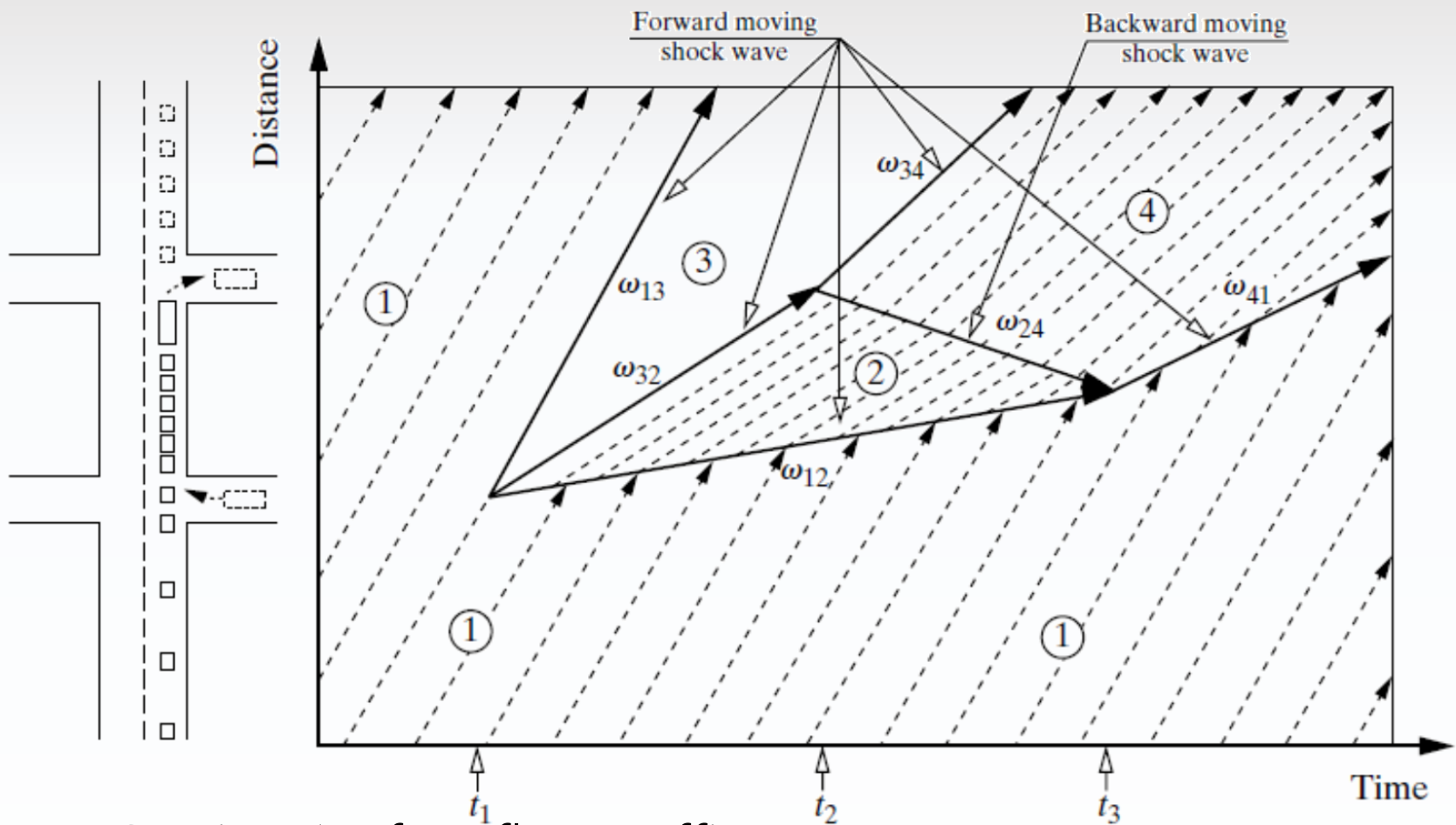
Traffic control:

- Traffic light (cyclical)
- Road gate (random), e.g. drawbridge.
- Toll booths, in a sense.

Traffic flow:

- Sources of traffic friction and safety headways may reduce capacity
- Wide load vehicles and other slow-moving vehicles





- Section 1 – free flow traffic
- Section 2 – following vehicles
- Section 3 – no traffic
- Section 4 – flow at capacity

EXAMPLE

The flow at a section of a two-lane highway is 1500 veh/h in each direction and the density=15.6 veh/km.

- A large dump truck loaded with soil from an adjacent construction site joins the traffic stream and travels at a speed of 16 km/h for a length of 4 km along the upgrade before turning off onto a dump site.
- It is impossible for any car to pass the truck.
- Vehicles just behind the truck therefore have to travel at the speed of the truck which results in the formation of a platoon having a density of 62.5 veh/km and a flow of 1000 veh/h.
- Determine how many vehicles will be in the platoon by the time the truck leaves the highway.

MULTI LANE STREAMS

Interaction of traffic as vehicles join, leave, or crosses a traffic stream.

- In controlled-access highways, ramp vehicles merge with the expressway stream.
- Freeway vehicles leaving the freeway onto frontage roads
- Changing of lanes by vehicles on a multilane highway
- In congested highways with a lane reduction, “zipper” merge is the normal etiquette.
 - Efficiency depends more on vehicle density than any particular merging scheme, though cutting in line is still considered rude and a great way to spark road rage.

LANE-CHANGE TYPES

Mandatory Lane Change (MLC): Mandatory lane change (MLC) occurs when a driver must change lane to follow a specified path.

- Suppose if a driver wants to make a right turn at the next intersection the he changes to the right most lane which is referred as Mandatory Lane change.



LANE-CHANGE TYPES

Discretionary Lane Change (DLC): Discretionary lane change (DLC) occurs when a driver changes to a lane perceived to offer better traffic conditions, he attempts to achieve desired speed, avoid following trucks, avoid merging traffic, etc.

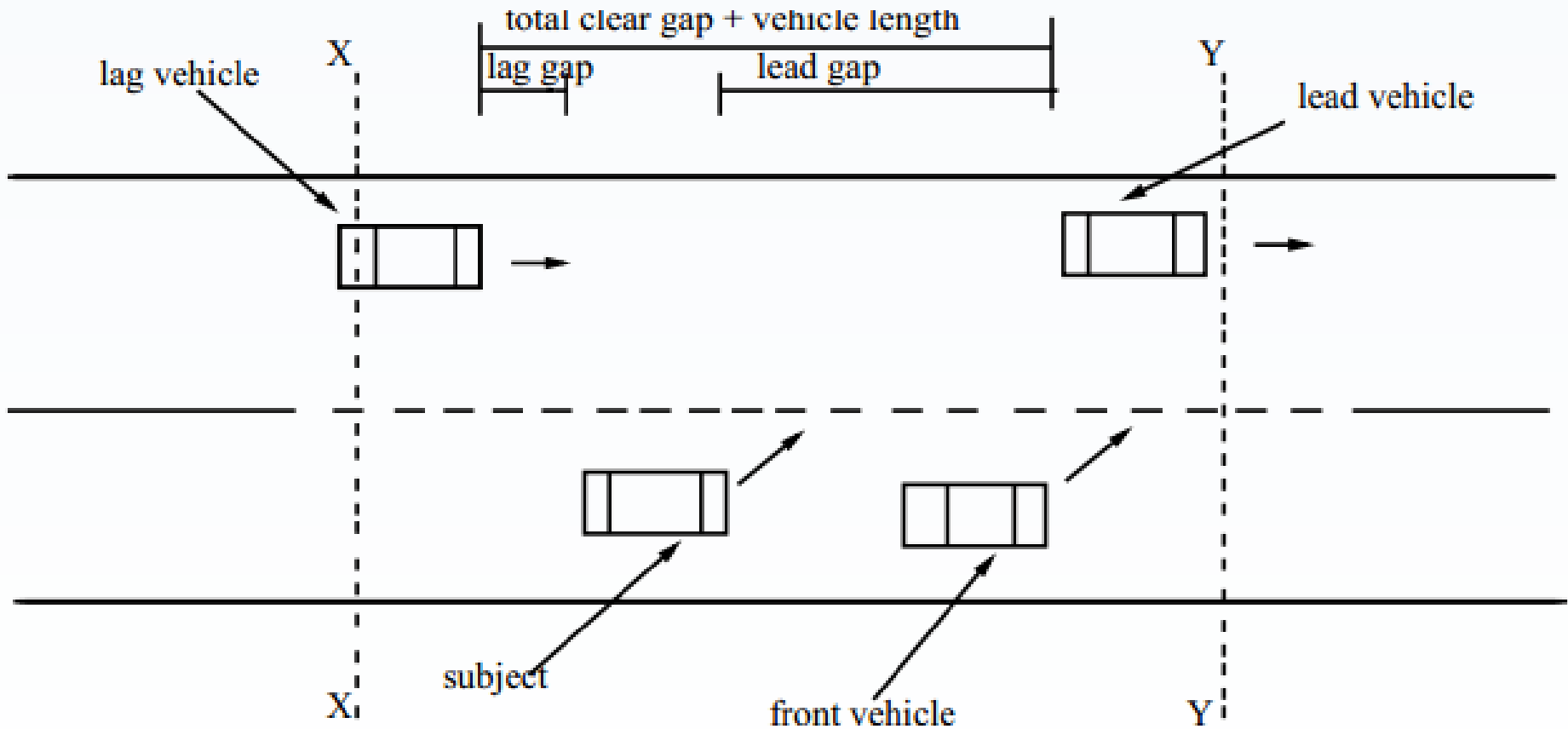
- Suppose if a driver perceives better driving conditions in the adjacent lane then he makes a Discretionary Lane change.



GAP

During a lane change, a vehicle looking to change lanes will first look for a suitable gap.

- In engineering terms, this gap is defined by the lead gap and the lag gap.
 - The **lead gap** is the spacing (expressed in seconds) between the hood of the merging vehicle and the rear bumper of the next forward car in the target lane.
 - The **lag gap** is the spacing (expressed in seconds) between the rear bumper of the merging vehicle and the hood of the next rear car in the target lane.
- The lead and lag gap are buffer zones between vehicles for safety.
 - Under stress or difficulty navigating a congested route, these gaps will often be reduced temporarily from ordinary following distances.



http://nptel.ac.in/courses/105101008/downloads/cete_15.pdf

MINIMUM GAP TIME

The critical (minimum) [forward] gap time for vehicle n at time step t is given by:

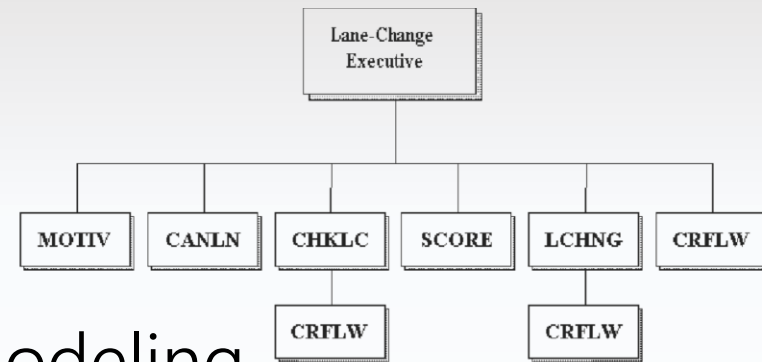
$$G_n^{g,cr}(t) = e^{X_n^g(t)\beta + \alpha V_n + \varepsilon_n}$$

Where ε_n = the random term follows log normal distribution

α = the parameter of driver specific random term V_n

http://nptel.ac.in/courses/105101008/downloads/cete_15.pdf

LANE-CHANGE EXECUTIVE



Six-step lane-change decision modeling.

- to determine whether lane change is considered or not (MOTIV)
- to check if either neighboring lanes are possible candidates for lane change (CANLN)
- to check lane change is feasible now (CHKLC)
 - safety constraint on lead and lag gap:
 - $P(G) = P(G_{lead} > G_{lead}^{cr}) \times P(G_{lag} > G_{lag}^{cr})$
- if both sides of are feasible candidates for lane change then score module will weigh the options (SCORE)
- execute the lane change (LCHNG)
- continue in car following mode (CRFLW)

For each vehicle, I:

```
CALL routine MOTIV to determine whether this driver is "motivated" to change lanes, now
IF so, THEN
    CALL routine CANLN to identify which of neighboring lanes (if either) are
        acceptable as potential target lanes
    IF the lane to the right is acceptable, THEN
        CALL routine CHKLC to determine whether a lane-change is feasible, now.
        Set flag if so.
    ENDIF
    IF the lane to the left is acceptable, THEN
        CALL routine CHKLC to determine whether a lane-change is feasible, now.
        Set flag, if so.
    ENDIF
    IF both lane-change flags are set (lane-change is feasible in either direction), THEN
        CALL routine SCORE to determine more favorable target lane
    ELSE IF one lane-change flag is set, THEN
        Identify that lane
    ENDIF
    IF a [favored] target lane exists, THEN
        CALL routine LCHNG to execute the lane-change
        Update lane-change statistics
    ELSE
        CALL routine CRFLW to move vehicle within this lane
        Set vehicle's process code (to indicate vehicle has been moved this time-step)
    ENDIF
ELSE (no lane-change desired)
    CALL routine CRFLW to move vehicle within its current lane
    Set vehicle's process code
ENDIF
```

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That's all for today!