Chapter 5
Traffic Flow Characteristics
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1. Introduction

- It is aimed to examine the flow of vehicles moving individually or in groups on a roadway or track, subject to constraints imposed by human behavior and vehicle dynamics.
- At the present time, there is no unified theory of traffic flow, much of the knowledge currently available in this field is largely empirical.
2. The Nature of Traffic Flow

- Traffic flow is a complex phenomenon, and a stochastic process, with random variations in vehicles and driver characteristics and their interactions.
- Relationship between traffic flow and speed
- Deterministic models vs. stochastic models
3. Approaches to Understanding Traffic Flow

- Three main approaches to the understanding and quantification of traffic flow:
  - Macroscopic approach: it looks at the flow in an aggregate sense.
  - Microscopic approach: it considers the response of each individual vehicle in a disaggregate manner.
  - Human-factor approach: it seeks to define the mechanism by which an individual driver (and his or her vehicle) locates himself or herself with reference to other vehicles and to the highway/guidance system.
4. Parameters Connected with Traffic Flow

- There are at least eight basic variables or measures used in describing traffic flow.
- The three primary variables are speed ($v$), volume ($q$), and density ($k$).
- Three other variables used in traffic flow analysis are headway ($h$), spacing ($s$), and occupancy ($R$).
- The corresponding measures of spacing and headway are two parameters: clearance ($c$) and gap ($g$).
\textbf{Speed}

- Speed is defined as a rate of motion, as distance per unit time, generally in miles per hour \((mph)\) or kilometers per hour \((km/hr)\).
- Because there is a broad distribution of individual speeds in a traffic stream, an average travel speed is considered.
Space mean speed ($v_s$)

- If the travel times $t_1$, $t_2$, ..., $t_n$, are observed for $n$ vehicles traversing a segment of length $L$, the average travel speed is:

$$v_s = \frac{L}{\sum_{i=1}^{n} \frac{t_i}{n}} = \frac{nL}{\sum_{i=1}^{n} t_i}$$

where

$v_s$ = space mean speed (mph)
$L$ = length of the highway segment (miles)
$t_i$ = travel time of the $i^{th}$ vehicle to traverse the section (hours)
$n$ = number of travel times observed
Time mean speed ($v_t$)

- This is the arithmetic mean of the measured speeds of all vehicles passing a fixed roadside point during a given interval of time, in which case, the individual speeds are known as “spot” speeds.
- The time mean speed is defined as follows:

$$v_t = \frac{\sum_{i=1}^{n} v_i}{n}$$

where $v_i$ is the spot speed, and $n$ is the number of vehicles observed.
It can be shown that whereas the time mean speed is the arithmetic mean of the spot speeds, the space mean speed is their harmonic mean.

Time mean speed is always greater than space mean speed except in the situation where all vehicles travel at the same speed.
Relationship between space mean speed and time mean speed:

\[ v_t = v_s + \frac{\sigma_s^2}{v_s} \quad v_s = v_t - \frac{\sigma_t^2}{v_t} \]

where \( \sigma_s^2 \) is the variance of the space mean speeds.
Volume and rate of flow

- Volume is the actual number of vehicles observed or predicted to be passing a point during a given time interval.
- The rate of flow represents the number of vehicles passing a point during a time interval less than 1 hour, but expressed as an equivalent hourly rate.
Density or concentration

- Density is defined as the number of vehicles occupying a given length of lane or roadway, averaged over time, usually expressed as vehicles per mile (veh/mi), and it is a critical parameter in describing freedom of maneuverability.
- Direct measurement of density can be obtained through aerial photography, but more commonly it is calculated from the following equation:

\[ q = v \times k \]

where,

- \( q \) = rate of flow (veh/hr)
- \( v \) = average travel speed (mph)
- \( k \) = average density (veh/mi)
Spacing and headway

- Spacing (s) is defined as the distance between successive vehicles in a traffic stream as measured from front bumper to front bumper.
- Headway is the corresponding time between successive vehicles as they pass a point on a roadway.
- Both spacing and headway are related to speed, flow rate, and density.
- Spacing (s) of vehicles can be observed from aerial photographs, and headways of vehicles can be measured using stopwatch observations as vehicles pass a point on a lane.
- Relationships of spacing, headway, and $q$, $k$, $v$

  - Avg. density ($k$), $\text{veh/mi} = \frac{5280 \text{, ft/mi}}{\text{avg spacing (s), ft/veh}}$

  - Avg. headway ($h$), $\text{sec/veh} = \frac{\text{avg spacing (s), ft/veh}}{\text{avg speed (v), ft/sec}}$

  - Avg. flow rate ($q$), $\text{veh/hr} = \frac{3600 \text{, sec/hr}}{\text{avg headway(h), sec/veh}}$
**Lane occupancy**

- Lane occupancy is a measure used in freeway surveillance.
- If one could measure the lengths of vehicles on a given roadway section and compute the following ratio, then $R$ could be divided by the average length of a vehicle to give an estimate of the density ($k$).

$$R = \frac{\sum L_i}{D}$$
• *Lane occupancy* (LO) can also be described as the ratio of the time that vehicles are present at a detection station in a traffic lane compared to the time of sampling.

• LO can be expressed through the following equation:

\[
LO = \frac{\sum t_0}{T}
\]
Speed obtained from loop detector
- Space mean speed can be obtained by measuring the time duration of a vehicle passing through a loop detector.
- It can be expressed through the following equation:

\[ t_0 = \frac{L + C}{v_s} \quad \text{or} \quad v_s = \frac{L + C}{t_0} \]

where \( L \) is the average length of the vehicle, and \( C \) is the distance between the loop of the detector.
Illustration of the use of a detector in traffic engineering work

![Diagram of traffic engineering work](image)

- $L =$ Length of vehicle
- $C =$ Distance between loops of detector

**Figure 5-1** Loop Detector.
The effective length of a vehicle as measured by the detector in use to calculate lane occupancy by the following expression:

\[ k = \frac{LO \times 5280}{L + C} \]

In most cases, the detector is actuated as soon as the front bumper crosses the detector and remains on until the rear bumper leaves the detector.
Clearance and gap

- Clearance and gap correspond to parameters of spacing \((ft)\) and headway \((sec)\).
- The difference between spacing and clearance is obviously the average length of a vehicle in feet.
- Similarly, the difference between headway and gap is the time equivalence of the average length of a vehicle \((L/v)\).
Relationships of clearance-gap and spacing-headway

\[ g = h - \left( \frac{L}{v} \right) \quad \text{and} \quad c = g \times v \]

where,

- \( g \) = mean gap (sec)
- \( L \) = mean length of vehicles (ft)
- \( c \) = mean clearance (ft)
- \( h \) = mean headway (sec)
- \( v \) = mean speed (ft/sec)
Clearance-Gap and Spacing-Headway Concept

![Diagram showing clearance-gap and spacing-headway concept.](image)

**Figure 5-2** Clearance-Gap and Spacing-Headway Concept.
5. Categories of Traffic Flow

- Vehicle flow on transportation facilities may be generally classified into two categories:
  - *Uninterrupted flow*: it can occur on facilities that have no fixed elements, such as traffic signals, external to the traffic stream, that cause interruptions to traffic flow.
  - Interrupted flow: it occurs on transportation facilities that have fixed elements causing periodic interruptions to traffic flow. Such elements include traffic signals, stop signs, and other types of controls.
Uninterrupted and interrupted flow are terms that describe the facility and not the quality of flow.

- Internal vs. external elements
- Multi-lane and two-lane highways may also operate with almost uninterrupted flow, especially in long segments between points of fixed interruptions, such as segments where signal spacing exceeds 2 miles.
## Types of Transportation Facilities

<table>
<thead>
<tr>
<th>Table 5-1 Types of Transportation Facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Uninterrupted flow</strong></td>
</tr>
<tr>
<td>Freeways</td>
</tr>
<tr>
<td>Multilane highways</td>
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<tr>
<td>Two-lane highways</td>
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<tr>
<td><strong>Interrupted flow</strong></td>
</tr>
<tr>
<td>Signalized streets</td>
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<tr>
<td>Unsignalized streets with stop signs</td>
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<tr>
<td>Arterials</td>
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<tr>
<td>Transits</td>
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<tr>
<td>Pedestrian walkways</td>
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<td>Bicycle paths</td>
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</table>
6. The Uninterrupted Traffic Flow Model

- The model can best be described by means of a typical speed-flow curve.
- Uninfluenced-flow (unforced-flow) region vs. forced-flow region
- Free-flow speed (point C) vs. maximum-density speed (point A)
- Capacity flow (point B)
Typical Speed-Flow Curve

Figure 5-3  Speed-Flow Curve.
If it is hypothesized that a linear relationship between the speed of traffic on an uninterrupted traffic lane and the traffic density (\textit{veh/mile}), then mathematically this relationship can be represented by:

\[ v = A - Bk \quad \text{or} \quad k = \frac{(v - A)}{-B} \]

where,

- \( v \) = mean speed of vehicles (\textit{mph})
- \( k \) = average density of vehicles (\textit{veh/mile})
- \( A, B \) = empirically determined parameters
Because the flow of an uninterrupted traffic stream is the product of the density and the speed, we have:

1) \( q = f(k) \quad q = kv = Ak - Bk^2 \) or

2) \( q = g(v) \quad q = kv = \frac{(v - A)v}{-B} = \frac{A}{B}v - \frac{v^2}{B} \)

At almost zero density, the mean free speed equals \( A \), and at almost zero speed, the jam density equals \( A/B \). The maximum flow occurs at about half the mean free speed and is equal to \( A^2/4B \).
Speed-Flow-Density Curves

Figure 5-4  Speed-Flow-Density Curves.
Flow-Density Curve

Figure 5-5  Flow-Density Curve.
Speed-Density and Speed-Flow Curves

**Figure 5-6** Speed-Density and Speed-Flow Curves.
Relationships between Mean Speed, Density, and Flow

**Figure 5-7** Curves Showing the Connections Between Mean Speed, Density, and Flow.

- Free flow
- Forced flow
- Maximum volume
- Jam density
8. Empirical Studies of Traffic Stream Characteristics

- Macroscopic Models for Traffic Flow
  - Greenshields’ Model
    - The general model connecting speed, flow, and density is a linear model proposed by Greenshields in 1935.
    - The evaluation of models proceeded along two lines:
      - Relationships of \( q-k-v \) were tested in terms of goodness of fit to actual field data.
      - Relationships were supposed to satisfy certain boundary conditions.
Greenberg’s Model

Greenberg (1959) developed a model taking speed, flow, and density measurements in Lincoln Tunnel resulting in a speed-density model, and used fluid-flow analogy concept, using the following form:

\[ v_s = C \ln\left( \frac{k_j}{k} \right) \]

- C is a constant, in fact C is the speed at maximum flow.
- Greenberg’s model shows better goodness-of-fit as compared to Greenshield’s model, although it violates the boundary conditions in that zero density can only be attained at an infinitely high speed.
General and Linear Speed-Density Relationship

- General speed-density relationship vs. linear speed-density relationship, and their corresponding traffic flow variables
- basic assumptions on speed-density relationships of the above two set of models: nonlinear vs. linear
General Speed-Flow-Spacing Relationship
General Speed-Flow-Spacing Relationship
Speed-Flow-Spacing-Density Relationship Based on Free Speed and a Linear Speed-Density Curve
**Diagram (b):**
- **Density at capacity** = \( \frac{1}{2} \) (jam density)
- Speed = Free
- DENSITY

**Diagram (c):**
- **DENSITY**
  - \( \frac{1}{3} \) (jam density)
- Parabola
- Flow

**Diagram (d):**
- **Spacing**
  - 2 (traffic jam)
  - Traffic jam
- Capacity
- Flow
- \( \frac{\text{Free} \times \text{jam density}}{4} \)
The Moving-Vehicle Estimation Method

- It consists of the following tasks:
  - making a series of runs in a test vehicle,
  - recording the number of vehicles that overtake the test vehicle,
  - the number of vehicles passed by the test vehicle, and
  - the travel time for the test vehicle.
9. Trajectory Diagrams

- aggregate behavior of vehicles in a traffic stream vs. the behavior of individual vehicles
- A trajectory diagram can provide individual vehicle behaviors.
- Each trajectory represents the movement through space and time of a particular vehicle, and the combination lines illustrates the interaction between vehicles.
- The slope of the trajectories are the speeds of vehicles.
- Such diagrams have wide applications in the study in platoon formation and dispersion, and the coordination of traffic.
Shock Waves and Bottlenecks

- “shock wave” – due to the geometric characteristics of roadway (e.g., uphill and downhill). Another “shock wave” – a decompression of traffic flow occurs.
- “shock wave” due to a bottleneck situation. A reverse “shock wave” may occur after vehicles have negotiated the bottleneck.
- “shock wave” due to traffic signal at an intersection.
Time-Space Diagram
Shock Wave Measurements
• Crawl speed: vehicles approaching the bottleneck are forced to reduce their speed to the maximum flow level of the bottleneck section.

• Wave velocity: the changes through the stream of vehicles travel at a velocity given by the following equation:

\[ u_w = \frac{dq}{dk} \]
The wave velocity can be represented by:

\[ u_w = \frac{q_B - q_A}{k_B - k_A} \]

- If the sign of the shock wave is positive, the wave is proceeding in the direction of the stream flow (downstream).
- If the sign of the shock wave is negative, the shock wave is moving against the stream flow (upstream).
- A stationary shock wave exists if \( u_w = 0 \).
Shock Wave Propagation

- assuming Greenshields’ traffic flow model, $v_f$ represents the mean free speed and $k_j$ is the jam density,

$$v_i = v_f \left(1 - \frac{k_i}{k_j}\right)$$

- and let $k_i/k_j = x$, then $v_i = v_f(1-x)$.
- General representation of shock wave propagation:

$$u_w = v_f \left[1 - (x_1 + x_2)\right]$$
• Shock wave caused by nearly equal densities

\[ u_w = v_f (1 - 2x_1) \]

• Shock wave caused by stopping \((x_2 = 1)\)

\[ u_w = v_f [1 - (x_1 + 1)] = -(v_f)(x_1) \]

• Shock wave caused by starting \((x_1 = 1)\)

\[ u_w = v_f [1 - (1 + x_2)] = v_f (-x_2) = -v_f x_2 \]
10. General Model of Vehicle Stream Flow

- Consider two successive vehicles (or trains), called the lead vehicle and following vehicle, moving at a cruising speed, \( v \) (ft/sec), along a long stretch of highway or guideway. Then the minimum headway can be written as:

\[
\text{minimum headway (sec)} = \frac{\text{minimum spacing (ft)}}{\text{cruise speed (ft/sec)}}
\]

- The minimum spacing consists of four components:
  - The distance covered during the \( P+R \) time
  - The difference between the braking distances of the following and lead vehicles
  - The distance between successive vehicles when stopped
  - The vehicle length
Expressing the above four components algebraically, the minimum spacing is given as:

$$s_{\text{min}} = vt_r + \left( \frac{v^2}{2b_2} - \frac{v^2}{2b_1} \right) + s_0 + L$$

where,
- $v$ = speed of vehicle (ft/sec)
- $t_r = P+R$ time (sec)
- $b_1, b_2$ = deceleration rate of leading and following vehicles, respectively (ft/sec)
- $s_0$ = distance between two vehicles when stopped
- $L$ = length of the vehicle (ft)
Vehicle Stream Flow

- $v$
- $L$
- $s$
- Direction of travel

- $1$
- $2$

Spacing, $s$
Combinations of Braking Rates

<table>
<thead>
<tr>
<th>Safety Policy</th>
<th>Leading Vehicle, $b_1$</th>
<th>Following Vehicle, $b_2$</th>
<th>Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\infty$</td>
<td>$b_n$</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>$\infty$</td>
<td>$b_e$</td>
<td>2</td>
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<td>3</td>
<td>$\infty$</td>
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<tr>
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<td>$b_e$</td>
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<tr>
<td>9</td>
<td>$b_n$</td>
<td>$\infty$</td>
<td>–</td>
</tr>
</tbody>
</table>
Distance vs. Speed

\[ L = 100 \text{ ft} \]
\[ v_i = 2 \text{ sec} \]
\[ b_n = 8 \text{ ft/sec}^2 \]
\[ b_x = 24 \text{ ft/sec}^2 \]
\[ s_0 = 10 \text{ ft} \]
Speed vs. Density

- $L = 100$ ft
- $t_r = 2$ sec
- $b_n = 8$ ft/sec$^2$
- $b_g = 24$ ft/sec$^2$
- $v_0 = 10$ ft
Flow vs. Speed

$L = 100$ ft
$t_r = 2$ sec
$b_r = 8$ ft/sec²
$b_s = 24$ ft/sec²
$s_0 = 10$ ft
Flow vs. Density
11. Centrally Versus Individually Controlled Modes

- Centrally controlled mode: rules of controlling the longitudinal spacing of vehicles, the stopping schedule of vehicles, and the time of operation are subject to their designer’s decisions. Most train modes operating on exclusive or principally exclusive right-of-way fall into this group.

- Individually controlled mode: individual drivers make their own decisions regarding headways, speed, and so on, subject to state or local traffic laws. Private automobiles as well as transit vehicles operating in mixed traffic fall into this group.
Centrally vs. Individually Controlled Flow