CHAPTER 3


Highways & Transportation I
ECIV 4333

INTRODUCTION

Components of highway mode of transportation

- The four main components of the highway mode of transportation are the driver, the pedestrian, the vehicle, and the road.

- The bicycle is also becoming an important component in the design of urban highways and streets.
INTRODUCTION

Importance of knowledge of characteristics

- To provide efficient and safe highway transportation, a knowledge of the characteristics and limitations of each of these components is essential.
- It is also important to be aware of the interrelationships that exist among these components in order to determine the effects, if any, that they have on each other.
- Their characteristics are also of primary importance when traffic engineering measures such as traffic control devices are to be used in the highway mode.

INTRODUCTION

Importance of knowledge of characteristics

- The road therefore must be designed to:
  - accommodate a wide range of vehicle characteristics
  - allow use by drivers and pedestrians with a wide range of physical and psychological characteristics.
- This chapter discusses the relevant characteristics of the main components of the highway mode and demonstrates their importance and their use in the design and operation of highway facilities.
3.1 DRIVER CHARACTERISTICS

Introduction

- One problem that faces traffic and transportation engineers is:
  - the **varying skills** and
  - **perceptual abilities** of drivers on the highway, demonstrated by a **wide range** of abilities to
    - hear,
    - see,
    - evaluate, and
    - react to information.
- Studies have shown that these abilities may also **vary** in an **individual** under **different** conditions, such as:
  - the influence of **alcohol**, 
  - **fatigue**, and
  - the **time of day**.

Therefore, it is important that **criteria** used for design purposes be **compatible** with the **capabilities** and **limitations** of most **drivers** on the highway.

- The use of an **average value**, such as mean reaction time, may **not** be **adequate** for a large number of drivers.
- Both the **85th percentile** and the **95th percentile** have been used to select design criteria; in general, the higher the chosen percentile, the wider the range covered.
THE HUMAN RESPONSE PROCESS

- **Actions** taken by drivers on a road result from their **evaluation** of and **reaction** to information they obtain from certain **stimuli** that they see or hear.
- However, evaluation and reaction must be carried out within a **very short time**, as the information being received along the highways is **continually changing**.
- It has been suggested that **most** of the information received by a driver is **visual**, implying that the **ability to see** is of fundamental importance in the driving task.

VISUAL RECEPTION

- The principal characteristics of the eye are;
  - Visual acuity, **حدة البصر**
  - Peripheral vision, **الرؤية المحيطية (الهامشية)**
  - Color vision, **رؤية الألوان**
  - Glare vision and recovery, **رؤية الوجه والاسترداد**
  - and Depth perception **إدراك العمق**
VISUAL RECEPTION - VISUAL ACUITY

- Visual acuity is the ability to see fine details of an object.
- It can be represented by the visual angle, which is the reciprocal of the smallest pattern detail in minutes of arc that can be resolved and given as (namely $\Phi$):

$$\phi = 2 \arctan \left( \frac{L}{2D} \right)$$

where
- $L =$ diameter of the target (letter or symbol)
- $D =$ distance from the eye to target in the same units as $L$
- $\arctan = \tan^{-1}$

VISUAL RECEPTION - VISUAL ACUITY

- For example, the ability to resolve a pattern detail with a visual acuity of one minute of arc ($1/60$ of a degree) is considered the normal vision acuity (20/20 vision).
VISUAL RECEPTION- VISUAL ACUITY

- Two types of visual acuity are of importance in traffic and highway emergencies:

  static and
dynamic visual acuity.

VISUAL RECEPTION- VISUAL ACUITY

  Static visual acuity.
  - The driver's ability to identify an object when both the object and the driver are stationary depends on his or her static acuity.
  - Factors that affect static acuity include background brightness, contrast, and time. 
  - Static acuity increases with an increase in illumination.
  - When other visual factors are held constant at an acceptable level, the optimal time required for identification of an object with no relative movement is between 0.5 and 1.0 seconds.
**VISUAL RECEPTION- VISUAL ACUITY**

Dynamic visual acuity.

- The driver's ability to clearly detect relatively moving objects, depends on the driver's **dynamic visual acuity**.
- Most people have:
  - clear vision within a **conical** angle of 3 to 5 degrees
  - and fairly clear vision within a conical angle of 10 to 12 degrees.
  - Vision beyond this range is usually **blurred (unclear)**.
- This is important when the **location** of traffic information devices is considered.
- Drivers will see **clearly** those devices that are within the **12 degree** cone, but objects **outside** this cone will be **blurred**.

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**VISUAL RECEPTION- PERIPHERAL VISION**

- Peripheral vision is the ability of people to see objects **beyond** the **cone** of **clearest** vision.
- Although objects can be seen within this zone, **details** and **color** are **not clear**.
- The cone for peripheral vision could be one subtending up to **160** degrees; this value is affected by the speed of the vehicle.
- **Age** also influences peripheral vision.
  - For instance, at about **age 60**, a significant change occurs in a person's peripheral vision.
**Visual Reception- Color Vision**

- **Color vision** is the ability to differentiate one color from another,
- but deficiency in this ability, usually referred to as **color blindness**,
- It is **not of great significance** in highway driving because **other** ways of recognizing traffic information devices (e.g., **shape**) can compensate for it.
- Combinations of **black and white** and **black and yellow** have been shown to be those to which the eye is most sensitive.

**Visual Reception- Glare Vision and Recovery**

- Occurs when the image reflected by the relatively bright light appears in the field of vision.
- Glare result in a **decrease of visibility** and cause **discomfort** to the eyes.
- It is also known that age has a significant effect on the sensitivity to glare, and that at about **age 40**, a significant change occurs in a person's sensitivity to glare.
VISUAL RECEPTION-
GLARE VISION AND RECOVERY

○ The time required by a person to recover from the effects of glare after passing the light source is known as glare recovery.

○ Studies have shown that this time is about:
  • 3 seconds when moving from dark to light and
  • can be 6 seconds or more when moving from light to dark.

○ Glare vision is of great importance during night driving; it contributes to the problem of serving older people, who see much more poorly at night.

○ This phenomenon should be taken into account in the design and location of street lighting so that glare effects are reduced to a minimum.

VISUAL RECEPTION-
GLARE VISION AND RECOVERY

○ Glare effects can be minimized by reducing luminaire brightness and by increasing the background brightness in a driver's field of view.

○ Specific actions taken to achieve this in lighting design include:
  • using higher mounting heights,
  • positioning lighting supports farther away from the highway, and
  • restricting the light from the luminaire to obtain minimum interference with the visibility of the driver.
**Visual Reception-Depth Perception**

- Depth perception affects the ability of a person to estimate **speed** and **distance**.
- It is particularly important on **two-lane** highways during passing maneuvers, when head-on crashes may result from a lack of proper judgment of speed and distance.
- The human eye is **not** very good at estimating **absolute values** of speed, distance, size, and acceleration.
- This is why traffic control devices are standard in size, shape, and color.

**Hearing Perception**

- The ear receives sound stimuli, which is important to drivers only when **warning sounds**, usually given out by emergency vehicles, are to be detected.
- **Loss** of some hearing ability is **not** a serious problem, since it normally can be corrected by a hearing aid.
3.2 PERCEPTION-REACTION PROCESS

The process through which a driver, cyclist, or pedestrian evaluates and reacts to a stimulus can be divided into four sub processes:

1. **Perception**: the driver sees a control device, warning sign, or object on the road
2. **Identification**: the driver identifies the object or control device and thus understands the stimulus
3. **Emotion**: the driver decides what action to take in response to the stimulus; for example, to step on the brake pedal, to pass, or to change lanes
4. **Reaction**: the driver actually executes the action decided on during the emotion sub-process
3.2 PERCEPTION-REACTION PROCESS

- The time that elapses from the start of perception to the end of reaction is the total time required for perception, identification, emotion, and reaction, referred to as perception-reaction time.
- Perception-reaction time is an important factor in the determination of braking distances, which in turn dictates the minimum sight distance required on a highway and the length of the yellow phase at a signalized intersection.

3.2 PERCEPTION-REACTION PROCESS

- Perception-reaction time varies among individuals and may, in fact, vary for the same person as the occasion changes.
- These changes in perception-reaction time depend on:
  - how complicated the situation is,
  - the existing environmental conditions,
  - age,
  - whether the person is tired or under the influence of drugs and/or alcohol, and
  - whether the stimulus is expected or unexpected.
3.2 PERCEPTION-REACTION PROCESS

- The researchers noted that the 85th-percentile time to brake, obtained from several situations, varied from 1.26 to over 3 seconds.
- The reaction time selected for design purposes should, however, be large enough to include reaction times for most drivers using the highways.
- Recommendations made by the American Association of State Highway and Transportation Officials (AASHTO) stipulate 2.5 seconds for stopping-sight distances.
- This encompasses the decision times for about 90 percent of drivers under most highway conditions.

EXAMPLES

**Example 3.1 Distance Traveled During Perception-Reaction Time**

A driver with a perception-reaction time of 2.5 sec is driving at 65 km/h when she observes that an accident has blocked the road ahead. Determine the distance the vehicle would move before the driver could activate the brakes. The vehicle will continue to move at 65 km/h during the perception-reaction time of 2.5 sec.

65 km/h = 65 * 1/3.6 = 18 m/s
Distance = v * t
18 * 2.5 = 45 m
**EXAMPLES**

**Example 2:**

A breakdown of car B occurred resulting to completely stopping of this car.
A driver in car A noticed this breakdown from a distance of 150 m and decided to brake. Do you think a collision will occur if:

a) the speed of car A was 90 km/hr  

b) the speed of car A was 80 km/hr

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Assume deceleration 1.5 m/s$^2$

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**Examples**

**Example 3:**

A driver in a vehicle travelling at 95 km/h, shifts her eyes from left to right and Focuses on construction activities along the right shoulder. Estimate the distance in meters the vehicle travels as the driver's eyes shift and fixate.

**Solution:**

The range of time for moving eyes is 0.1 to 0.3 seconds assume that it is 0.2 seconds on average.

The driver also requires about one second to gain information and another 0.2 seconds to get back to the original sight.

Total time required  = 0.2 + 1 + 0.2  = 1.4 seconds.  
Speed (v)  = 95 km/h  = 95/3.6  = 26.39 m/s  
Distance travelled  = v * t  
                 = 26.39 * 1.4  = 36.94 m
3.4 PEDESTRIAN CHARACTERISTICS

- The pedestrian is the major user of the roadway when the system fails; he/she is a major victim.
- About 28% of all traffic death are pedestrian fatalities in USA, in urban area 7000 pedestrians are killed each year, and about 70,000 are injured.
- The very young & the very old are most affected
- The traffic engineer is responsible for designing a safe & convenient facilities for pedestrians
- To save: Small children, elderly, Physically handicapped and blind

Information required by the designer are:
Space requirements (needs) for pedestrians
Walking & running speeds
Traffic flow characteristics of groups of pedestrians

3.4 PEDESTRIAN CHARACTERISTICS

**Space needs**

A study indicated that for the 95th percentile:

- Shoulder breadth 22.8” = 58 cm
- Body depth 13” = 33 cm

We should give the pedestrian slightly more spaces to avoid bodily contact with others & for things, that many pedestrian carry with them

Total area = 2.3 ft² = 0.214 m² (Standing), 61 cm * 35 cm = 2135 cm² = 0.214 m²

The above area is useful to determine the space needs or capacity where pedestrians are standing rather than walking (elevators & conveyance)

**Example:** Assume that the area of Alyarmook is about 33,000 m². What is the capacity of this place for standing people?

**Ans.:** 154,205 persons
3.4 PEDESTRIAN CHARACTERISTICS

Space needs (continued)

For sidewalks or other pedestrian corridors we should consider the dynamic spatial requirements for avoiding collisions with other pedestrians.

Allow space of 2.30 m$^2$ / pedestrian for walking freely.

Average distance preferred between two pedestrians following each other = $8/244$ cm = 2.40m, time spacing of 2 seconds.

Example: Assume that the width of Omar Elmokhtar road is 30 m. Estimate a maximum number of demonstrator when their walking platoon is 2000m?

Ans. 26086

3.4 PEDESTRIAN CHARACTERISTICS

Walking & running speeds

Under free flow conditions
Pedestrian speed are normally distributed

Range: 2 to 6 ft/sec, or 0.6 m/s to 1.82 m/s

2.16 km/h to 6.55 km/h

Mean walking speed: 4.0 to 4.5 ft/s

1.22 m/s to 1.37 m/s

4.4 km/h to 5 km/h

In design use 4 ft/s (1.22 m/s)

If number of elderly is high use (0.9 m/s)

Lower if significant number of handicapped is present.
3.4 PEDESTRIAN CHARACTERISTICS

Walking & running speeds

Walking speed decreases with the increase in pedestrian density.
Running speed 470ft/min or 7.80 ft/s = 2.38 m/s = 8.6 km/h
Fastest speed = 33 ft/s = 10 m/s = 36.2 km/h

Example:

a) Determine the time required for a pedestrian to cross a road of 20m width.
Answer = 16s

b) Find width of pedestrian crossing if 20 pedestrian want to cross a road of 20m width in 20 second.
Answer = 6.65m

3.5 BICYCLISTS AND BICYCLES CHARACTERISTICS

- The basic human factors discussed for the automobile driver also apply to the bicyclist, particularly with respect to perception and reaction.
- Unlike the automobile driver, the bicyclist is not only the driver of the bicycle, but he/she also provides the power to move the bicycle.
- The bicycle and the bicyclist therefore unite to form a system, thus requiring that both be considered jointly.
3.5 BICYCLISTS AND BICYCLES CHARACTERISTICS

- Three classes of bicyclists (A, B, and C) have been identified in the Guide for the Development of Bicycle Facilities by AASHTO.
- Experienced or advanced bicyclists are within class A, while less experienced bicyclists are within class B, and children riding on their own or with parents are classified as C.
- Class A bicyclists typically consider the bicycle as a motor vehicle and can comfortably ride in traffic.

- Class B bicyclists prefer to ride on neighborhood streets and are more comfortable on designated bicycle facilities, such as bicycle paths.
- Class C bicyclists use mainly residential streets that provide access to schools, recreational facilities, and stores.
3.5 BICYCLISTS AND BICYCLES
CHARACTERISTICS

- In designing urban roads and streets, it is useful to consider the feasibility of incorporating bicycle facilities that will accommodate class B and class C bicyclists.
- The bicycle, like the automobile, also has certain characteristics that are unique.
- For example, based on the results of studies conducted in Florida, Pein suggested that the minimum design speed for bicycles on level terrain is 32 km/h,
- but downgrade speeds can be as high as 50 km/h, while upgrade speeds can be as low as 13 km/h.
- Pein also suggested that the mean speed of bicycles when crossing an intersection from a stopped position is 13 km/h and the mean acceleration rate is 1 m/s².
3.6 VEHICLE CHARACTERISTICS

- Criteria for the geometric design of highways are partly based on the static, kinematic, and dynamic characteristics of vehicles.
- Static characteristics include the weight and size of the vehicle, while kinematic characteristics involve the motion of the vehicle without considering the forces that cause the motion.
- Dynamic characteristics involve the forces that cause the motion of the vehicle.

3.6 VEHICLE CHARACTERISTICS

- Since nearly all highways carry both passenger-automobile and truck traffic, it is essential that design criteria take into account the characteristics of different types of vehicles.
- A thorough knowledge of these characteristics will aid the highway and/or traffic engineer in designing highways and traffic-control systems that allow the safe and smooth operation of a moving vehicle, particularly during the basic maneuvers of passing, stopping, and turning.
3.6 VEHICLE CHARACTERISTICS

- Therefore, designing a highway involves the selection of a design vehicle, whose characteristics will encompass those of nearly all vehicles expected to use the highway.
- The characteristics of the design vehicle are then used to determine criteria for geometric design, intersection design, and sight-distance requirements.

3.6.1 Static Characteristics

- The size of the design vehicle for a highway is an important factor in the determination of design standards for several physical components of the highway.
- These include lane width, shoulder width, length and width of parking bays, and lengths of vertical curves.
- The axle weights of the vehicles expected on the highway are important when pavement depths and maximum grades are being determined.
3.6.1 STATIC CHARACTERISTICS

- For many years, each state prescribed by law the size and weight limits for trucks using its highways, and in some cases local authorities also imposed more severe restrictions on some roads.
- Table 3.1 shows some features of static characteristics for which limits were prescribed. A range of maximum allowable values is given for each feature.

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<table>
<thead>
<tr>
<th>Type</th>
<th>Allowable Lengths (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus</td>
<td>35 – 60</td>
</tr>
<tr>
<td>Single truck</td>
<td>35 – 60</td>
</tr>
<tr>
<td>Trailer, semi/full</td>
<td>35 – 48</td>
</tr>
<tr>
<td>Semitrailer</td>
<td>55 – 85</td>
</tr>
<tr>
<td>Truck trailer</td>
<td>55 – 85</td>
</tr>
<tr>
<td>Tractor semitrailer trailer</td>
<td>55 – 85</td>
</tr>
<tr>
<td>Truck trailer trailer</td>
<td>65 – 80</td>
</tr>
<tr>
<td>Tractor semitrailer, trailer</td>
<td>60 – 105</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Allowable Weights (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-axle</td>
<td>18,000 – 24,000</td>
</tr>
<tr>
<td>Tandem-axle</td>
<td>32,000 – 40,000</td>
</tr>
<tr>
<td>State maximum gross vehicle weight</td>
<td>73,280 – 164,000</td>
</tr>
<tr>
<td>Interstate maximum gross vehicle</td>
<td>73,280 – 164,000</td>
</tr>
</tbody>
</table>

3.6.1 Static Characteristics

The static characteristics of vehicles expected to use the highway influence the selection of design criteria for the highway. It is therefore necessary that all vehicles be classified. AASHTO has selected four general classes of vehicles:

- passenger cars,
- buses,
- trucks, and
- recreational vehicles.

3.6.1 Static Characteristics

Classes of Vehicles

- The passenger-car class:
  sport/utility vehicles, minivans, vans, and pick-up trucks.
- The bus class:
  intercity motor coaches and city transit, school, and articulated buses.
- The class of trucks:
  single-unit trucks, truck tractor-semitrailer combinations, and trucks or truck tractors with semitrailers in combination with full trailers.
- The class of recreational vehicles:
  motor homes, cars with camper trailers, cars with boat trailers, and motor homes pulling cars.
the passenger-car class (sport/utility vehicles)

- A sport utility vehicle (SUV) is a generic marketing term for a vehicle similar to a station wagon, but built on a light-truck chassis. It is usually equipped with four-wheel drive for on- or off-road ability, and with some pretension or ability to be used as an off-road vehicle.

the passenger-car class (vans)

- A van is a kind of vehicle used for transporting goods or groups of people.
**the passenger-car class (minivans)**

- A van is a kind of vehicle used for transporting goods or groups of people.

![Minivan Image]

**the passenger-car class (pickup truck)**

- A pickup truck (also pick-up truck, pickup, bakkie in South Africa, or ute—an abbreviation of "utility vehicle"—in Australia and New Zealand) is a light motor vehicle with an open-top rear cargo area (bed) which is almost always separated from the cab[1] to allow for chassis flex when carrying or pulling heavy loads.

![Pickup Truck Image]
the Bus class (intercity motor coaches)

- A coach (also motor coach) is a large motor vehicle for conveying passengers on excursions and on longer distance express coach scheduled transport between cities - or even between countries.

Example is New York City Transit buses. New York City Transit buses, marked on the buses MTA New York City Bus, is a bus service that operates in all five boroughs of New York City,
the Bus class (school bus)

- school bus is a type of bus designed and manufactured for student transport: carrying children and teenagers to and from school and school events.

the Bus class (articulated bus)

- An articulated bus is a bus which is articulated, essentially meaning it bends in the middle.
the Truck Class

Single Unit Trucks

Conventional Combination Vehicles

5-Axle Tractor Semi-Trailer
6-Axle Tractor Semi-Trailer
STAA or "Western" Double

Longer Combination Vehicles (LCVs)

Rocky Mountain Double
Tampike Double
8-Axle B-Train Double Trailer Combination
Triple Trailer Combination

Figure 3.1 Examples of Different Types of Trucks
the recreational vehicles class
(motor homes)

Recreational vehicle or RV is, in North America, the usual term for a Motor vehicle or trailer equipped with living space and amenities found in a home.

the recreational vehicles class
(cars with camper trailers)
the recreational vehicles class
(cars with boat trailers)

the recreational vehicles class
(motor homes pulling cars)
3.6.1 Static Characteristics

Design Vehicles

- 19 different design vehicles have been selected to represent the different categories of vehicles within all four classes.
- Table 3.2 shows the physical dimensions for each of these design vehicles, and
- Figure 3.1 shows examples of different types of trucks.

### Table 3.2

<table>
<thead>
<tr>
<th>Design Vehicle Type</th>
<th>Symbol</th>
<th>Overall Dimensions (ft)</th>
<th>Typical Fringe</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Height</td>
<td>Width</td>
</tr>
<tr>
<td>Smaller Car</td>
<td>P</td>
<td>4.25</td>
<td>7</td>
</tr>
<tr>
<td>Single Unit Truck</td>
<td>SU</td>
<td>15-18.5</td>
<td>8.0</td>
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<tr>
<td>Trucks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Utility Box</td>
<td>UE</td>
<td>12.0</td>
<td>8.5</td>
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<tr>
<td>City Bus</td>
<td>C-BUS</td>
<td>17.0</td>
<td>8.5</td>
</tr>
<tr>
<td>Conventional Bus</td>
<td>S-BUS</td>
<td>18.5</td>
<td>8.0</td>
</tr>
<tr>
<td>Luggage Box</td>
<td>L-BUS</td>
<td>18.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Articulated Bus</td>
<td>A-BUS</td>
<td>17.0</td>
<td>8.5</td>
</tr>
<tr>
<td>Trucks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intermediate Semitractor</td>
<td>WB-40</td>
<td>13.5</td>
<td>8.0</td>
</tr>
<tr>
<td>Heavy-Duty Semitractor</td>
<td>WB-60</td>
<td>17.5</td>
<td>8.5</td>
</tr>
<tr>
<td>Heavier Semitractor</td>
<td>WB-80</td>
<td>23.5</td>
<td>8.5</td>
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<tr>
<td>&quot;Double-Box&quot; Semitractor/Trailer</td>
<td>WB-DCD</td>
<td>15.5</td>
<td>8.5</td>
</tr>
<tr>
<td>Semi-Semitractor/Trailer</td>
<td>WB-WS</td>
<td>15.5</td>
<td>8.5</td>
</tr>
<tr>
<td>Triaxle-Semi-Semitractor/Trailer</td>
<td>WB-WSS2</td>
<td>15.5</td>
<td>8.5</td>
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<tr>
<td>Boxed Vans</td>
<td>MRH</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>Cargo and Cargo Truck</td>
<td>IVT</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Luggage Box and Cargo Truck</td>
<td>PB</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Motor Home and Cargo Truck</td>
<td>MBH</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Farm Truck*</td>
<td>FK</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>

* = Design Vehicle with 40-ft trailer as adopted by NCHRP (National Cooperative Highway Research Program) and AASHTO (American Association of State Highway and Transportation Officials).

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**Design Vehicles**

* = Design Vehicle with 53-ft trailer as adopted by NCHRP (National Cooperative Highway Research Program) and AASHTO (American Association of State Highway and Transportation Officials).

** = Combined dimension is typically 110 ft.

+ = Combined dimension is typically 150 ft.

** = Combined dimension is typically 125 ft.

# = Dimensions are for a 100-200 ft trailer extending any length greater than 100 ft.

** = To obtain the overall length of the vehicle, add the length of the trailer or semitrailer to the length of the truck unit(s) and trailer(s).

** = The overall length of the vehicle is measured from the front to the rear of the vehicle.
AASHTO also has suggested the following guidelines for selecting a design vehicle:

- For parking lots:
  a passenger car may be used

- For intersections on residential streets and park roads:
  a single-unit truck could be considered

- For the design of intersections of state highways and city streets that serve bus traffic but with relatively few large trucks:
  a city transit bus may be used

- For the design of intersections of highways with low-volume county and township/local roads with Average Annual Daily Traffic (AADT) of 400 or less:
  a large school bus with a capacity of 84 passengers or a conventional bus with a capacity of 65 passengers may be used.

- For intersections of freeway ramp terminals and arterial highways, and for intersections of state highways and industrial streets with high traffic volumes, or with large truck access to local streets:
  the WB-20 (WB-65 or 67) may be used.
DESIGN VEHICLES

Minimum turning radii

- In carrying out the design of any of the intersections referred to above: the minimum turning radius for the selected design vehicle traveling at a speed of 16 km/h should be provided.
- Minimum turning radii at low speeds (16 km/h or less) are dependent mainly on the size of the vehicle.
- The turning-radii requirements for single-unit (SU) truck and the WB-20 (WB-65 and WB-67) design vehicles are: given in Figures 3.2 and 3.3 respectively.
Minimum turning radii

- The turning-radii requirements for other vehicles can be found in:

  AASHTO's Policy on Geometric Design of Highways and Streets.

  *(you may download it from internet)*

  *Called the Bible of transport engineers*
3.6.2 **Kinematic Characteristics**

**Definition**
- Kinematic characteristics involve the motion of the vehicle *without* considering the forces that cause the motion.
- The primary element among kinematic characteristics is the acceleration capability of the vehicle.

**Importance**

*Acceleration capability is important in:*

- several traffic operations such as: passing maneuvers and gap acceptance.
- the dimensioning of highway features such as: freeway ramps and passing lanes.
- determining the forces that cause motion.
3.6.2 Kinematic Characteristics

Mathematical relationships

The study of the kinematic characteristics of the vehicle primarily involves:
- a study of how acceleration rates influence the elements of motion, such as velocity and distance.
- Review the mathematical relationships among acceleration, velocity, distance, and time.

Let us consider a vehicle moving along a straight line from point 0 to point m, a distance x in a reference plane T. The position vector of the vehicle after time t may be expressed as

\[ r_{om} = x \hat{T} \]

where

- \( r_{om} = \text{position vector for } m \text{ in } T \)
- \( \hat{T} = \text{a unit vector parallel to line } om \)
- \( x = \text{distance along the straight line} \)
3.6.2 Kinematic Characteristics

Mathematical relationships

- The velocity and acceleration for \( m \) may be simply expressed as:
  \[
  u_m = \dot{r}_{om} = \dot{x}_i \\
  a_m = \ddot{r}_{om} = \ddot{x}_i 
  \]
  where
  \[
  u_m = \text{velocity of the vehicle at point } m \\
  a_m = \text{acceleration of the vehicle at point } m
  \]
  \[
  \dot{x} = \frac{dx}{dt} \\
  \ddot{x} = \frac{d^2x}{dt^2}
  \]

Acceleration Assumed Constant

Two cases are of interest:
1. acceleration is assumed constant;
2. acceleration is a function of velocity.
3.6.2 **Kinematic Characteristics**

**Acceleration Assumed Constant**

When the acceleration of the vehicle is assumed to be constant,

The constants $C_1$ and $C_2$ are determined either by the initial conditions on velocity and position or by using known positions of the vehicle at two different times.

\[ \ddot{x} = a \]
\[ \frac{d\dot{x}}{dt} = a \]
\[ \dot{x} = at + C_1 \]
\[ x = \frac{1}{2} at^2 + C_1 t + C_2 \]

**Acceleration as a Function of Velocity**

The lower the speed, the higher the acceleration rate that can be obtained.

Figures 3.4a and 3.4b show maximum acceleration rates for
- passenger cars and
- tractor-semitrailers
at different speeds on level roads.
3.6.2 **Kinematic Characteristics**

![Graph](image1)

(a) Passenger Cars

![Graph](image2)

(b) Tractor-Semitrailers

**Figure 3.4** Acceleration Capabilities of Passenger Cars and Tractor-Semitrailers on Level Roads
3.6.2 KINEMATIC CHARACTERISTICS

Acceleration as a Function of Velocity

One model that is used commonly in this case is:

\[
\frac{du_t}{dt} = \alpha - \beta u_t
\]

where \(\alpha\) and \(\beta\) are constants.

After derivation, the velocity and the position are as follows:

\[
u_t = \frac{\alpha}{\beta} (1 - e^{-\beta t}) + u_0 e^{-\beta t}
\]

\[
x = \left(\frac{\alpha}{\beta}\right) t - \frac{\alpha}{\beta^2} (1 - e^{-\beta t}) + \frac{u_0}{\beta} (1 - e^{-\beta t})
\]

---

3.6.2 KINEMATIC CHARACTERISTICS

Example

Example 3.3 Distance Traveled and Velocity Attained for Variable Acceleration

The acceleration of a vehicle can be represented by the following equation.

\[
\frac{du_t}{dt} = 1 - 0.04u
\]

where \(u\) is the vehicle speed in m/sec. If the vehicle is traveling at 70 km/h, determine its velocity after 5 sec of acceleration and the distance traveled during that time.
3.6.3 Dynamic Characteristics

Several forces act on a vehicle while it is in motion:

- air resistance,
- grade resistance,
- rolling resistance, and
- curve resistance

Air Resistance

- A vehicle in motion has to overcome the resistance of the air in front of it as well as the force due to the frictional action of the air around it.
- The force required to overcome these is known as the air resistance and is related to:
  - the cross-sectional area of the vehicle in a direction perpendicular to the direction of motion and to
  - the square of the speed of the vehicle.
3.6.3 Dynamic Characteristics

The Air Resistance force can be estimated from the formula:

\[ R_d = 0.5 \left( \frac{0.077 p C_D A u^2}{g} \right) \]

Where:

- \( R_d \) = air resistance force (kg)
- \( p \) = density of air (1.227 kg/m³) at sea level; less at higher elevations
- \( C_D \) = aerodynamic drag coefficient (current average value for passenger cars is 0.4; for trucks, this value ranges from 0.5 to 0.8, but a typical value is 0.5)
- \( A \) = frontal cross-sectional area (m²)
- \( u \) = vehicle speed (km/h)
- \( g \) = acceleration of gravity (9.81 m/sec²)

---

3.6.3 Dynamic Characteristics

**Grade Resistance**

- When a vehicle moves up a grade, a component of the weight of the vehicle acts downward, along the plane of the highway.
- This creates a force acting in a direction opposite that of the motion. This force is the grade resistance.
- A vehicle traveling up a grade will therefore tend to lose speed unless an accelerating force is applied.
- Note: grade resistance = weight X grade, in decimal.
3.6.3 **DYNAMIC CHARACTERISTICS**

**Rolling Resistance**

- There are forces **within the vehicle** itself that offer resistance to motion.
- These forces are due mainly to:
  - frictional effect on **moving parts** of the vehicle,
  - frictional slip between the **pavement surface and the tires**.
- The sum effect of these forces on motion is known as rolling resistance.
- It depends on:
  - the **speed** of the vehicle and the **type of pavement**.
- Rolling forces are relatively **lower on smooth pavements** than on rough pavements.

---

3.6.3 **DYNAMIC CHARACTERISTICS**

**Rolling Resistance**

- The rolling resistance force for passenger cars on a smooth pavement can be determined from the relation

\[ R_t = (C_{rs} + 0.077C_{rv} u^2)W \]

Where:
- \( R \) = rolling resistance force (kg)
- \( C_{rs} \) = constant (typically 0.012 for passenger cars)
- \( C_{rv} \) = constant (typically \( 7 \times 10^{-6} \) \( \text{s}^2/\text{m}^2 \) for passenger cars)
- \( u \) = vehicle speed (km/h)
- \( W \) = gross vehicle weight (kg)
3.6.3 Dynamic Characteristics

Rolling Resistance

For trucks, the rolling resistance can be obtained from

\[ R_r = (C_a + 0.278 C_b u) W \]

where

- \( R_r \) = rolling resistance force (kg)
- \( C_a \) = constant (typically 0.02445 for trucks)
- \( C_b \) = constant (typically 0.00147 s/m for trucks)
- \( u \) = vehicle speed (km/h)
- \( W \) = gross vehicle weight (kg)

Curve Resistance

- When a passenger car is maneuvered to take a curve, external forces act on the front wheels of the vehicle.
- These forces have components that have a retarding effect on the forward motion of the vehicle.
- The sum effect of these components constitutes the curve resistance.
- This resistance depends on the radius of the curve, the gross weight of the vehicle, and the velocity at which the vehicle is moving.
3.6.3 Dynamic Characteristics

Curve Resistance

• It can be determined as:

\[ R_c = 0.5 \frac{(0.077u^2W)}{gR} \]

where

- \( R_c \) = curve resistance (kg)
- \( u \) = vehicle speed (km/h)
- \( W \) = gross vehicle weight (kg)
- \( g \) = acceleration of gravity (9.81 m/sec^2)
- \( R \) = radius of curvature (m)

3.6.3 Dynamic Characteristics

Power requirements

• Power is the rate at which work is done.
• It is usually expressed in horsepower (a U.S. unit of measure), where 1 horsepower is 746 W.
• The performance capability of a vehicle is measured in terms of the horsepower the engine can produce to overcome:
  • air, grade, curve,
  • and friction resistance forces
  • and put the vehicle in motion.
3.6.3 Dynamic Characteristics

Power requirements

Figure 3.6 shows how these forces act on the moving vehicle.

![Figure 3.6 Forces Acting on a Moving Vehicle](image)

- The power delivered by the engine is:

\[ P = \frac{2.91 Ru}{746} \]

where

- \( P \) = horsepower delivered (hp)
- \( R \) = sum of resistance to motion (N)
- \( u \) = speed of vehicle (km/h)
3.6.3 Dynamic Characteristics

Solve the following question?

Example 3.4 Vehicle Horsepower Required to Overcome Resistance Forces:

Determine the horsepower produced by a passenger car traveling at a speed of 105 km/h on a straight road of 5% grade with a smooth pavement.

Assume the weight of the car is 1800 kg and the cross-sectional area of the car is 3.8 m².

Example 3.4

Solution

• R = air resistance
  + rolling resistances
  + upgrade resistance
  + curve resistance

• Use Eq. 3.13 to determine air resistance.

\[ R_a = 0.5 \left( \frac{0.077 p C_D A u^2}{g} \right) \]

= 0.5 \times \frac{0.077 \times 1.277 \times 0.4 \times 3.8 \times 105 \times 105}{9.81}

= 80.7 kg
EXAMPLE 3.4

SOLUTION

- Use Eq. 3.14 to determine rolling resistance.

\[ R_r = (C_{d,0} + 0.077C_{d,0}u^2)(1800) \]
\[ = (0.012 + 0.077 \times 7 \times 10^{-6} \times 105 \times 105) \times 1800 \]
\[ = (0.012 + 0.006) \times 1800 \]
\[ = 0.018 \times 1800 \]
\[ = 32.3 \text{ kg} \]

Grade resistance = 1800 × \(\frac{5}{100}\) = 90 kg

- Determine total resistance.

\[ R = R_u + R_r + \text{grade resistance} = 80.7 + 32.3 + 90 = 203 \text{ kg} \]

- Use Eq. 3.17 to determine horsepower produced.

\[ P = \frac{0.278Ru}{76} \]
\[ = \frac{0.278 \times 203 \times 105}{76} \]
\[ = 78 \text{ hp} \]

3.6.3 DYNAMIC CHARACTERISTICS

Braking distance

- The action of the forces (shown in Figure 3.6) on the moving vehicle and the effect of perception-reaction time are used to determine:
  - the braking distance of a vehicle and
  - the minimum radius of a circular curve for a vehicle traveling with speed \(u > 16 \text{ km/h}\).
### 3.6.3 Dynamic Characteristics

**Braking distance**

\( D_b \) the horizontal distance

\[
\begin{align*}
W &= \text{weight of vehicle} & u &= \text{speed when brakes applied} \\
f &= \text{coefficient of friction} & D_b &= \text{braking distance} \\
g &= \text{acceleration of gravity} & \gamma &= \text{angle of incline} \\
a &= \text{vehicle acceleration} & G &= \tan \gamma \quad (% \text{ grade/100}) \\
x &= \text{distance traveled by the vehicle along the road during braking}
\end{align*}
\]

Frictional force on the vehicle = \( Wf \cos \gamma \)

**Equations**

\[
\begin{align*}
W \sin \gamma - Wf \cos \gamma &= \frac{Wa}{g} \\
a &= -\frac{u^2}{2x} \\
W \sin \gamma - Wf \cos \gamma &= -\frac{Wu^2}{2gx} \\
D_b &= x \cos \gamma \\
\frac{Wu^2}{2gD_b} \cos \gamma &= Wf \cos \gamma - W \sin \gamma \\
\frac{u^2}{2gD_b} &= f - \tan \gamma
\end{align*}
\]

\[
D_b = \frac{u^2}{2g(f - \tan \gamma)}
\]

If \( g \) is taken as 9.81 m/sec\(^2\)

\( u \) is expressed in km/h,

\[
D_b = \frac{u^2}{254(f - G)}
\]
• A similar equation could be developed for a vehicle traveling uphill, in which case the following equation is obtained.

\[ D_b = \frac{u^2}{254(f + G)} \]

• A general equation for the braking distance can therefore be written as:

\[ D_b = \frac{u^2}{254(f \pm G)} \]

AASHTO recommends the coefficient of friction to be \( a/g \) and \( a \) to be 4.51 m/s\(^2\), then braking distance becomes:

\[ D_b = \frac{u^2}{254\left(\frac{a}{g} \pm G\right)} \]

• the horizontal distance traveled in reducing the speed of a vehicle from \( U_1 \) to \( U_2 \) in km/h during a braking maneuver is given by:

\[ D_b = \frac{u_1^2 - u_2^2}{254\left(\frac{a}{g} \pm G\right)} \]

• The distance traveled by a vehicle between the time the driver observes an object in the vehicle's path and the time the vehicle actually comes to rest is longer than the braking distance, since it includes the distance traveled during perception-reaction time.

• This distance is referred to in this text as the stopping sight distance \( S \) and is given as
• This distance is referred to in this text as the stopping sight distance \( S \) and is given as

\[
S (\text{m}) = 0.278 ut + \frac{u^2}{254\left( \frac{a}{g} \pm G \right)}
\]

• \( t \) is the perception-reaction (in seconds)
• \( u \) is the velocity in km/h at which the vehicle was traveling when the brakes were applied.

3.6.3 Dynamic Characteristics

Solve the following questions?

Example 3.5 Determining Braking Distance

A student trying to test the braking ability of her car determined that she needed 5.64 m more to stop her car when driving downhill on a road segment of 5% grade than when driving downhill at the same speed along another segment of 3% grade. Determine the speed at which the student conducted her test and the braking distance on the 5% grade if the student is traveling at the test speed in the uphill direction.

Example 3.6 Exit Ramp Stopping Distance

A motorist traveling at 105 km/h on an expressway intends to leave the expressway using an exit ramp with a maximum speed of 56 km/h. At what point on the expressway should the motorist step on her brakes in order to reduce her speed to the maximum allowable on the ramp just before entering the ramp, if this section of the expressway has a downgrade of 3%?
3.6.3 Dynamic Characteristics
Solve the following questions?

Example 3.7 Distance Required to Stop for an Obstacle on the Roadway

A motorist traveling at 89 km/h down a grade of 5% on a highway observes a crash ahead of him, involving an overturned truck that is completely blocking the road. If the motorist was able to stop his vehicle 9 m from the overturned truck, what was his distance from the truck when he first observed the crash? Assume perception-reaction time = 2.5 sec.

3.6.3 Dynamic Characteristics
Estimation of Velocities

It is sometimes necessary to estimate the speed of a vehicle just before it is involved in a crash. This may be done by using the braking-distance equations if skid marks can be seen on the pavement. The steps taken in making the speed estimate are as follows:

Step 1. Measure the length of the skid marks for each tire and determine the average. The result is assumed to be the braking distance Db of the vehicle.
3.6.3 Dynamic Characteristics

**Estimation of Velocities**

**Step 2:** Determine the coefficient of friction \( f \) by performing trial runs at the site under similar weather conditions, using vehicles whose tires are in a state similar to that of the tires of the vehicle involved in the accident. This is done by driving the vehicle at a known speed \( U_k \) and measuring the distance traveled \( D_k \) while braking the vehicle to rest. The coefficient of friction \( f_k \) can then be estimated by using:

\[
f_k = \frac{u_k^2}{254D_k} + G
\]

Alternatively, a value of 0.35 for \( a/g \) can be used for \( f_k \).

**Step 3:** Use the value of \( f_k \) obtained in step 2 to estimate the unknown velocity \( u_u \) just prior to impact; that is, the velocity at which the vehicle was traveling just before observing the crash. This is done by using Eq. 3.26.

If it can be assumed that the application of the brakes reduced the velocity \( u_o \) to zero, then \( u_u \) may be obtained from:

\[
D_b = \frac{u_o^2 - u_u^2}{254\left(1 \pm \frac{a}{g} \pm G\right)}
\]

\[
D_k = \frac{u_o^2}{254\left(\frac{u_o^2}{254D_k} \pm G \pm G\right)} = \left(\frac{u_o^2}{u_k^2}\right)D_k = \left(\frac{D_b}{D_k}\right)^{1/2}u_k
\]
3.6.3 Dynamic Characteristics

Estimation of Velocities

However, if the vehicle involved in the accident was traveling at speed $U_1$ when the impact took place and the speed $U_1$ is known, then using Eq. 3.24, the unknown speed $U_u$ just prior to the impact may be obtained from

$$D_b = \frac{u_u^2 - u_1^2}{254\left(\frac{u_k^2}{254D_k} + G \pm G\right)} = \left(\frac{u_u^2 - u_1^2}{u_k^2}\right)D_k$$

$$u_u = \left(\frac{D_b}{D_k}u_k^2 + u_1^2\right)^{1/2}$$

---

3.6.3 Dynamic Characteristics

Estimation of Velocities: Solve the following questions?

**Example 3.8** Estimating the Speed of a Vehicle from Skid Marks

In an attempt to estimate the speed of a vehicle just before it hit a traffic signal pole, a traffic engineer measured the length of the skid marks made by the vehicle and performed trial runs at the site to obtain an estimate of the coefficient of friction. Determine the estimated unknown velocity if the following data were obtained.

- Length of skid marks = 178 m, 180 m, 177 m, and 181 m
- Speed of trial run = 48 km/h
- Distance traveled during trial run = 90 m

Examination of the vehicle just after the crash indicated that the speed of impact was 56 km/h.