110401367 Transportation Engineering and Planning

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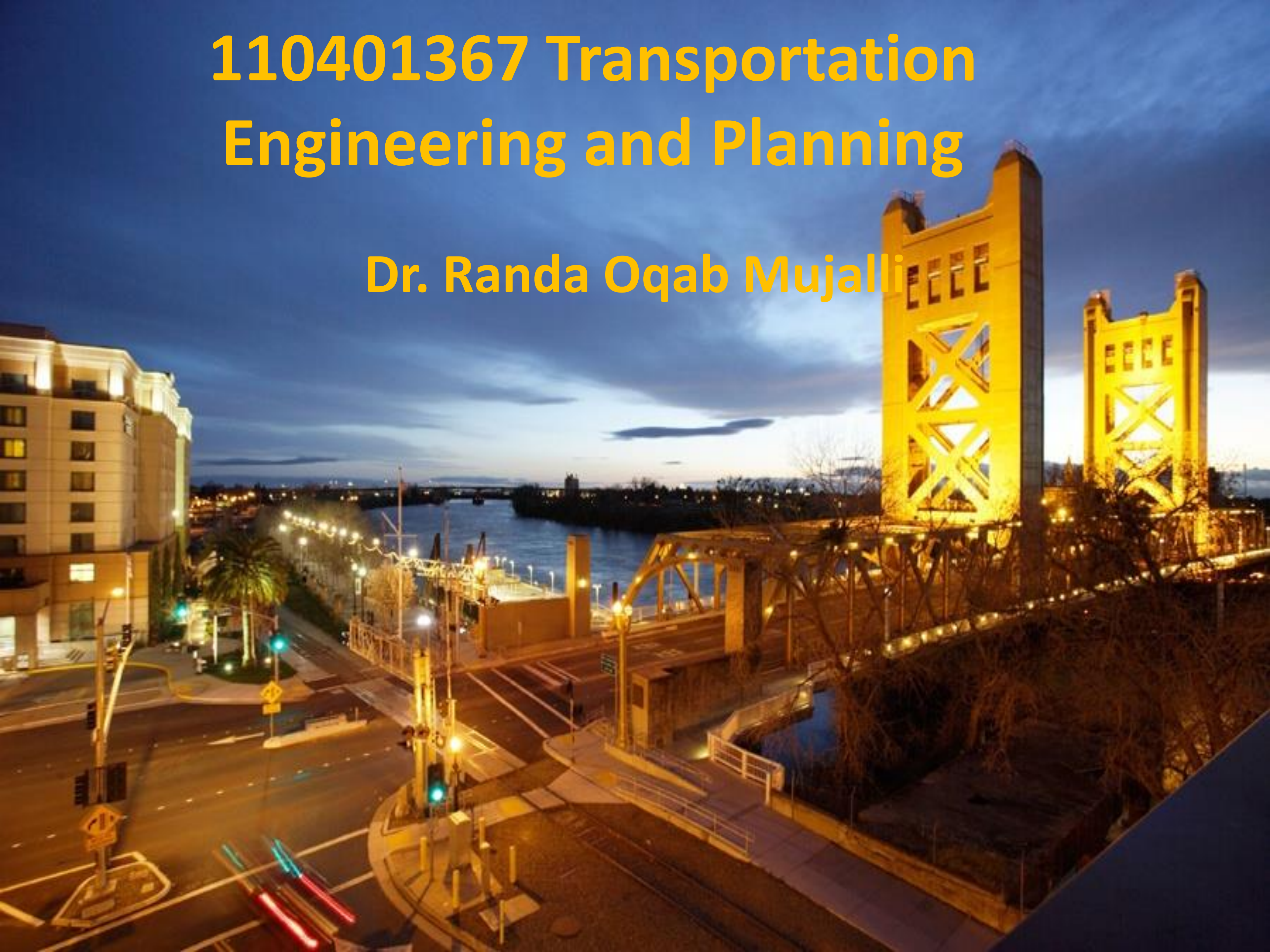


Introduction of Transportation Engineering

Importance of Transportation to Economy:

Transportation as a Share of Consumer Spending

<u>In Jordan according to DOS statistics:</u>

• Average Annual Income HH	JD 8823.9 (2010)
• Private vehicle ownership	45.7% (2012)
• Housing	27.8% (2010)
• Transportation	17.2% (2010)
• Health Care	2.7% (2010)
• Education	6.5 % (2010)

Transportation Engineering

1- Introduction

Transportation:

Movement of people and goods

Modes of Transportation:

1. **Highway Transportation (cars)**

2. Rail Transportation (trains)

3. Air Transportation (airplanes)

4. Water Transportation (ships)

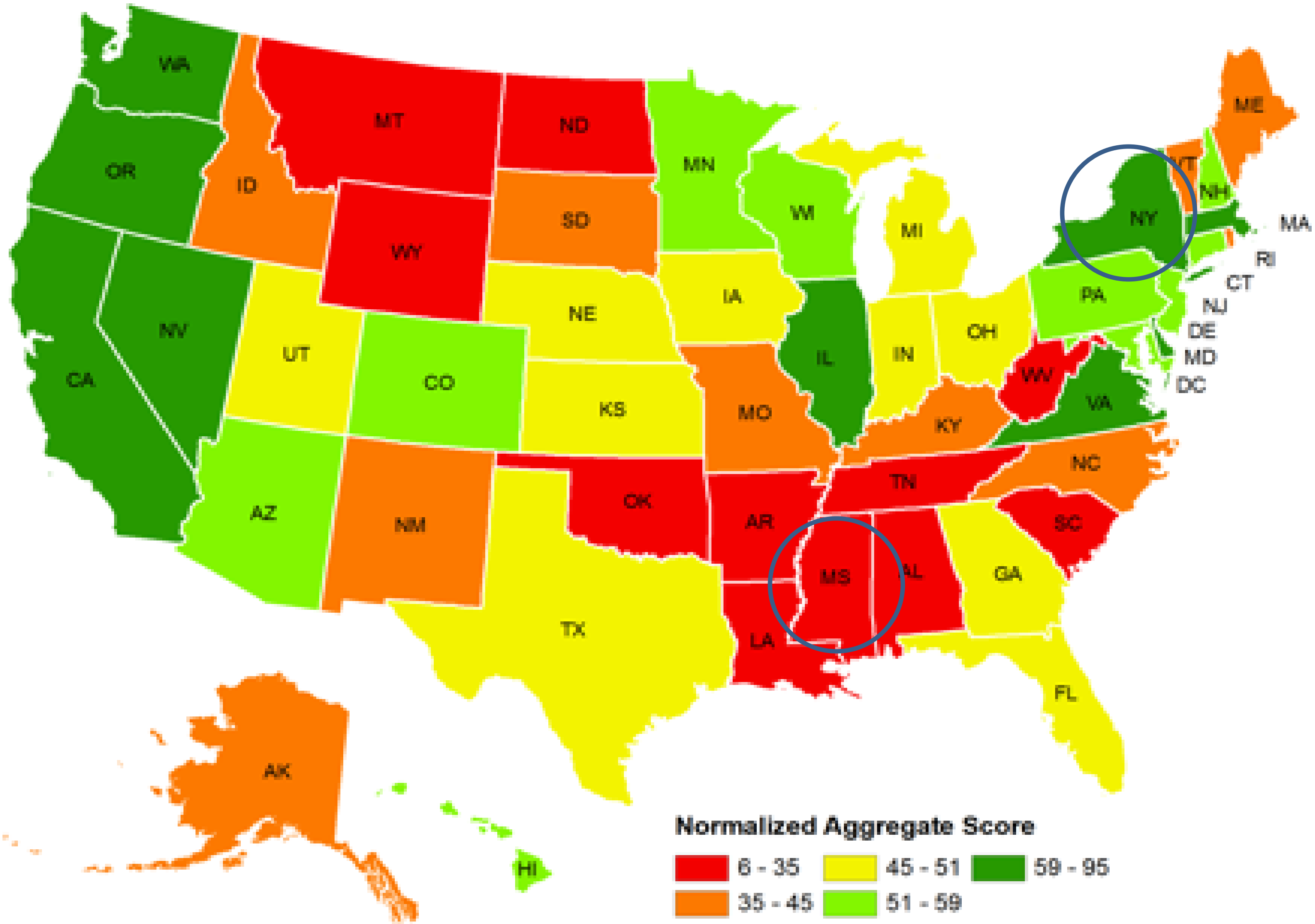
5. **pipeline Transportation (oil, gas,…)**

Roles of Transportation in Society:

A. Economically:

1. availability of goods and services
2. effective use of natural resources
3. expansion of trade
4. decentralization of industries & promotion of regional specialization
5. increasing large scale production & reducing the cost of production
6. providing competition that produces low prices & high quality

→*Transportation level is an index of economy and development.*



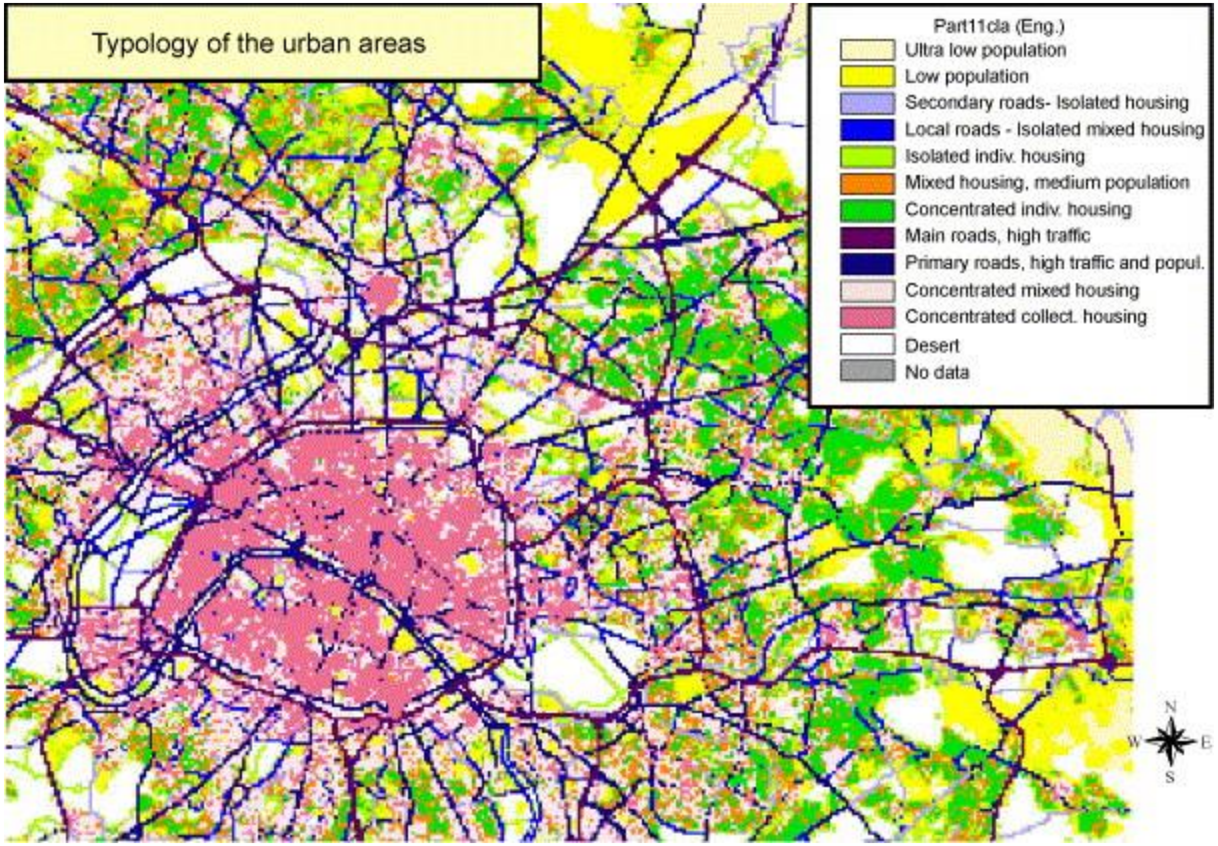
Index of Economic Impact of Transportation (red = worst, green = best)

B. Socially:

1. **provides mobility for cultural, recreational and social purposes**

2. **Affects population distribution and housing requirements**

3. **Affects employment opportunities**



Mobility model in Smart Town

PRT

C. Environmentally:

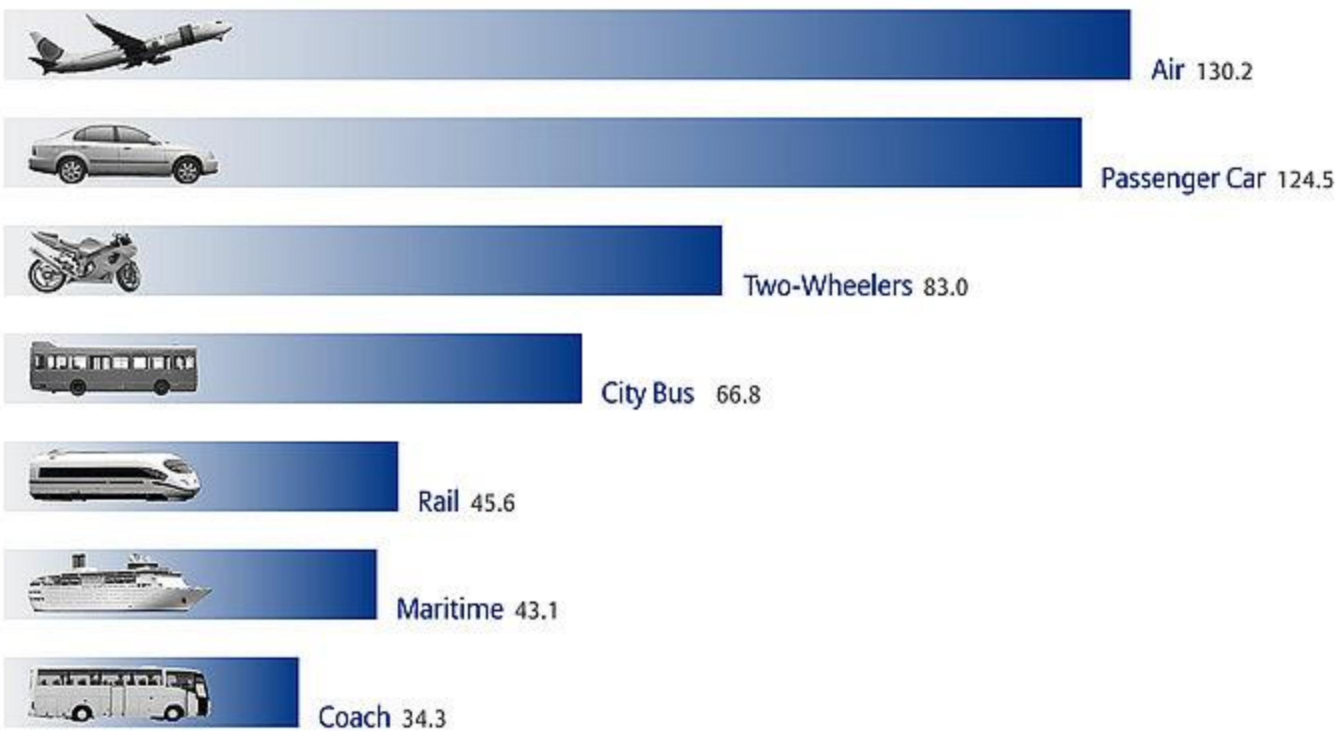
Its pollution affects the air, water & land qualities which are dangerous to human, animal & plant lives.

The Climate Impacts of How We Get Around

Allianz

Transportation accounts for over 23 percent of all global carbon dioxide emissions.
See what modes of human transport produce the most emissions per kilometer.

CO_2 Emissions Per Passenger (grams per kilometer)



Source: European Environment Agency
The publication of this graphic is free of charge provided that users credit Allianz SE.
Graphics are available in the media section of the Allianz Knowledge Partnersite: www.knowledge.allianz.com/en/media/graphics

D. Politically:

1. increase the ability of the country to defend itself

2. promotes the political unity of the nation

F117

Transportation Engineering

Transportation Engineering is a branch of the engineering that deals with planning, design, & operation of various transportation systems and their components, to achieve a safe, efficient, convenient and economical movement of persons and goods.

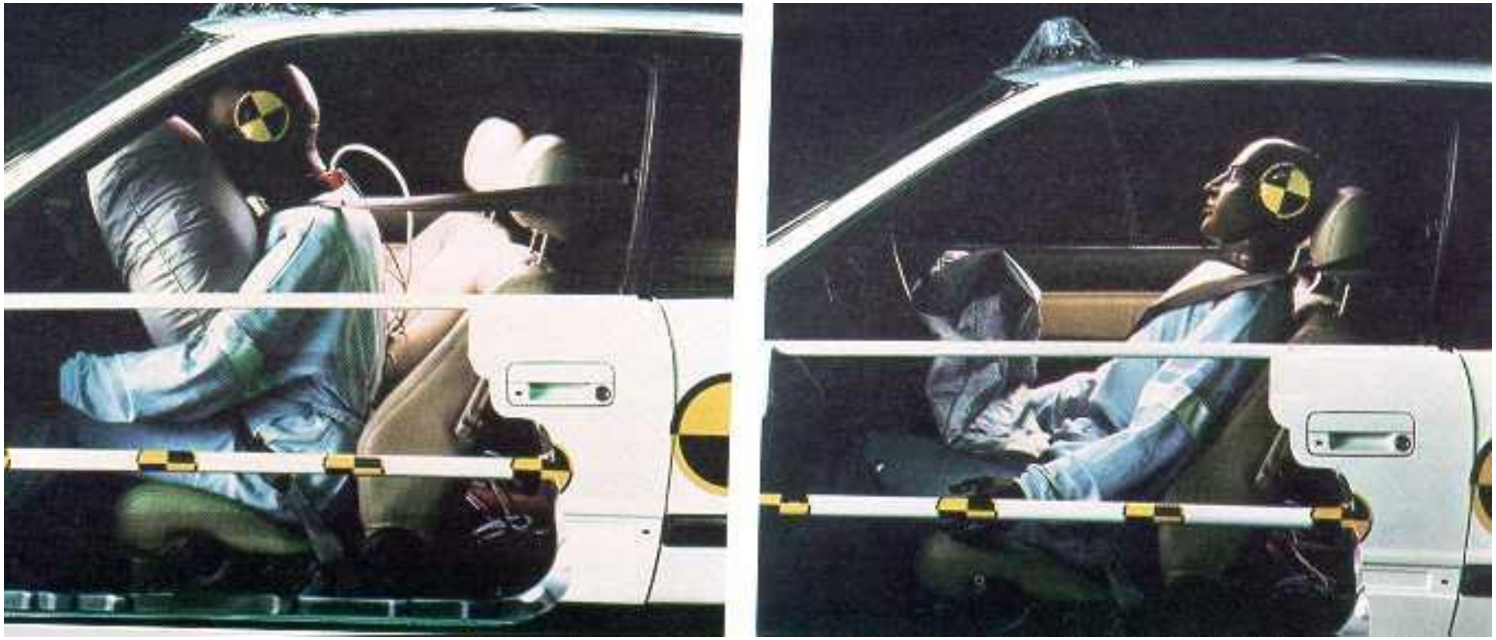
Transportation Problems:

1. Congestion, pollution
2. Energy problems
3. Environmental problems
4. Safety problems

Congestion in Urban “Freeways”

Congestion in Urban “Freeways”

Highway Safety



System Approach to Problem Solving:

1. **I**dentifying the problem
2. **D**efining goals and objectives in solving the problem
3. **S**earching for alternative methods of meeting the requirement
4. **C**hoosing & developing the best alternative
5. **I**mplementing its operation

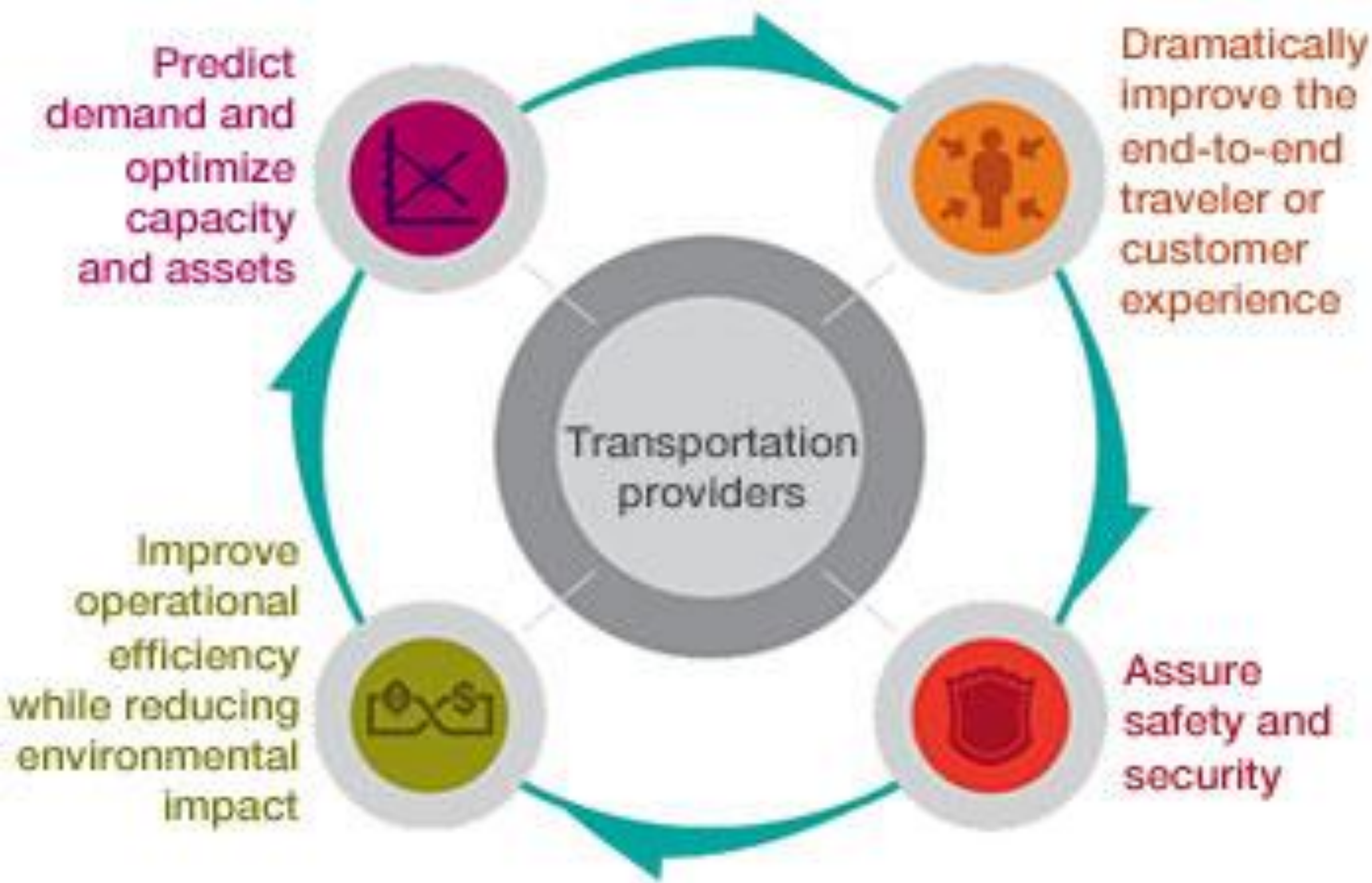
Trends in Transportation Development

1. Integration of transportation systems

Integrate the networks

- **Plan globally**
- **Invest in intermodal platforms**
- **Promote market opening**
- **Connect to neighbouring regions**

2. Optimization of transportation systems



[Source: http://www.ibm.com/smarterplanet/us/en/transportation_systems/imperatives/index.html](http://www.ibm.com/smarterplanet/us/en/transportation_systems/imperatives/index.html)

3. Employment of computers & new technologies

4. Minimization of energy use

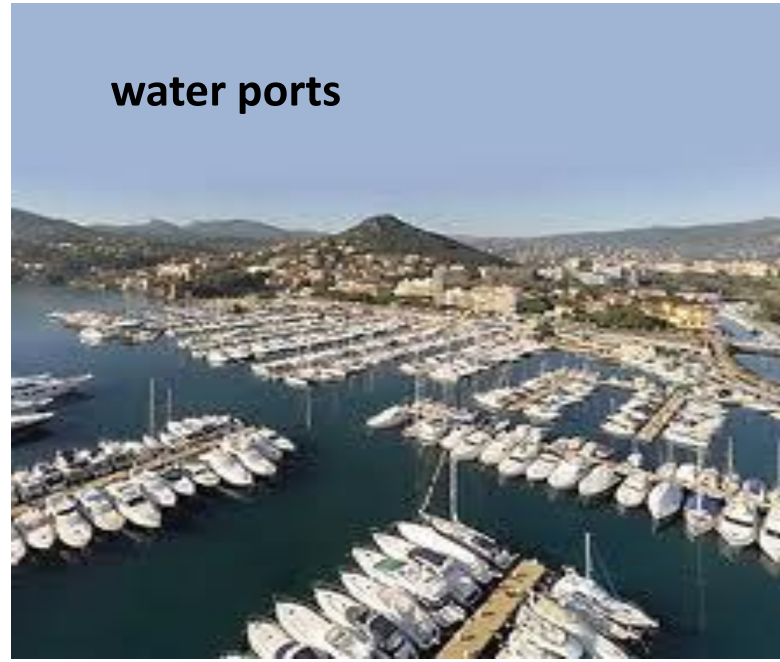
5. Increasing efficiency of existing facilities

Safety, Congestion, Schedules, Pollution, Prices …etc.

Physical elements of the transportation system:

1. Travel ways

2. Terminals

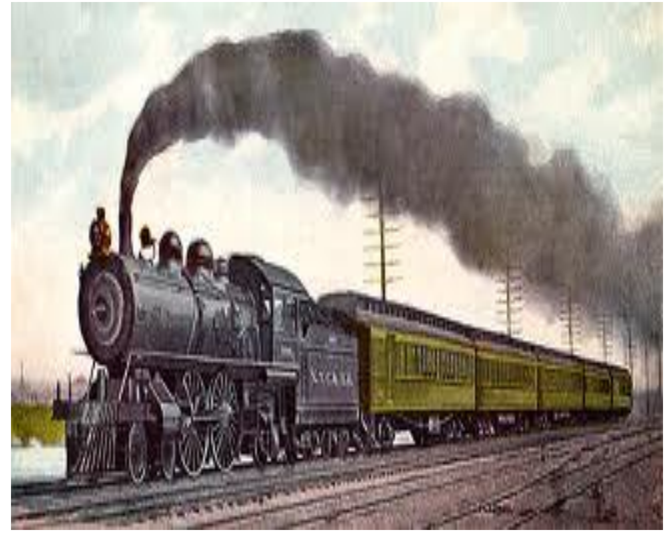


train stations

3. Carriers

automobiles

trains



airplanes

ships

Transportation Planning

- It is a methodological process of preparing physical facilities and services of modes for transportation needs

- Needed because of:

- Increased demand of new facilities and services
- Huge investments in transportation projects
- Land use development
- Many alternatives exist for any transportation project

BASIC ELEMENTS OF TRANSPORTATION PLANNING

1. Situation definition
2. Problem definition
3. Search for solutions
4. Analysis of performance
5. Evaluation of alternatives
6. Choice of project
7. Specification and construction

Basic elements of Transportation Planning

1. **Situation definition:**

- The present system is analyzed and its characteristics are described
- Information about the surrounding area, its people, and their travel habits may be obtained.
- Previous reports and studies that may be relevant to the present situation are reviewed

Basic elements of Transportation Planning :

2. Problem Definition:

- **Objectives** to be accomplished by the project (such as to reduce traffic congestion; to improve safety; to maximize net highway-user benefits; and to reduce noise)

- **Translate** those objectives into criteria that can be quantified, for example, the objective "to reduce traffic congestion" might use "travel time" as the measure of effectiveness.

Basic elements of Transportation Planning

3. Search for Solutions:

- consideration is given to a variety of ideas, designs, locations, and system configurations that might provide solutions to the problem.
- “brainstorming stage”
- includes preliminary feasibility studies
- some data gathering, field testing, and cost estimating to determine the practicality and financial feasibility of the alternatives being proposed

Basic elements of Transportation Planning

4. **Analysis of Performance:**

- To estimate performance of proposed alternatives under present and future conditions.
- Determination of the investment cost of building the transportation project, as well as annual costs for maintenance and operation.
- Involves the use of mathematical models for estimating travel demand.
- Determine use of the system (such as trip length, travel by time of day, and vehicle occupancy)
- Environmental effects are estimated

Basic elements of Transportation Planning

5. Evaluation of Alternatives:

- How well each alternative will achieve the objectives of the project as defined by the criteria.

- Performance data produced in the analysis phase are used to compute the benefits and costs that will result if the project is selected.

Basic elements of Transportation Planning

6. Choice of Project:

- It is made after considering all the factors involved.
  - Whether the factors were a single criterion such as cost (select the lower cost)
  - In more complex projects other factors might be considered, selection is based on how the results are perceived by those involved in decision-making

Basic elements of Transportation Planning

7. Specification and Construction:

- Detailed design phase in which each of the components of the facility is specified.

- This involves its physical location, geometric dimensions, and structural configuration.

Summary:

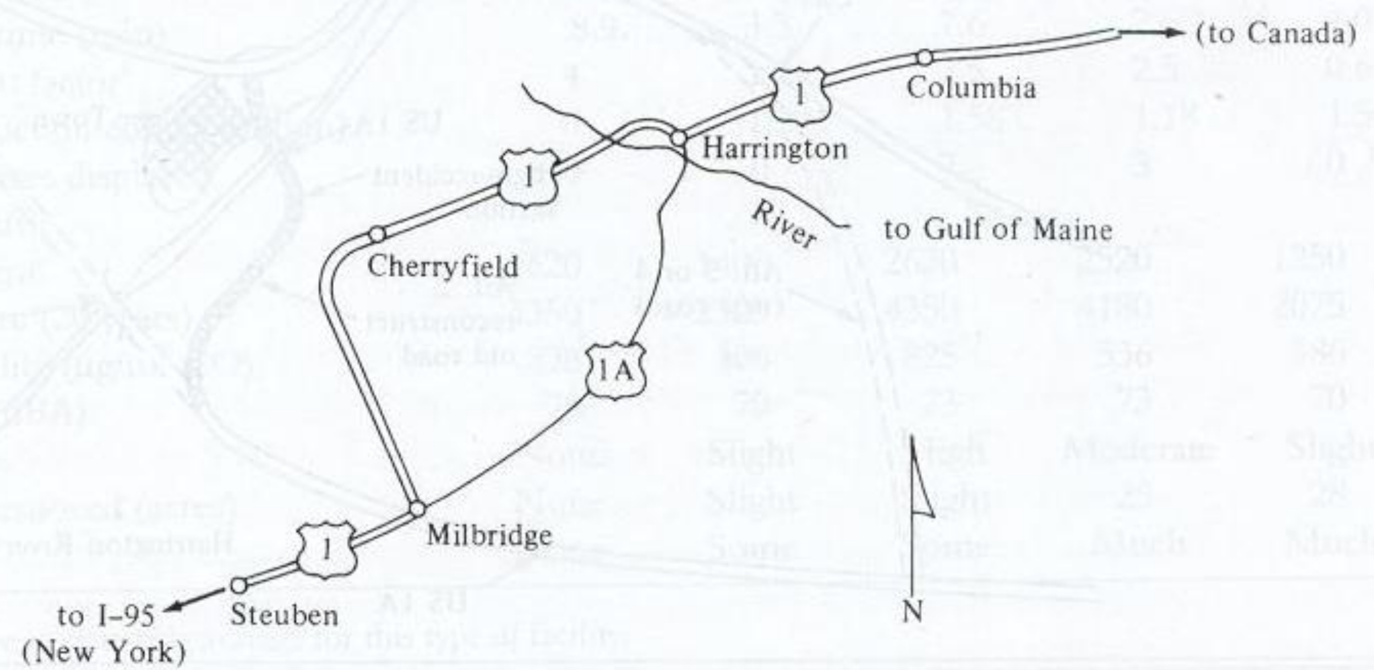
Situation definition	Inventory transportation facilities, Measure travel patterns, Review prior studies
Problem definition	Define objectives (e.g., Reduce travel time), Establish criteria (e.g., Average delay time), Define constraints, Establish design standards
Search for solutions	Consider options (e.g., locations and types, structure needs, environmental considerations)
Analysis of performance	For each option, determine cost, traffic flow, impacts
Evaluation of alternatives	Determine values for the criteria set for evaluation (e.g., benefits vs. cost, cost-effectiveness, etc)
Choice of project	Consider factors involved (e.g., goal attainability, political judgment, environmental impact, etc.)
Specification and construction	Once an alternative is chosen, design necessary elements of the facility and create construction plans

Example: Planning the relocation of a rural road (simple, yet good enough to explain the steps…)

Step 1: Situation definition:

- to understand the situation that gave rise to the perceived need for a transportation improvement

Figure 11.2 ■ Location Map for Highways U.S. 1 and U.S. 1A

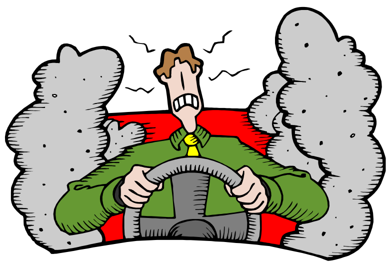


Step 2: Problem definition

Purpose of the step: Describe the problem in terms of the objectives to be accomplished and translate those objectives into criteria.

Example:

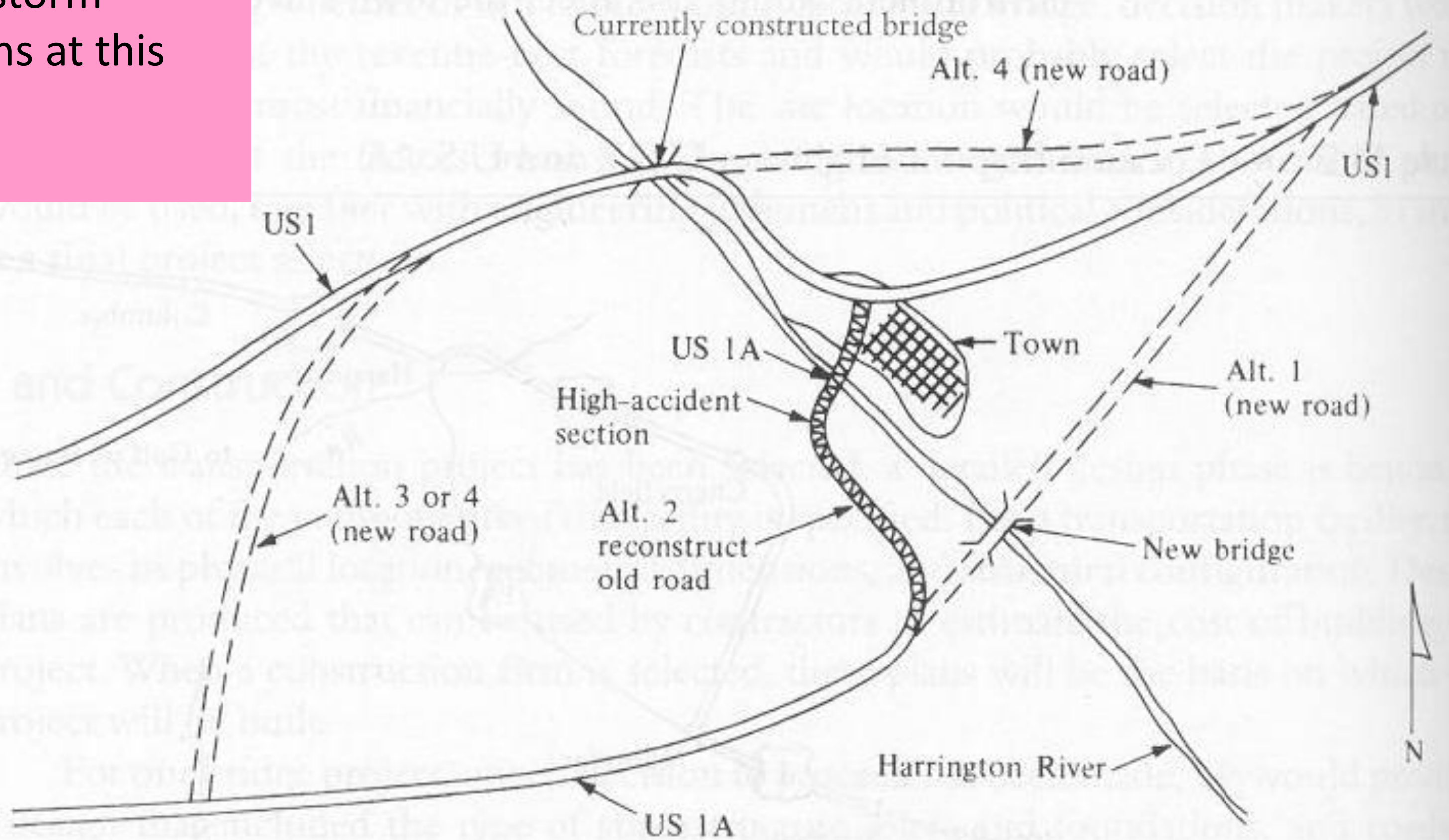
- Objective = Statements of purpose: Reduce traffic congestion, Improve safety, Maximize net highway-user benefits, etc.
- Criteria = Measures of effectiveness: Travel time, accident rate, delays (interested in reductions in these measures of effectiveness (MOEs)



Step 3: Search for solutions

Brainstorm options at this stage.

■ Alternative Routes for Highway Relocation



Step 4: Analysis of performance

- Estimate how each of the proposed alternatives would perform under present and future conditions.

Table 11.1
Measures of Effectiveness for Rural Road Alternatives

Criteria	Alternatives 0	1	2	3	4
Speed (mph)	25	55	30	30	55
Distance (mi)	3.7	3.2	3.8	3.8	3.7
Travel time (min)	8.9	3.5	7.6	7.6	4.0
Accident factor[a]	4	1.2	3.5	2.5	0.6
Construction cost ($ million)	0	1.50	1.58	1.18	1.54
Residences displaced	0	0	7	3	0
City traffic					
Present	2620	1400	2620	2520	1250
Future (20 years)	4350	2325	4350	4180	2075
Air quality ($\mu g/m^3$ CO)	825	306	825	536	386
Noise (dBA)	73	70	73	73	70
Tax loss	None	Slight	High	Moderate	Slight
Trees removed (acres)	None	Slight	Slight	25	28
Runoff	None	Some	Some	Much	Much

[a] Relative to statewide average for this type of facility.

pass th
re

Step 4: (cont) Ranking of alternatives (in terms of MOE)

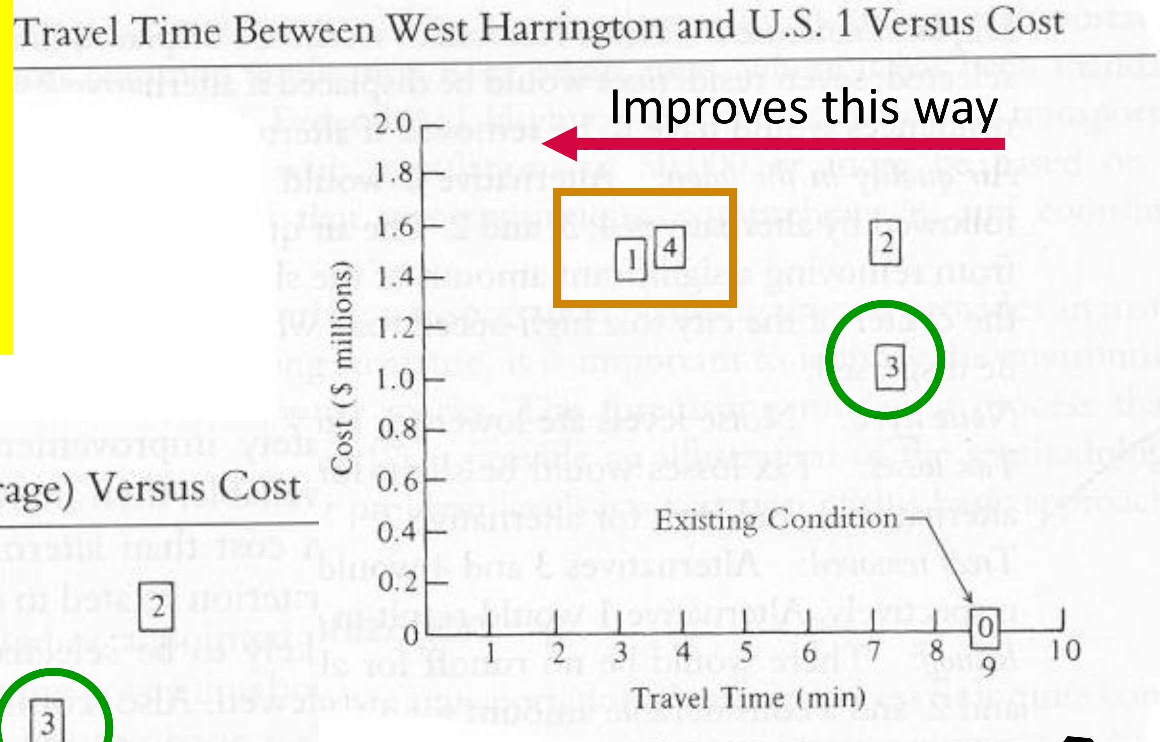
Table 11.2
Ranking of Alternatives

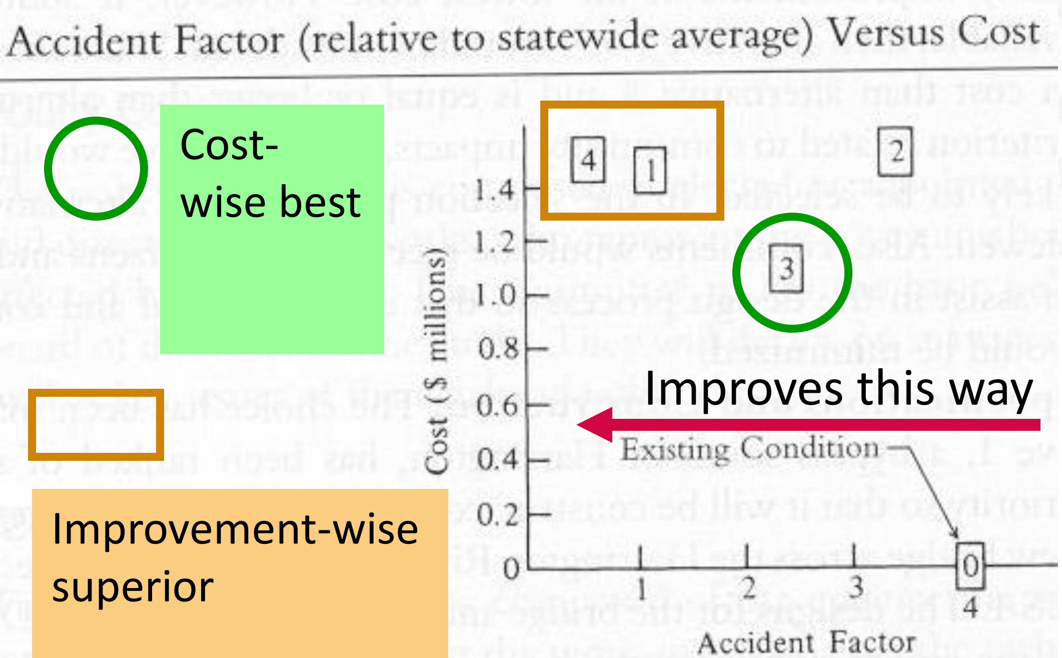
	Alternatives				
Criterion/Alternative	0	1	2	3	4
Travel time	4	1	3	3	2
Accident factor[a]	5	2	4	3	1
Cost ($ millions)	1	3	5	2	4
Residences displaced	1	1	3	2	1
Air quality	4	1	4	3	2
Noise	2	1	2	2	1
Tax loss	1	2	4	3	2
Trees removed (acres)	1	2	2	3	4
Increased runoff	1	2	2	3	3

Note: 1 = highest; 5 = lowest.
[a] Relative to statewide average for this type of facility.

Step 5: Evaluation of alternatives

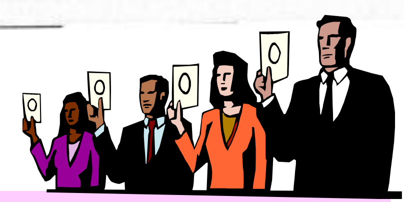
- Determine how well each alternative will achieve the objectives of the project as defined by the criteria.





Cost-wise best

Improvement-wise superior



This is a multi-objective evaluation problem.

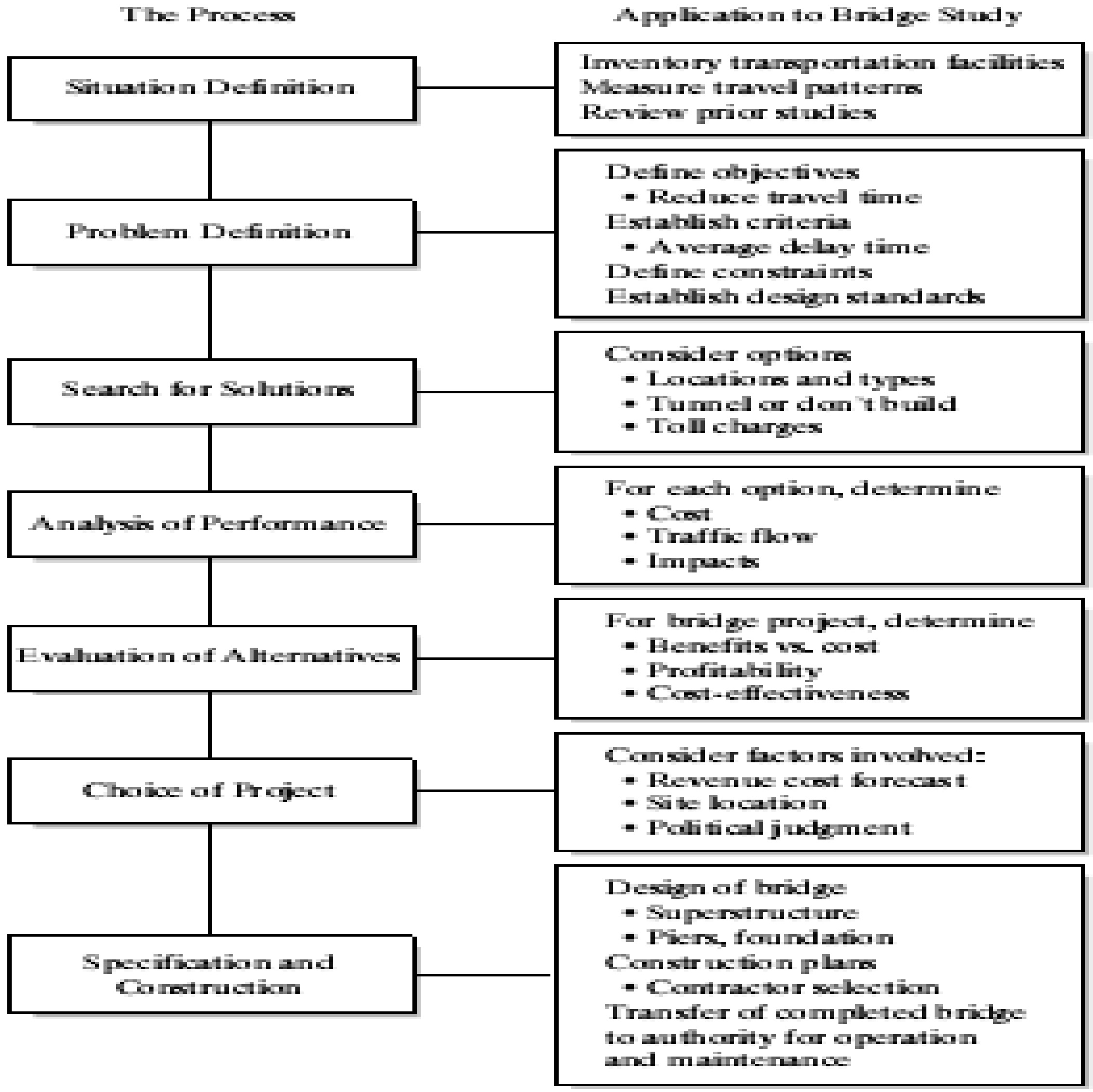


Figure 11.1 Basic Elements in the Transportation Planning Process Applied to Consider the Feasibility of a New Bridge

Urban Transportation Planning

- Involves the evaluation and selection of highway or transit facilities to serve present and future land uses.

- For example, the construction of a new shopping center, airport, or convention center will require additional transportation services. Also, new residential development, office space, and industrial parks will generate additional traffic, requiring the creation or expansion of roads and transit services.

Urban transportation planning time horizons.

1. short-term:

- to select projects that can be implemented within a 1- 3 year period
- These projects are designed to provide better management of existing facilities by making them as efficient as possible.
- Involve programs such as
  - ✓ traffic signal timing to improve flow,
  - ✓ car and van pooling to reduce congestion,
  - ✓ park-and-ride fringe parking lots to increase transit ridership,
  - ✓ and transit improvements.

Pictured above: Leesburg, VA Park & Ride Lot w/ bus shelters and bike lockers

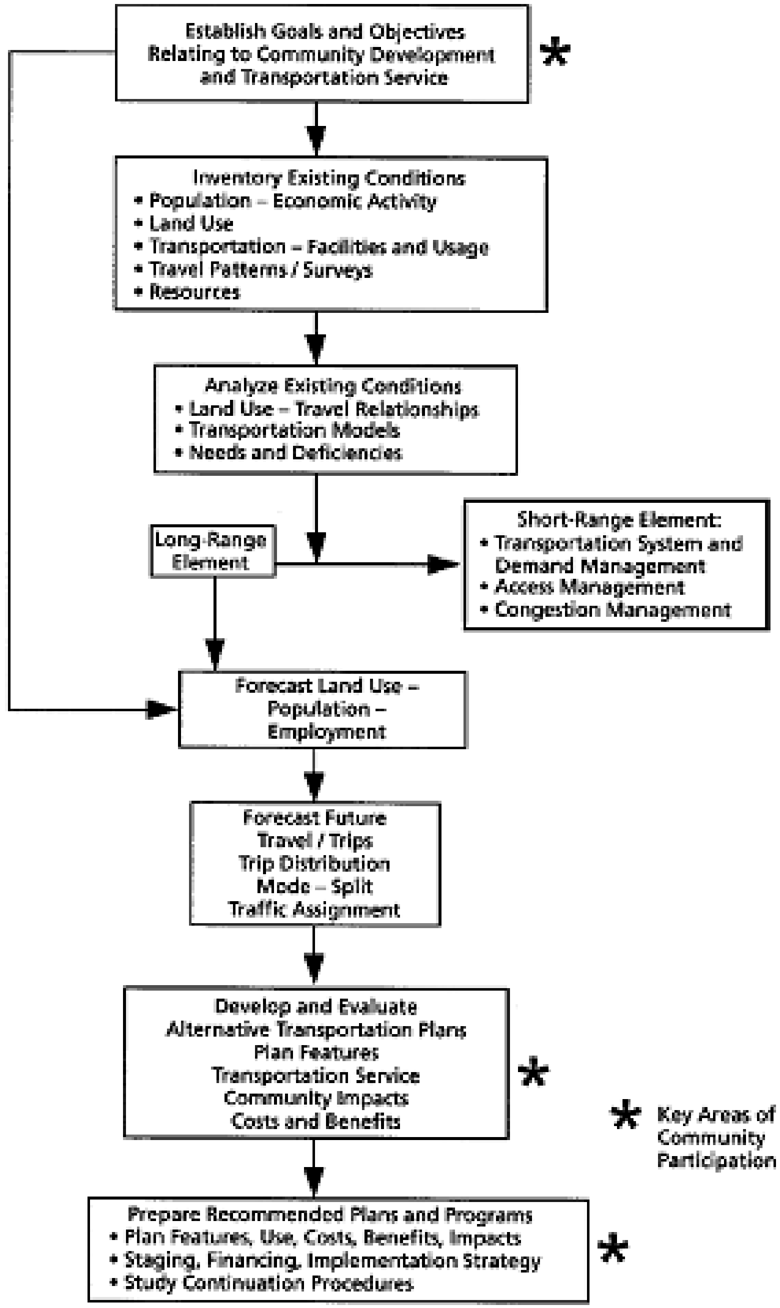
http://www.commuterconnections.org/commuters/transit/park-ride-locations/

Highway bus lane on Gyeongbu Expressway in South Korea.

Urban transportation planning time horizons.

2. long-range:

- identifies the projects to be constructed over a 20-year period.
- Involve programs such as
  - ✓ adding new highway elements,
  - ✓ additional bus lines or freeway lanes,
  - ✓ rapid transit systems and extensions,
  - ✓ or access roads



Comprehensive Urban Area Transportation Planning Process

Urban Transportation Planning

Why Functional classification is important?

- It is a method of communication among Engineers, Administrators, and the General public.

Functional Classification

- It is the grouping of highways by the character of service they provide, and it was developed for transportation planning purposes.

- It is an importatnt planning tool, and it is considered as the predominant method of grouping of highways

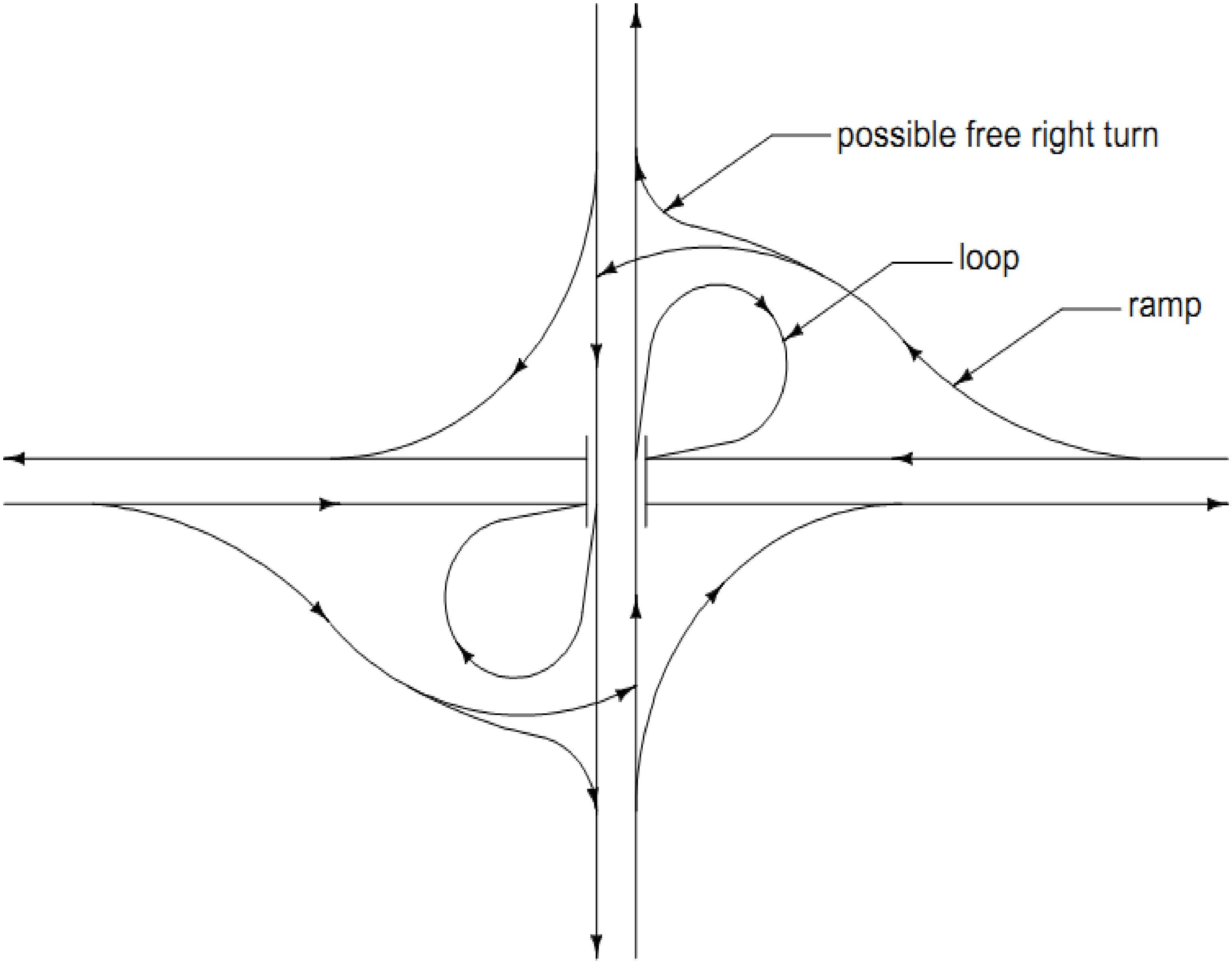
Hierarchies of movement and Components

- The complete functional design system provides a series of distinct movements.

- There are 6 recognizable stages in most trips:

  - Main movement (Principal arterials such as freeways: high efficiency and mobility) (V1)
  - Transition (ramps, loops) (V2)
  - Distribution (moderate speed arterial) (V3)
  - Collection (penetrate neighborhoods) (V4)
  - Access (direct approaches to individual residences or other termination) (V5)
  - Termination (parking) (V6)

Movement heirarchy is based on the total amount of traffic volume


possible free right turn
loop
ramp

The Cross Bronx Expressway in New York, United States

Highway 401 in Southern Ontario, Canada. An example of a collector-express freeway design, the route features four carriageways throughToronto

Highway Functional Classification

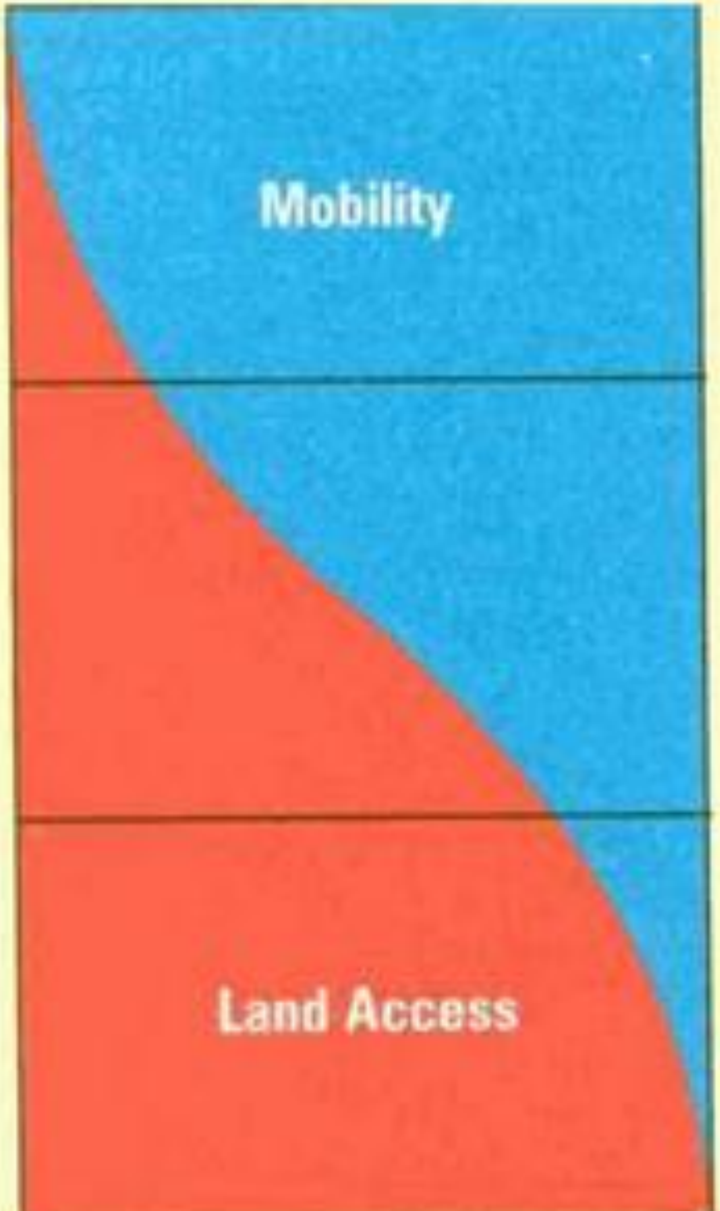
1. **Land access roads:** provide access to property, traffic volume is low

2. **Collectors:** provide access to higher type roads, these include primary highways and secondary urban arterial highways and other collector roads.

Highway Functional Classification

3. Major Arterial: provide primarily for relatively high volumes of traffic between population centers, this includes primary state highways and major urban arterial highways

4. Freeways: they connect large population centers, carrying heavy volumes of traffic, long distance in and around metropolitan area, provide no access to abutting property



Arterials

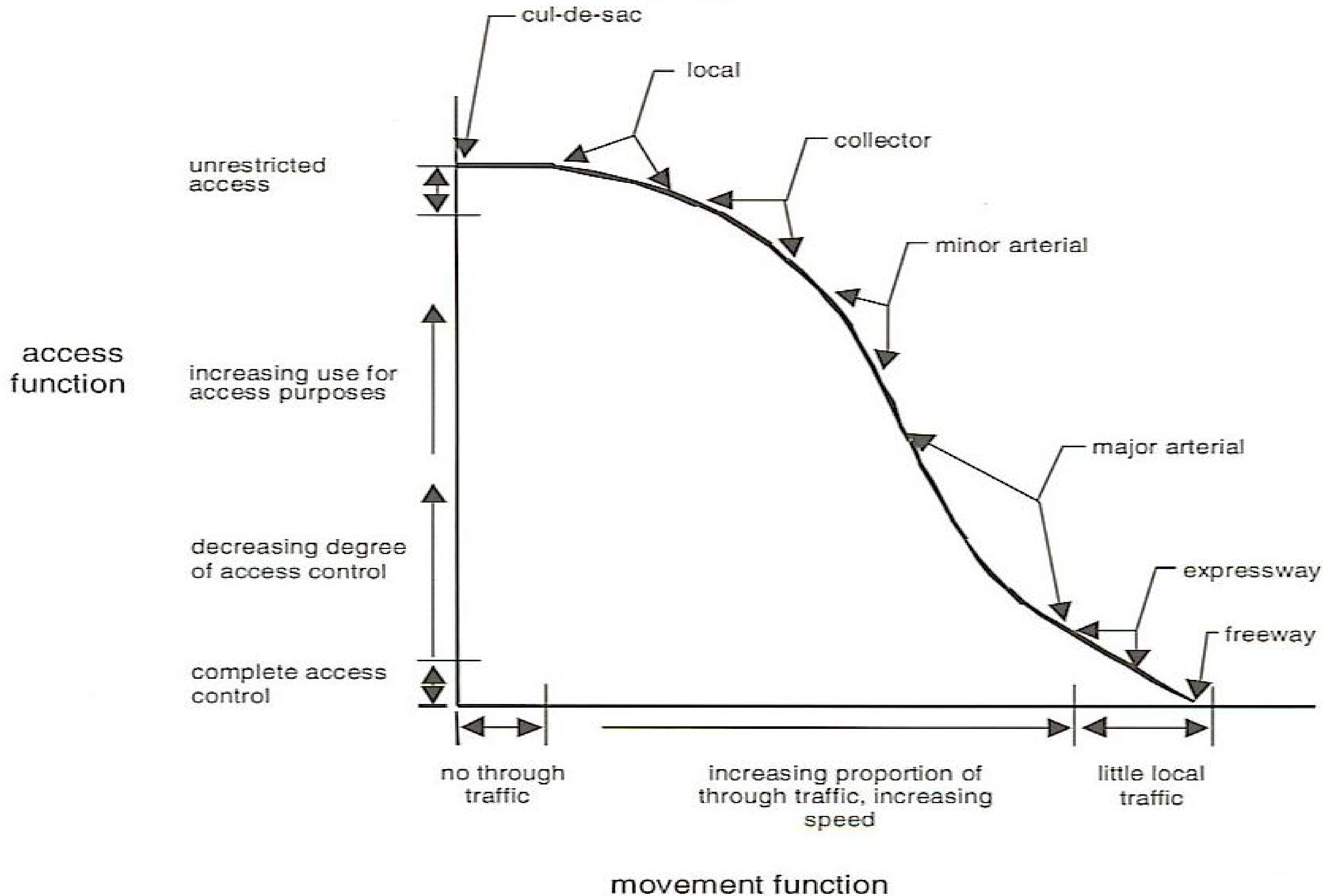
- higher mobility
- low degree of access

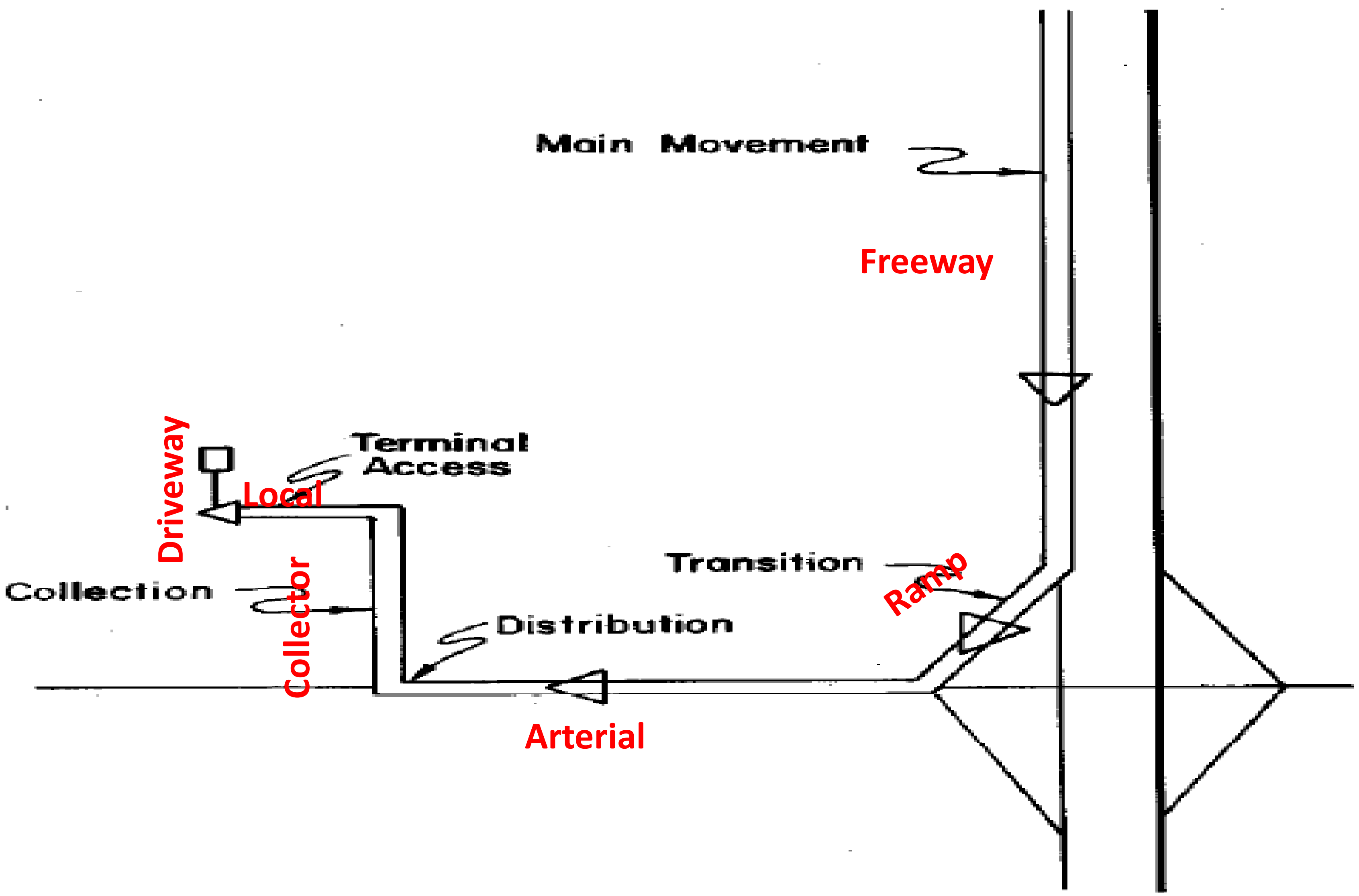
Collectors

- balance between mobility and access

Locals

- lower mobility
- high degree of access


cul-de-sac
local
collector
minor arterial
major arterial
expressway
freeway
unrestricted access
access function
increasing use for access purposes
decreasing degree of access control
complete access control
no through traffic
increasing proportion of through traffic, increasing speed
little local traffic
movement function



Hierarchy of Movement

Functional Classification

- Thus functional classification groups streets and highways according to the service they are intended to provide.

- Inividual roads and streets do not serve travel independently.

Definition of Urban and Rural Areas

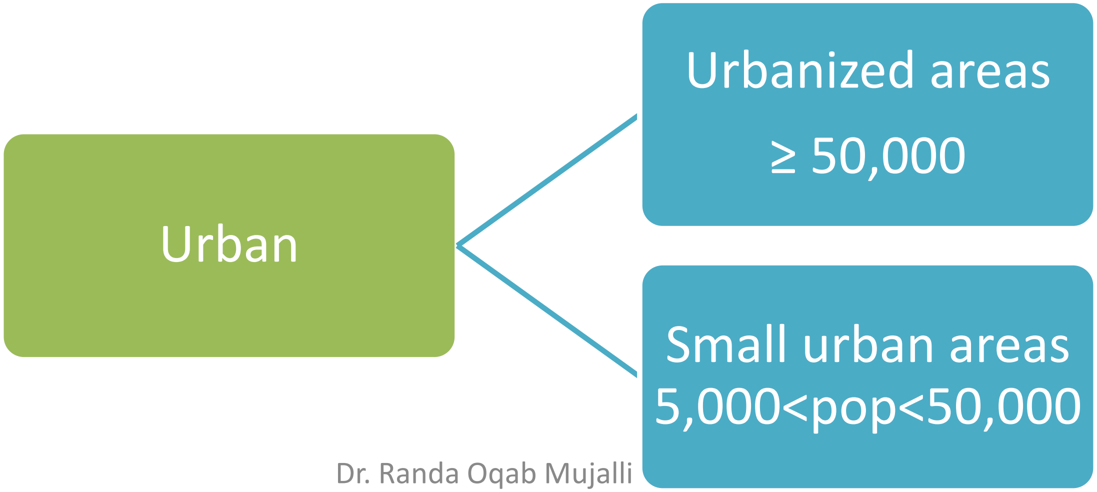
- Urban and rural functional systems are classified separately since they have different characteristics with regards to:
  - Density and types of land use
  - Density of street and highway networks
  - Nature and travel patterns
  - The way these elements are related

Definition of Urban and Rural Areas

- **Urban Areas:**

▪ Places within boundaries set by the responsible agencies/officials within the country having a population of ≥ 5,000

▪



Definition of Urban and Rural Areas

- **Rural Areas:**

Those areas outside the boundaries of urban areas

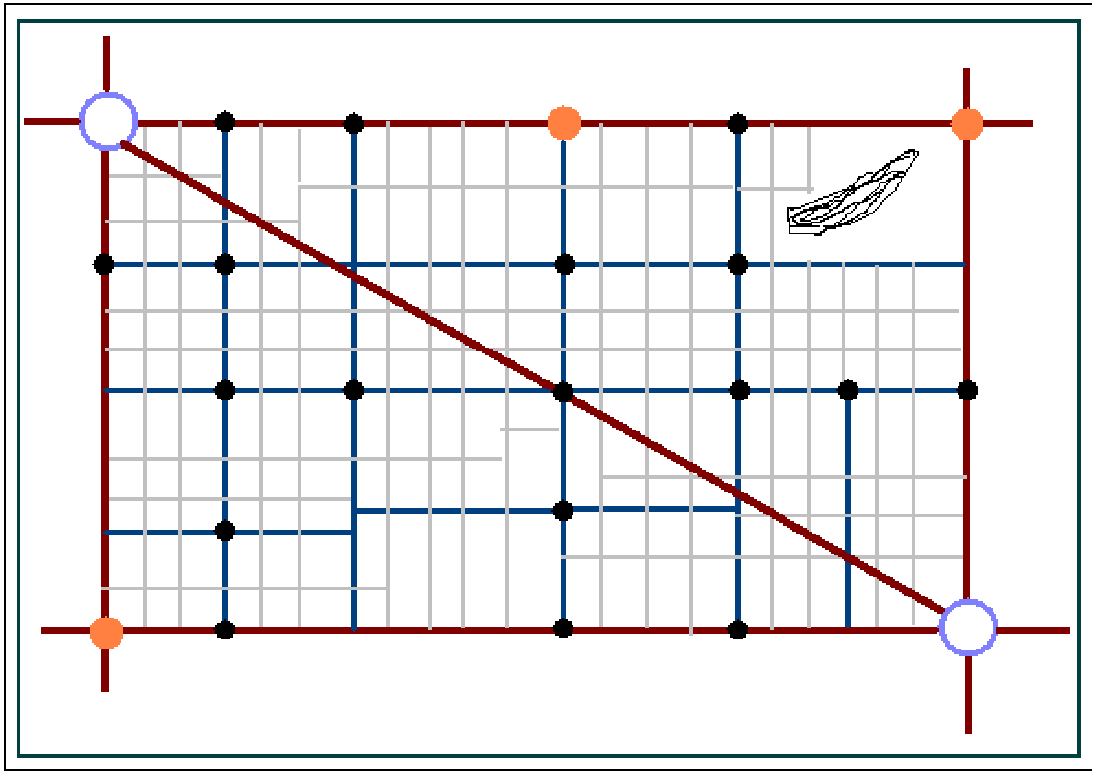
Functional Systems for rural and Urban areas

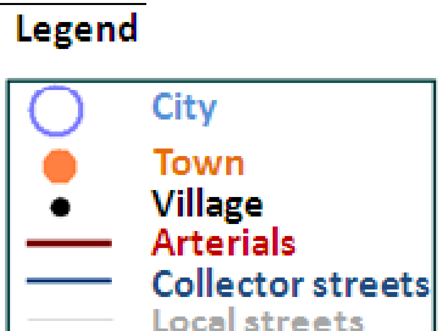
- Generally, the heirarchy of the functional systems consists of:

1. Principal arterials (for main movemets)
2. Minor arterials (distributers)
3. Collectors
4. Local roads and streets

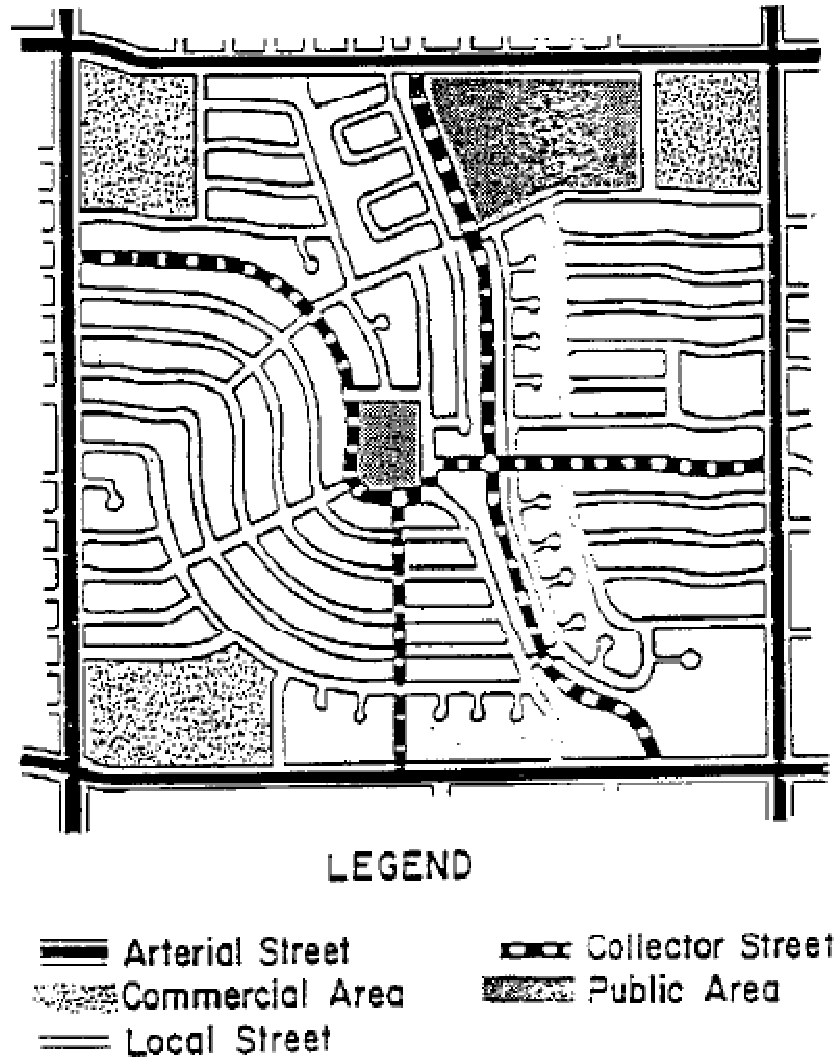
In general,

- ➢ In urban areas there are relatively more arterials
- ➢ In rural areas there are more collectors





Schematic of a rural highway network serving towns, villages, and cities.

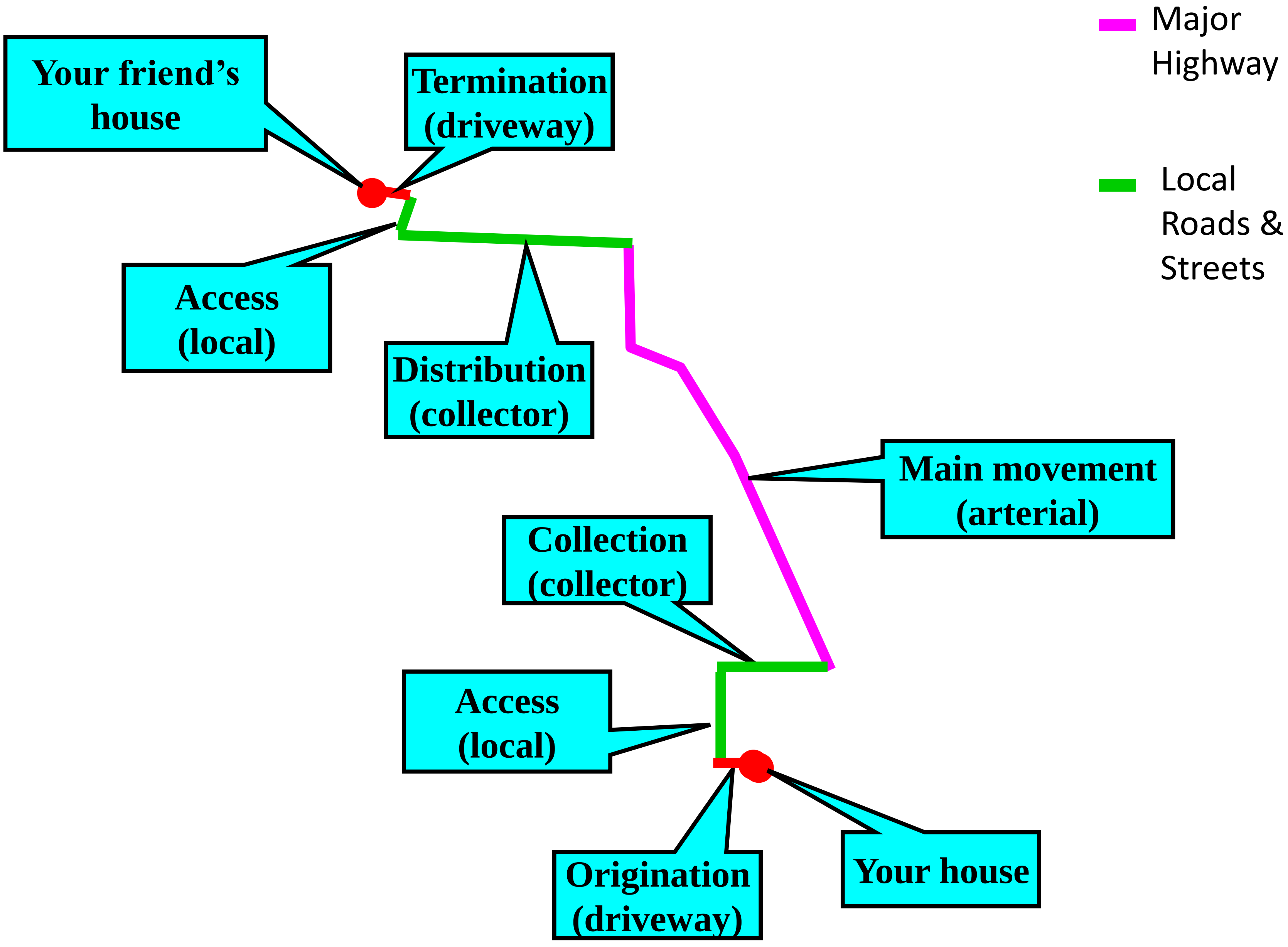


Schematic Illustration of a Portion of a Suburban Street Network

- Trip Phases

  – origination (driveway)
  – access (local road)
  – collection (collector)
  – transition (ramp)
  – main movement (arterial highway)
  – transition (ramp)
  – distribution (collector)
  – access (local road)
  – termination (driveway)

Hierarchy of Movements and Roads



Urban Transportation Planning Process (UTP)

Consists of 9 steps

1. Coding and Zoning
2. Inventory Studies (land use, socio-economic characteristics, link volume, link capacity, travel time)
3. Travel Studies (OD surveys)
4. Forecasts for the Horizontal Year (for design year estimates for: population, employment, land use, economic &social activity)
5. Trip General Analysis
6. Trip Distribution Analysis
7. Modal Split Analysis
8. Network Assignment Analysis
9. Evaluation (alternatives are compared based on system performance & environmental impact)

Travel demand model flowchart

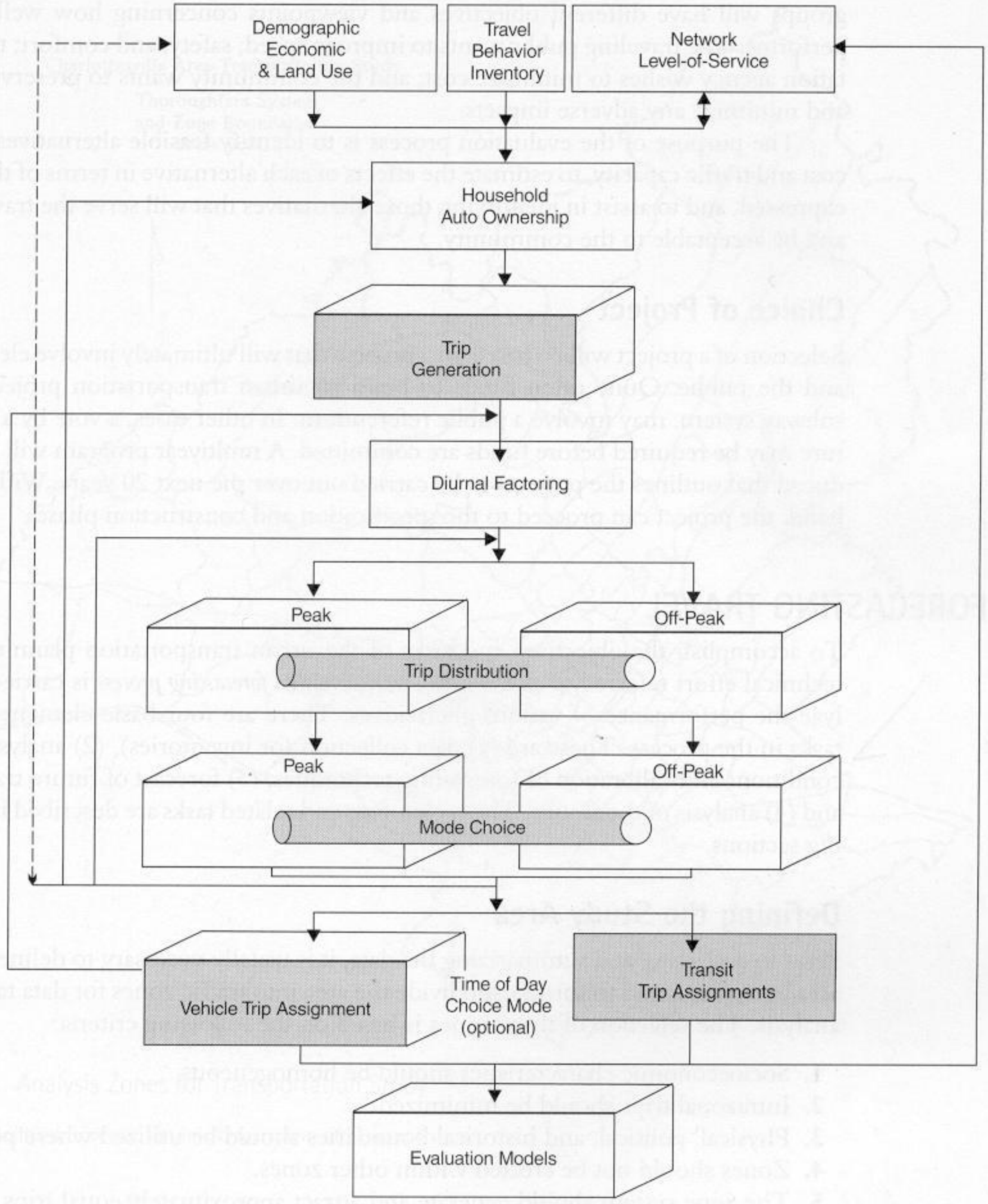
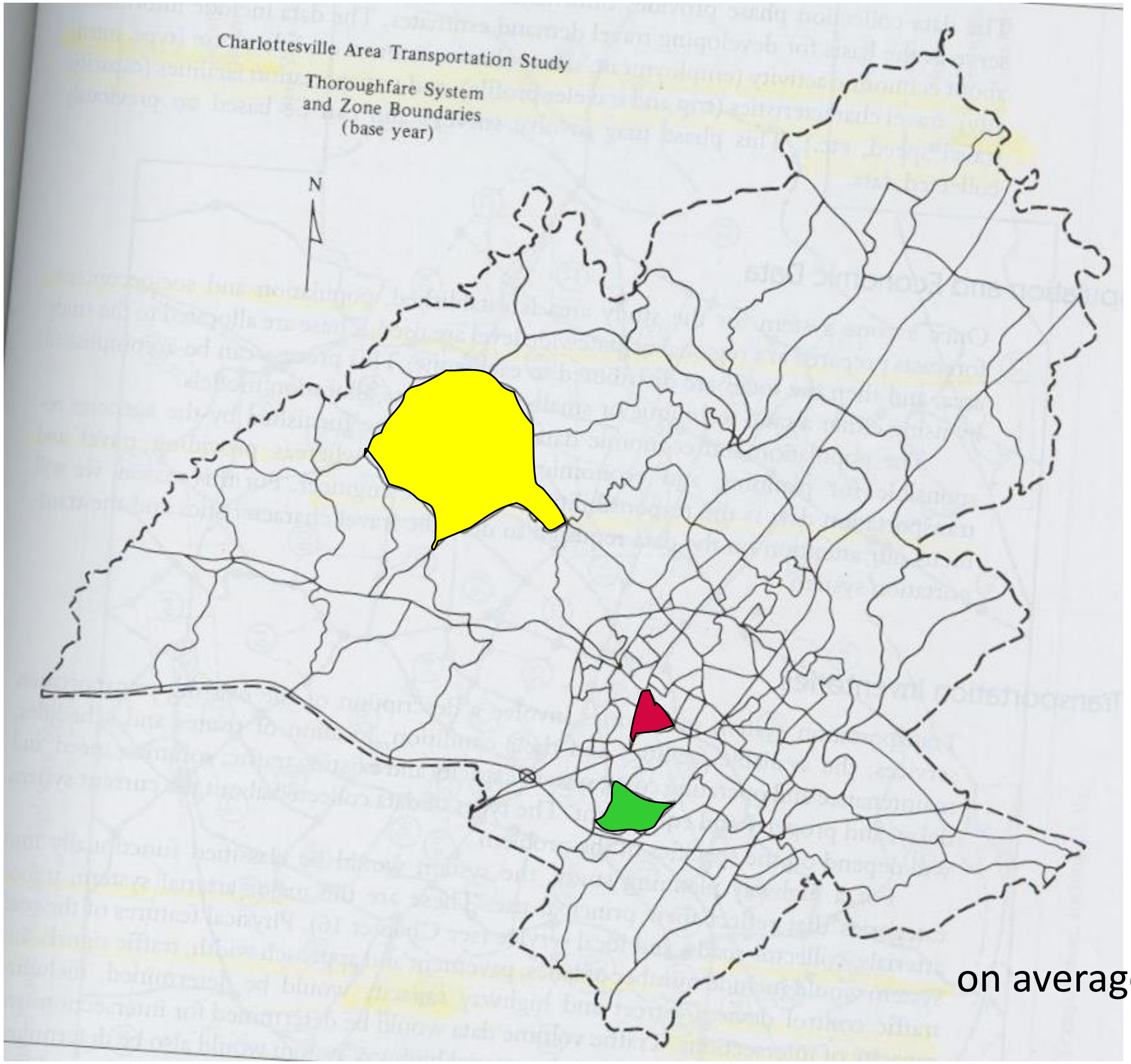


Figure 11.7 Travel Demand Model Flowchart

Four basic elements of the urban transportation forecasting process

Data collection (population, land use, etc.)	Economic activity (employment, sales volume, income, etc.), land use (type, intensity), travel characteristics (trip and traveler profile), and transportation facilities (capacity, travel speed, etc.), population and demography, Origin-destination trip data.
Analysis of existing conditions and calibration	Analyze the data collected in the data collection stage. You may build mathematical models describe the existing conditions and then use the relationships you have found in the existing parameters to forecast future values.
Forecast of future travel demand	4-step transportation demand forecasting process (Aggregate Sequential Demand Models)
Analysis of the results	Analyze what you get from the 4-stop demand forecasting process

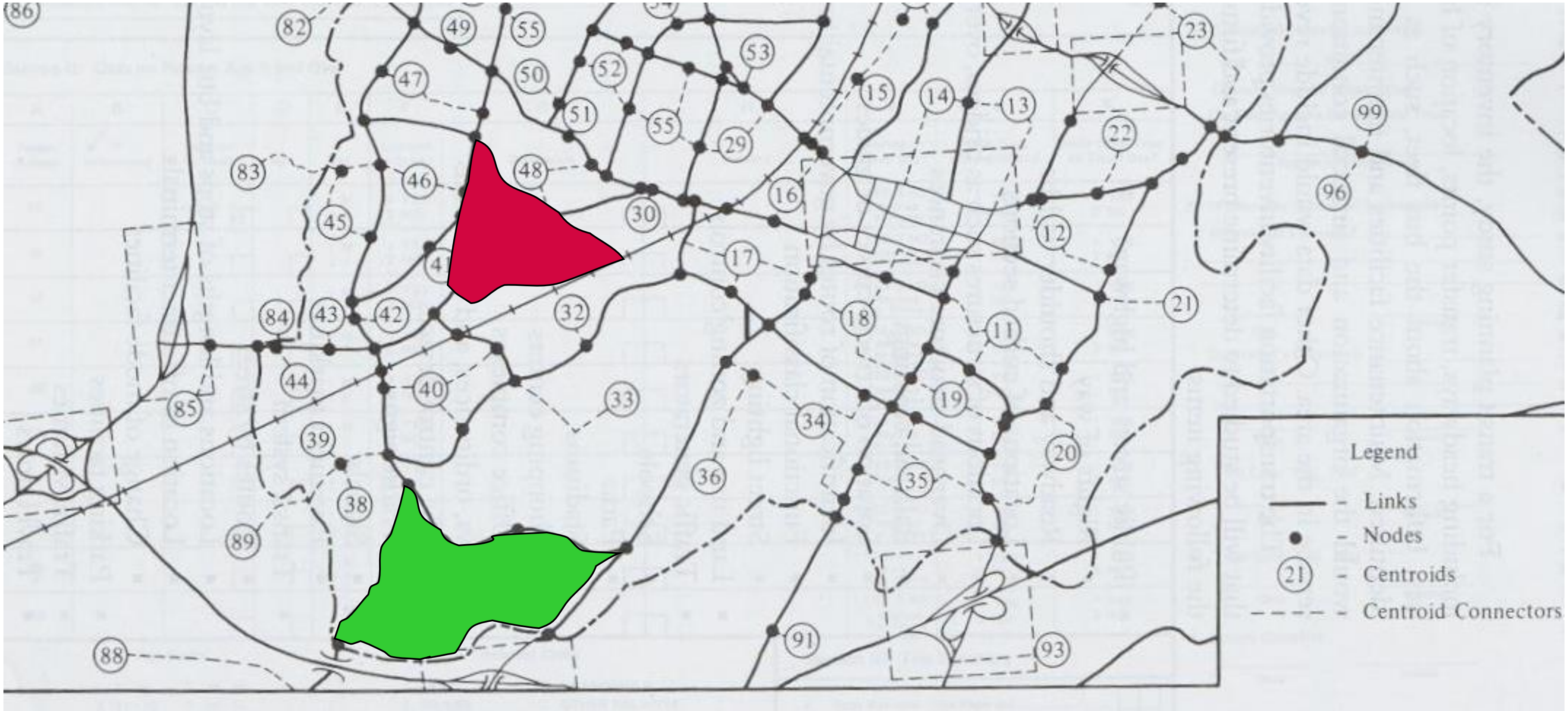
Analysis zones for transportation study (TAZ)



on average, one zone per 1,000 people

Link-node map for highway system

• Link-node maps are the starting point for the 4-step transportation demand forecasting process

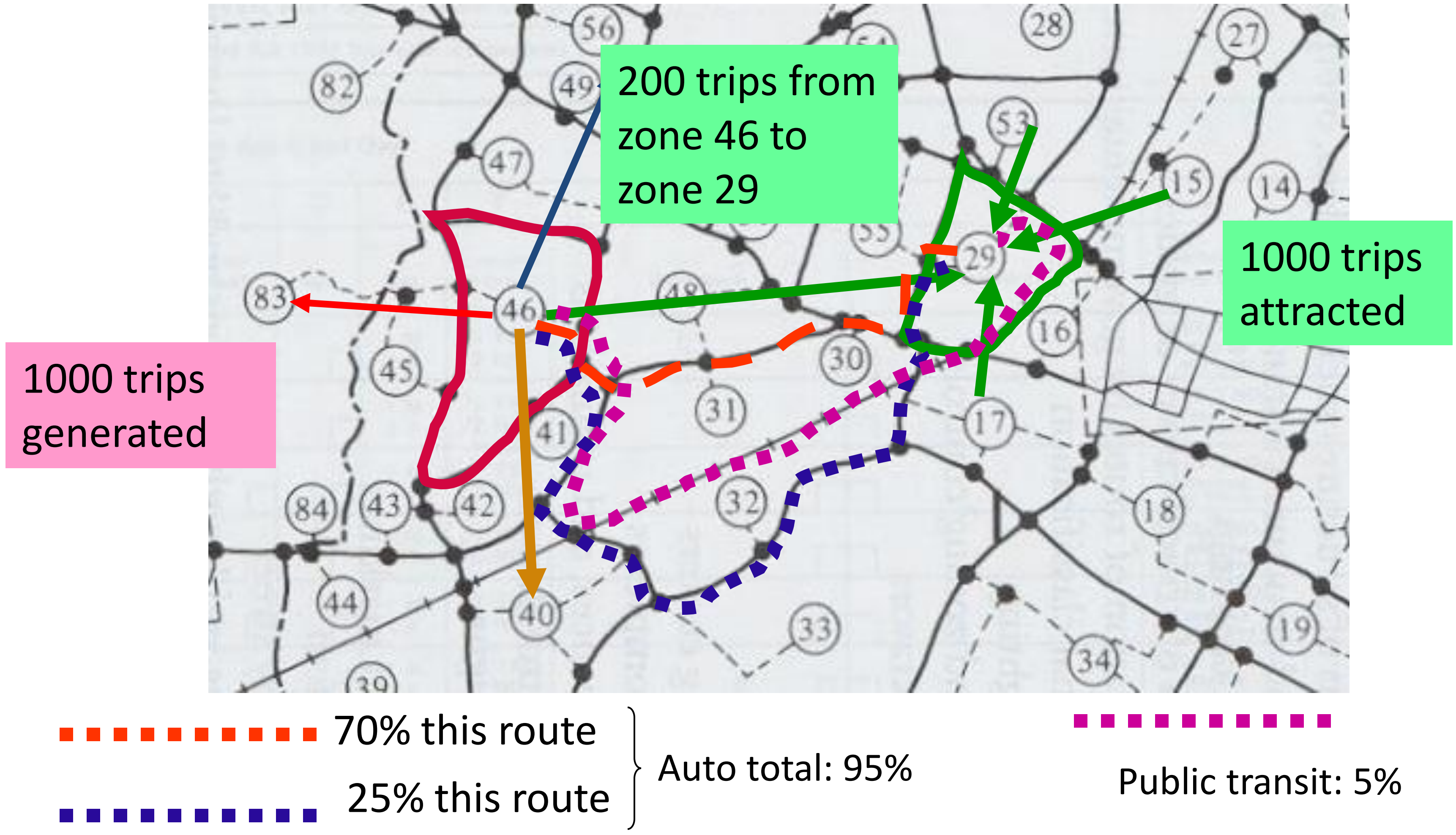


4-step transportation demand forecasting process

- Preparation: population and economic analysis and land use analysis

Trip generation	Determines how many trips each activity (center) (residential area, commercial area, etc) will produce or attract
Trip distribution	Determines the origin or destination of trips that are generated at a given activity
Modal split	Determines which mode of transportation will be used to make the trip
Traffic assignment	Determines which route on the transportation network will be used when making the trip

Graphical way of understanding the 4-step demand forecasting process



Transportation Demand Forecasting

- **A) TRIP GENERATION:**

- Trip generation analysis has two functions:
  - (1) to develop a relationship between trip end production or attraction and land use
  - (2) to use the relationship to estimate the number of trips generated at some future date under a new set of land use conditions.

Trip purposes normally defined:

1. Home-based work (HBW)
2. Home-based other (HBO)
3. Non-home based (NHB)

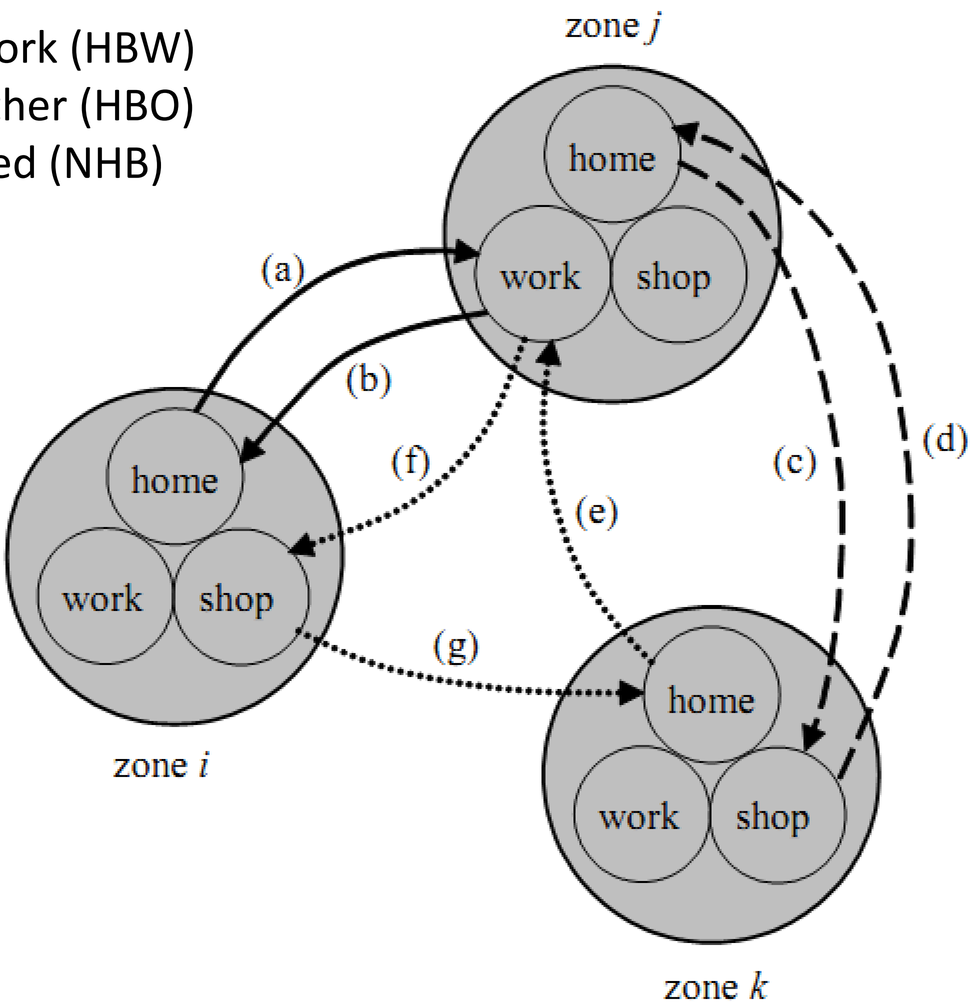


Figure 4.1: *Trip productions and attractions versus origins and destinations*

Transportation Demand Forecasting

- **Cross-Classification:** to determine the number of trips that begin or end at the home

- The first step is to develop a relationship between **socioeconomic** measures and **trip production**.

- The two variables most commonly used are **average income** and **auto ownership**.

- Other variables that could be considered are **household size** and **stage in the household life cycle**.

- **Example:** A travel survey produced the data shown in Table

Based on the data provided, develop a set of curves showing the number of trips per household versus income and auto Ownership?

Table 12.1 Survey Data Showing Trips per Household, Income, and Auto Ownership

Household Number	*Trips Produced per Household*	*Household Income ($1000s)*	*Autos per Household*
1	2	16	0
2	4	24	0
3	10	68	2
4	5	44	0
5	5	18	1
6	15	68	3
7	7	38	1
8	4	36	0
9	6	28	1
10	13	76	3
11	8	72	1
12	6	32	1
13	9	28	2
14	11	44	2
15	10	44	2
16	11	52	2
17	12	60	2
18	8	44	1
19	8	52	1
20	6	28	1

Table 12.2 Number and Percent of Household in Each Income Category versus Car Ownership

	Autos Owned			
Income ($1000s)	*0*	*1*	*2+*	*Total*
≤24	2(67) =2/3=0.67	1(33)	0(0)	3(100)
(24–36]	1 20	3(60	1 20)	5(100)
36–48	1(20)	2(40)	2(40)	5(100)
48–60	—	1(33)	2(67)	3(100)
>60	—	1(25)	3(75)	4(100)
Total	4	8	8	20

Note: Values in parentheses are percent of automobiles owned at each income range.

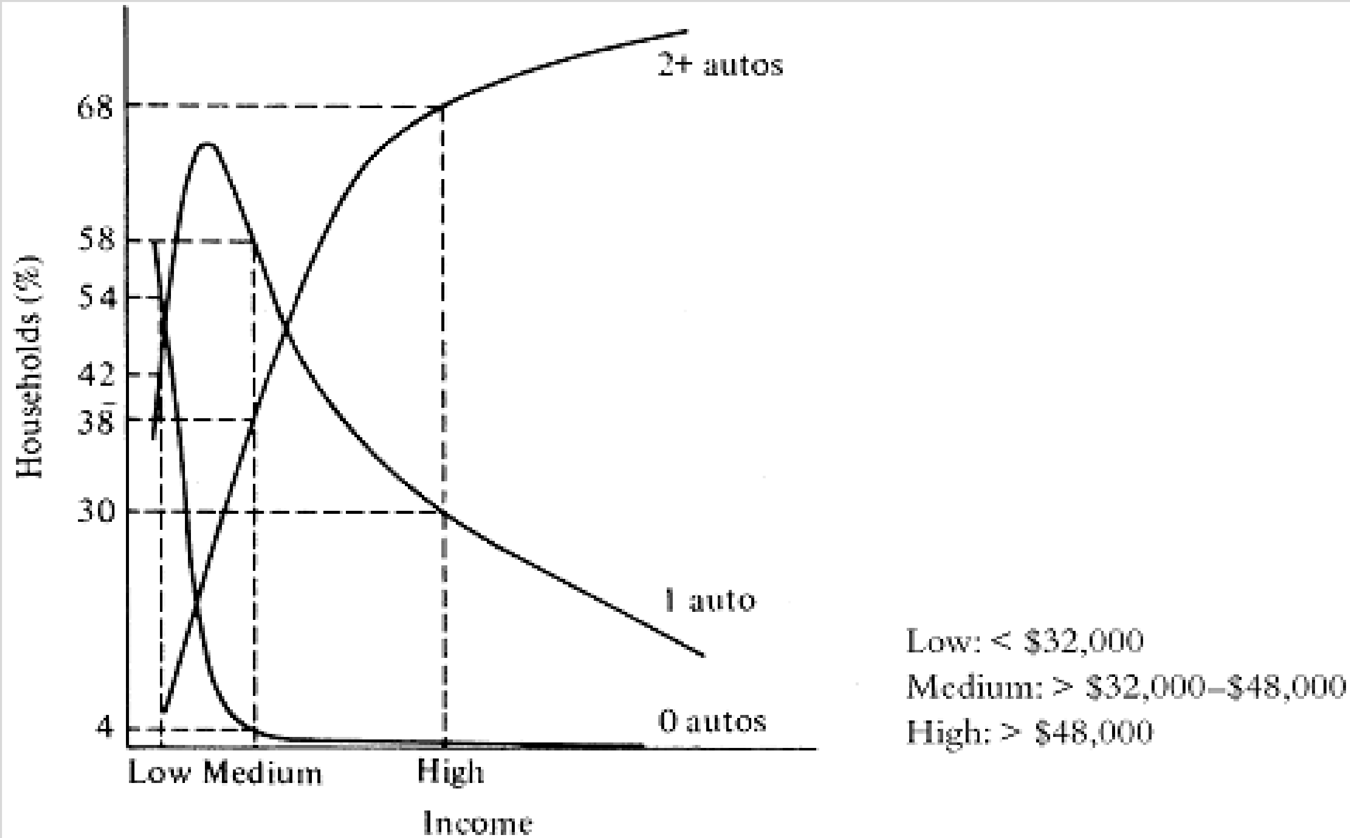


Figure 12.3 Households by Automobile Ownership and Income Category

SOURCE: Modified from *Computer Programs for Urban Transportation Planning*, U.S. Department of Transportation, Washington, D.C., April 1977.

- Step 2: the average number of trips per household versus income and cars owned.

Table 12.3 Average Trips per Household versus Income and Car Ownership

	Autos Owned				
Income ($1000s)	*0*		*1*		*2+*
≤24	3	=(2+4)/2	5	=5/1	–
24–36	4		6	=6+6+6/3	9
36–48	5		7.5		10.5
48–60	–		8.5		11.5
>60	–		8.5		12.7

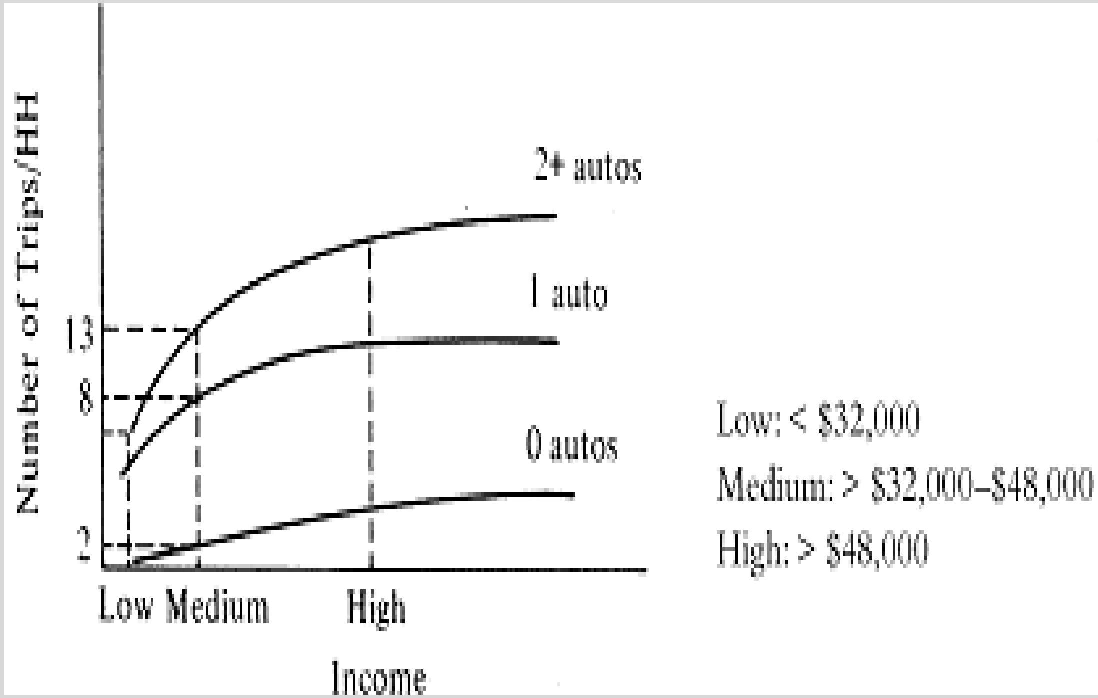


Figure 12.4 Trips per Household per Day by Auto Ownership and Income Category

SOURCE: Modified from *Computer Programs for Urban Transportation Planning*, U.S. Department of Transportation, Washington, D.C., April 1977.

- **Step 3:** additional O-D data (not shown in Table 12.1) can be used to determine the percentage of trips by each trip purpose for each income category.

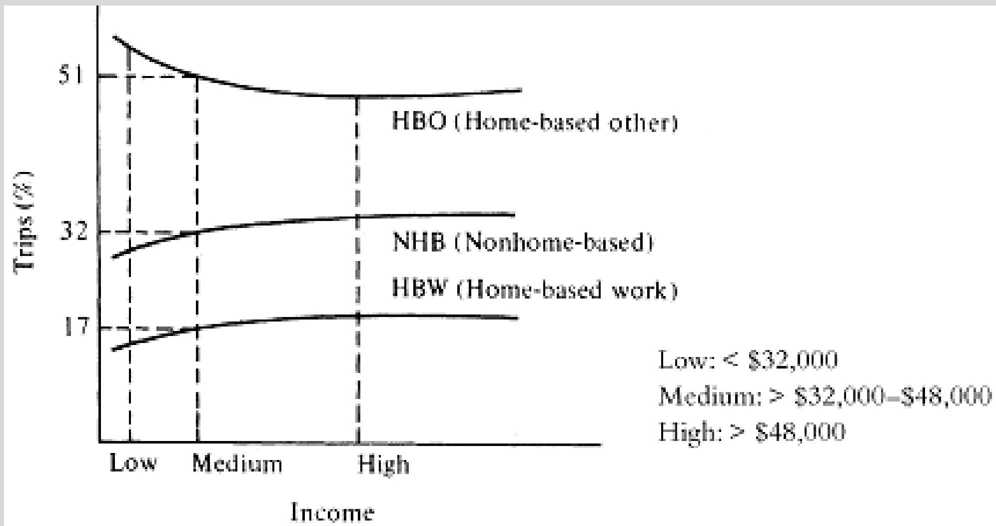


Figure 12.5 Trips by Purpose and Income Category

SOURCE: Modified from *Computer Programs for Urban Transportation Planning*, U.S. Department of Transportation, Washington, D.C., April 1977.

Example 12.2 Computing Trips Generated in a Suburban Zone

Consider a zone that is located in a suburban area of a city. The population and income data for the zone are as follows.

Number of dwelling units: 60
Average income per dwelling unit: $44,000

Determine the number of trips per day generated in this zone for each trip purpose, assuming that the characteristics depicted in Figures 12.2 through 12.5 apply in this situation. The problem is solved in four basic steps.

- **Step 1:** Determine the percentage of households in each economic category

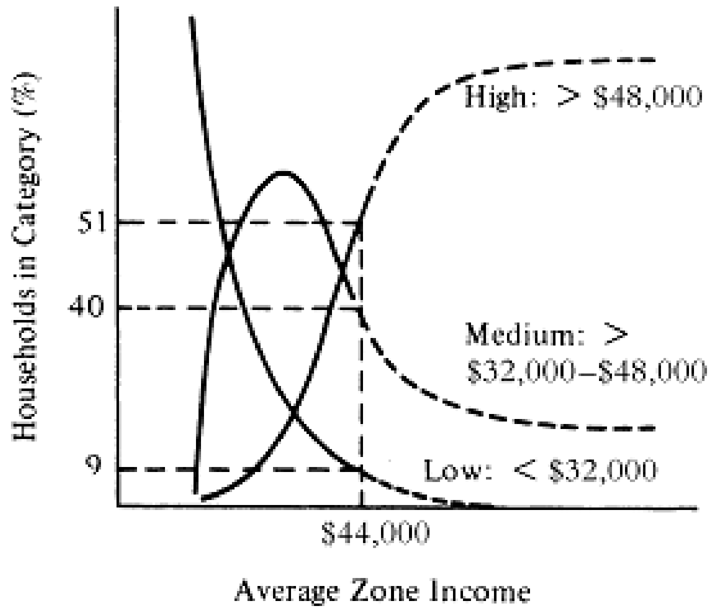


Figure 12.2 Average Zonal Income versus Households in Income Category

Income ($)	*Households (%)*
Low (under 32,000)	9
Medium (32,000 – 48,000)	40
High (over 48,000)	51

- **Step 2:** Determine the distribution of auto ownership per household for each income category.

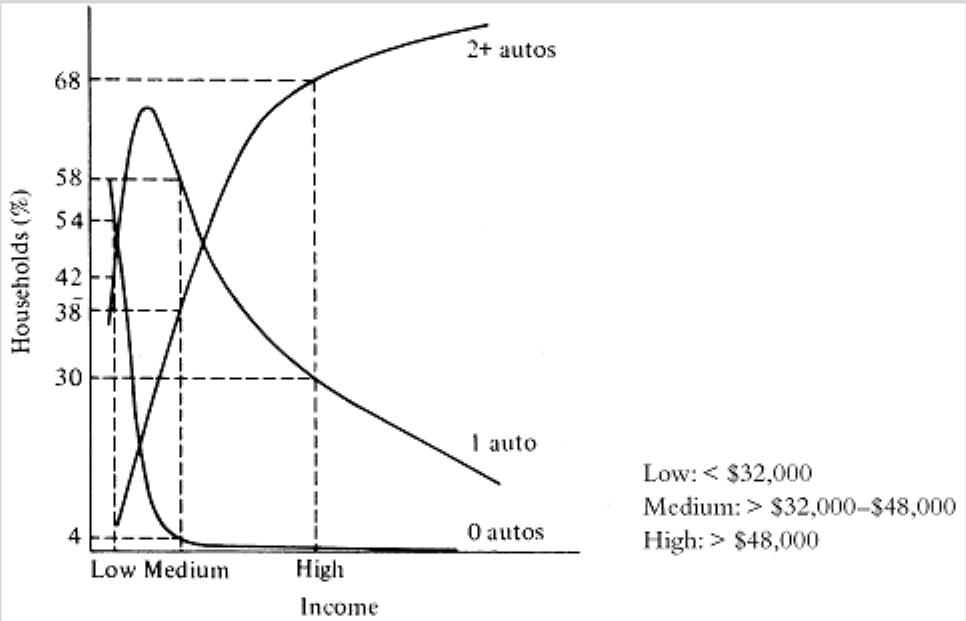


Figure 12.3 Households by Automobile Ownership and Income Category

Table 12.4 Percentage of Households in Each Income Category versus Auto Ownership

	Autos/Household		
Income	*0*	*1*	*2+*
Low	54	42	4
Medium	4	58	38
High	2	30	68

- **Step 3:** Determine the number of trips per household per day for

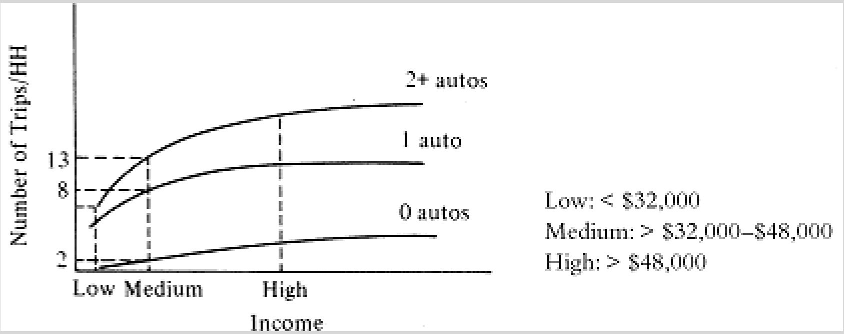


Figure 12.4 Trips per Household per Day by Auto Ownership and Income Category

Table 12.5 Number of Trips per Household per Day

	Autos/Household		
Income	*0*	*1*	*2+*
Low	1	6	7
Medium	2	8	13
High	3	11	15

Table 12.6 Number of Trips per Day Generated by Sixty Households

	Income, Auto Ownership	*Total Trips by Income Group*
$60 \times 0.09 \times 0.54 \times 1 = 3$ trips	L, 0+	
$60 \times 0.09 \times 0.42 \times 6 = 14$ trips	L, 1+	
$60 \times 0.09 \times 0.04 \times 7 = 2$ trips	L, 2+	19
$60 \times 0.40 \times 0.04 \times 2 = 2$ trips	M, 0+	
$60 \times 0.40 \times 0.58 \times 8 = 111$ trips	M, 1+	
$60 \times 0.40 \times 0.38 \times 13 = 119$ trips	M, 2+	232
$60 \times 0.51 \times 0.02 \times 3 = 2$ trips	H, 0+	
$60 \times 0.51 \times 0.30 \times 11 = 101$ trips	H, 1+	
$60 \times 0.51 \times 0.68 \times 15 = 312$ trips	H, 2+	415
Total $= 666$ trips		666

- Table 12.4 shows that 58% of medium-income families own one auto per household.
- Also, from the previous step, we know that a zone, with an average income of \$44,000, contains 40% of households in the medium-income category.

Step 5. Determine the percentage of trips by trip purpose. As a final step, we can calculate the number of trips that are HBW, HBO, and NHB. If these percentages are 17, 51, and 32, respectively (see Figure 12.5), for the medium-income category, then the number of trips from the zone for the three trip purposes are $232 \times 0.17 = 40$ HBW, $232 \times 0.51 = 118$ HBO, and $232 \times 0.32 = 74$ NHB. (Similar calculations would be made for other income groups.) The final result, which is left for the reader to verify, is obtained by using the following percentages: low income at 15, 55, and 30, and high income at 18, 48, and 34. These yield 118 HBW, 327 HBO, and 221 NHB trips.

- A likely result of the trip generation process is that the number of trip productions may not be equal to the number of trip attractions.

- **Trip productions, which are based on census data, are considered to be more accurate than trip attractions.**

- trip attractions are usually modified so that they are equal to trip productions.

Rates Based on Activity Units

- Trips generated at the household end are referred to as productions, and they are attracted to zones for purposes such as work, shopping, visiting friends, and medical trips.

- An activity unit can be described by measures such as:

  – Square feet of floor space or,
  – Number of employees.

Table 12.7 Trip Generation Rates by Trip Purpose and Employee Category

	Attractions per Household	*Attractions per Nonretail Employee*	*Attractions per Downtown Retail Employee*	*Attractions per Other Retail Employee*
HBW	–	1.7	1.7	1.7
HBO	1.0	2.0	5.0	10.0
NHB	1.0	1.0	3.0	5.0

- Rate: it refers to the number of trips per day per activity center.

Example 12.3 Computing Trips Generated in an Activity Zone

A commercial center in the downtown contains several retail establishments and light industries. Employed at the center are 220 retail and 650 non-retail workers. Determine the number of trips per day attracted to this zone.

Solution: Use the trip generation rates listed in Table 12.7.

$$\text{HBW: } (220 \times 1.7) + (650 \times 1.7) = 1479$$
$$\text{HBO: } (220 \times 5.0) + (650 \times 2.0) = 2400$$
$$\text{NHB: } (220 \times 3.0) + (650 \times 1.0) = 1310$$
$$\text{Total} = 5189 \text{ trips/day}$$

Note that three trip purposes are given in Table 12.7: home-based work (HBW), home-based other (HBO), and non-home-based (NHB). For example, for HBO trips, there are 5.0 attractions per downtown retail employee (in trips/day) and 2.0 attractions per non-retail employee.

Balancing Home-Based Work Trips

Zone	Unbalanced HBW Trips		Balanced HBW Trips	
	Productions	*Attractions*	*Productions*	*Attractions*
1	100	240	100	180
2	200	400	200	300
3	300	160	300	120
Total	600	800	600	600

The factor to balance trip productions/attractions= total prod./total attr.

The same procedure is followed for HBO

Balancing Non-Home-Based Trips

Zone	*Unbalanced NHB Trips* NHB Productions	*Unbalanced NHB Trips* NHB Attractions	*Balanced NHB Trips* NHB Productions	*Balanced NHB Trips* NHB Attractions
1	100	240	180	180
2	200	400	300	300
3	300	160	120	120
Total	600	800	600	600

- 1. Multiply by the factor (total prod./total attr.)
- 2. The productions are to be equal to attractions

B) TRIP DISTRIBUTION:

- is a process by which the trips generated in one zone are allocated to other zones in the study area.
- These trips may be within the study area (internal-internal) or between the study area and areas outside the study area (internal-external)
- For example, if the trip generation analysis results in an estimate of 200 HBW trips in zone 10, then the trip distribution analysis would determine how many of these trips would be made between zone 10 and all the other zones.

- Several basic methods are used for trip distribution. Among these are the **gravity model**

Origins	Destinations				$\sum_j T_{ij}$
	1	2	...	n	
1					P1
2		?			P2
...					...
m					Pm
$\sum_i T_{ij}$	A1	A2	...	An	

trip distribution

- **Gravity Model:** states that the number of trips between two zones is **directly proportional** to the **number of trip attractions generated by the zone of destination** and **inversely** proportional to a **function of time of travel between the two zones**.

Terminology

Friction factor is a function of impedance of travel from production to attraction, measured in terms of travel time and cost. Friction factor (or the perception of distance) varies by trip type.

Gravity model is adapted from Newton's Law of Gravity. It requires estimates of the relative attractiveness of a TAZ as well as a measure of the impedances between TAZs.

K-factors are used to model individual zonal variation not otherwise accounted for in the gravity model.

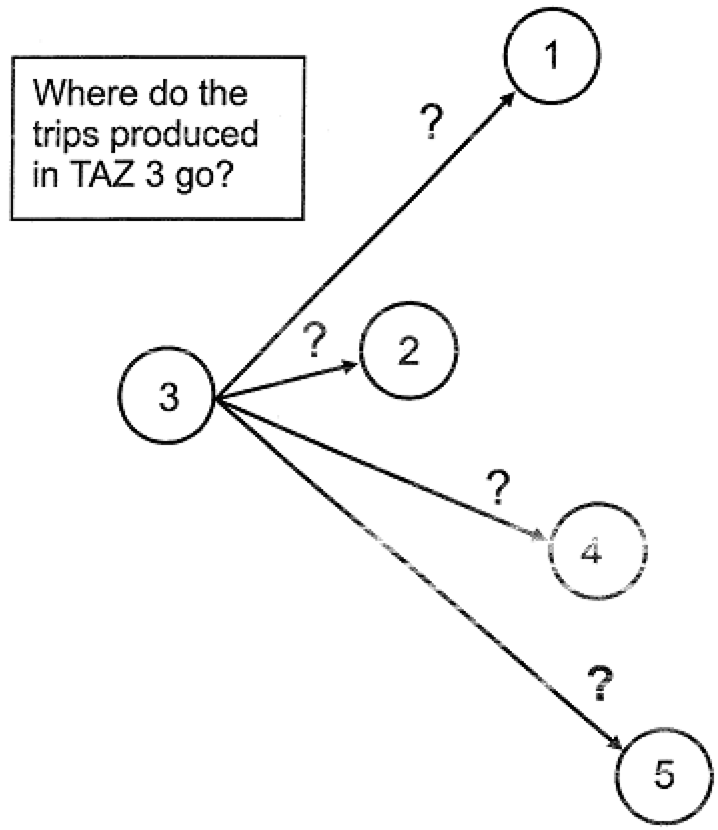
Trip distribution uses trip ends from trip generation and network impedance to link trip ends to TAZs.

Key Concepts

Trip distribution is a method to determine where the trips are going

- Distribute trips produced in one TAZ to all other TAZs
- Calibrate to reflect current travel patterns
- Apply to forecast future travel patterns

Gravity Model

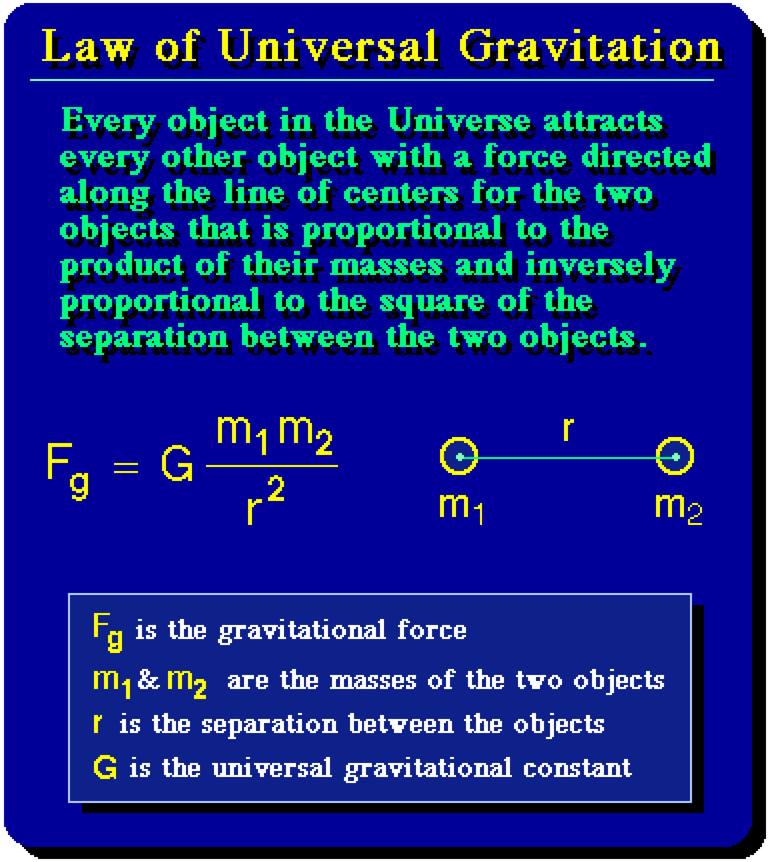


Gravity Model

The gravity model was adapted from Newton's Law of Gravitation, which states that the amount of gravitational force between masses is a function of the mass of the bodies and distance between them.

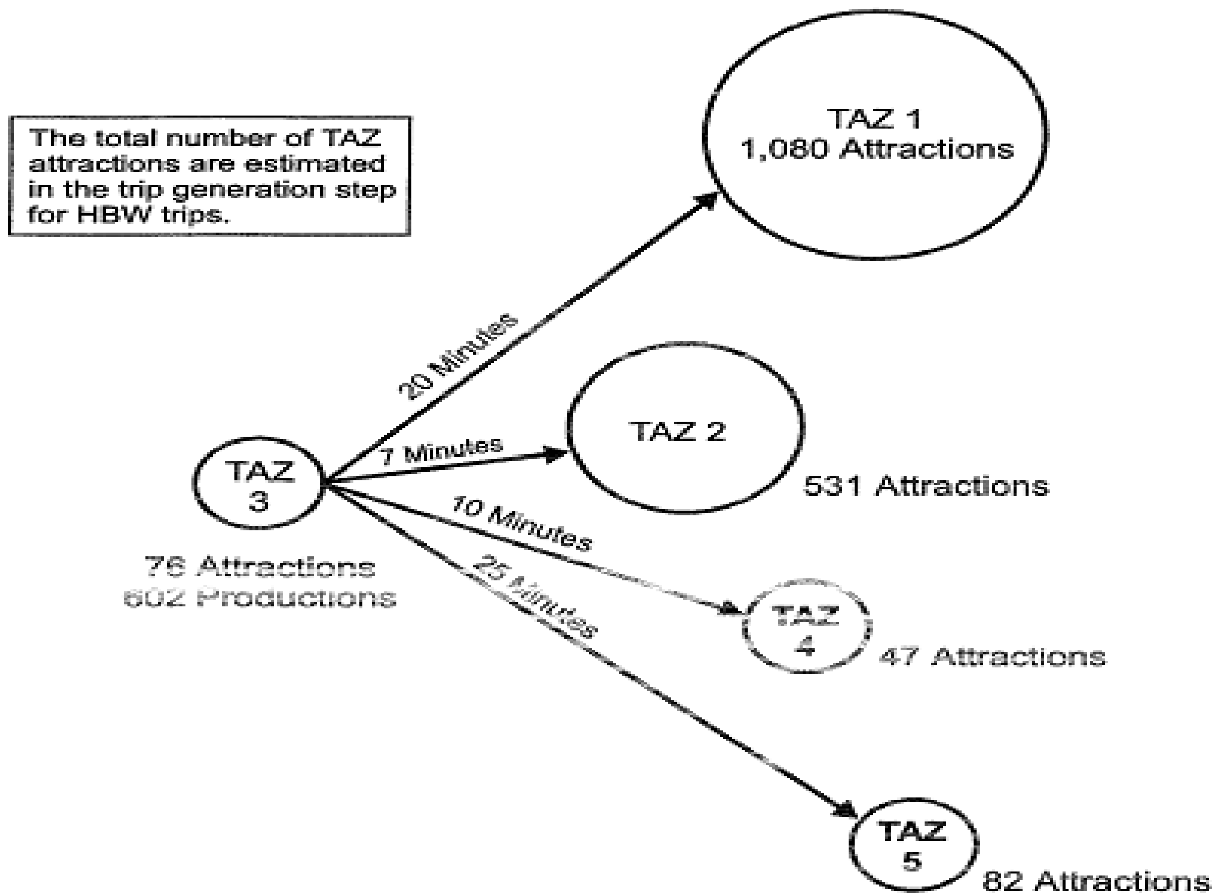
Again, the focus is to apply the gravity model to determine where trips go. The gravitational force in the gravity model will now become the amount of travel between TAZs. This application is possible if the calculations using the gravity model are based on the *relative attractiveness* of the zones. To apply the gravity model to travel, some modifications are needed. To convert the gravity model equation to represent the amount of travel or number of trips as opposed to gravitational force, two modifications must be made:

- accessibility is used instead of distance, and
- number of attractions is used instead of mass.



gravitational constant = 6.67398 × 10^{-11} m^3 kg^{-1} s^{-2}

Calculating TAZ Attractiveness



Gravity Model

$$\text{Trips between TAZ 3 and "TO" TAZ} = \text{Trips produced in TAZ 3} \times \frac{\text{Attractiveness of "TO" TAZ}}{\text{Attractiveness of all TAZs}}$$

Gravity Model Equation

$$\text{Trips}_{ij} = \text{Productions}_i \times \frac{\text{Attractions}_j \times FF_{ij} \times K_{ij}}{\Sigma\ \text{Attractions}_j \times FF_{ij} \times K_{ij}}$$

Where:

Trips_{ij}	Trips between TAZs i and j
Productions_i	Productions from TAZ i
Attractions_j	Attractions to TAZ j
Friction Factor (FF_{ij})	Friction factor for TAZs i and j
Socioeconomic factor (K_{ij})	Socioeconomic factor for TAZs i and j

i=production TAZ
j=attraction TAZ

Gravity Model:

$$T_{ij} = P_i \left[\frac{A_j F_{ij} K_{ij}}{\sum_j A_j F_{ij} K_{ij}} \right]$$

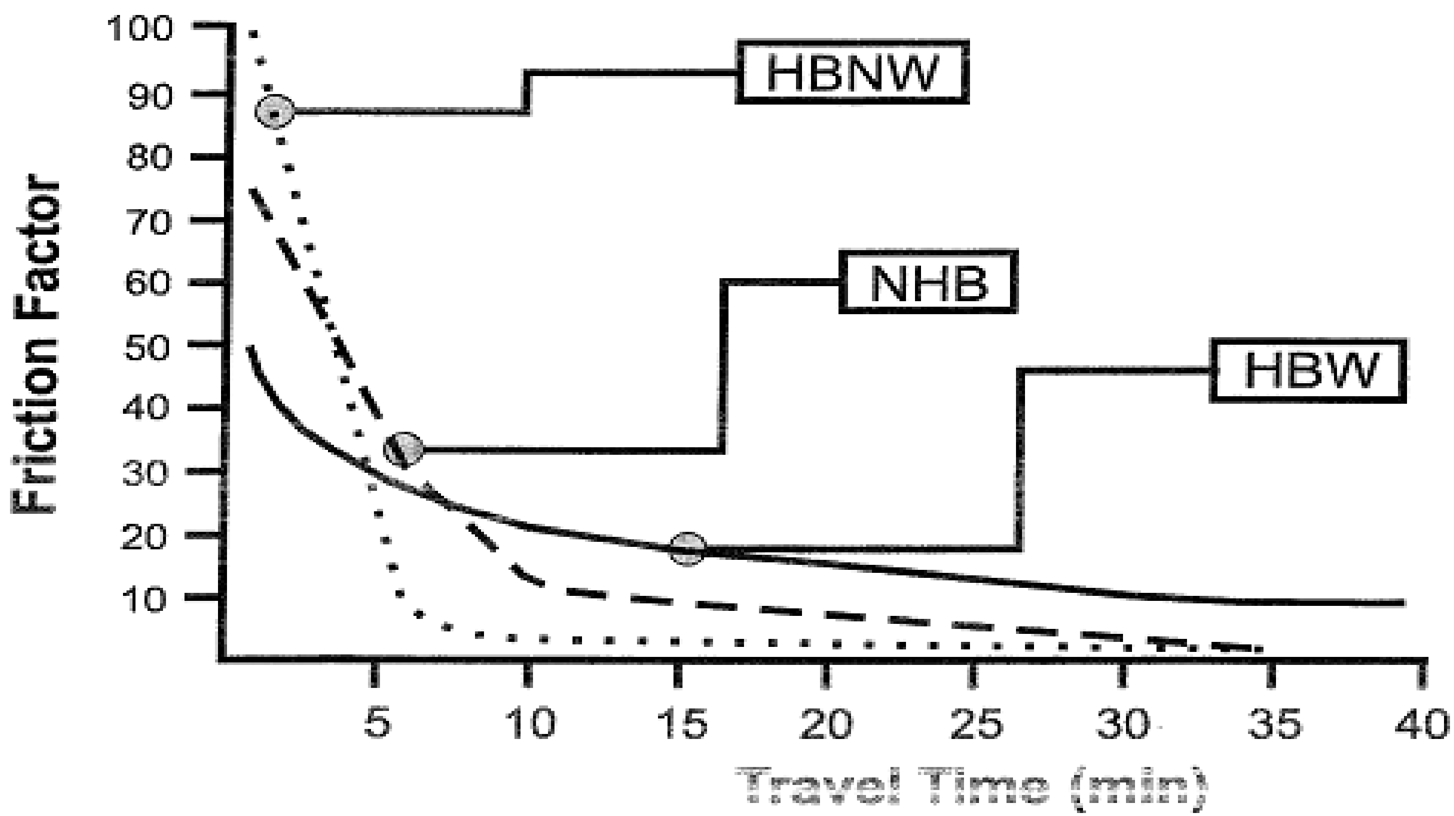
where

T_{ij} = number of trips that are produced in zone i and attracted to zone j
P_i = total number of trips produced in zone i
A_j = number of trips attracted to zone j
F_{ij} = a value which is an inverse function of travel time
K_{ij} = socioeconomic adjustment factor for interchange ij

The values of Pi and Aj have been determined in the trip generation process.

The sum of Pi for all zones must equal the sum of Aj for all zones.

Friction Factors



K-Factors

- K-factors account for socioeconomic linkages not accounted for by the gravity model
- Common application is for blue-collar workers living near white-collar jobs
- K-factors are i-j TAZ specific
- If i-j pair has too many trips, use K-factor less than 1.0
- If i-j pair has too few trips, use K-factor greater than 1.0
- Once calibrated, keep constant for forecast
- Use K-factors sparingly and with caution

K-factors are applied to the gravity model as a fraction. If there is a deficiency of trips between TAZs and the condition cannot be corrected using calibrated friction factors, a K-factor greater than 1.0 would be applied, making the zone more attractive. If the zonal interchange has too many trips, a K-factor less than 1.0 would be applied. To prohibit trips, a zero is used.

Example 12.4 Use of Calibrated *F* Values and Iteration

To illustrate the application of the gravity model, consider a study area consisting of three zones. The data have been determined as follows: the number of productions and attractions has been computed for each zone by methods described in the section on trip generation, and the average travel times between each zone have been determined. Both are shown in Tables 12.9 and 12.10. Assume K_{ij} is the same unit value for all zones. Finally, the F values have been calibrated as previously described and are shown in Table 12.11 for each travel time increment. Note that the intrazonal travel time for zone 1 is larger than those of most other inter-zone times because of the geographical characteristics of the zone and lack of access within the area. This zone could represent conditions in a congested downtown area.

Determine the number of zone-to-zone trips through two iterations.

Solution: The number of trips between each zone is computed using the gravity model and the given data. (*Note*: F_{ij} is obtained by using the travel times in

Table 12.9 Trip Productions and Attractions for a Three-Zone Study Area

Zone	*1*	*2*	*3*	*Total*
Trip productions	140	330	280	750
Trip attractions	300	270	180	750

Table 12.10 Travel Time between Zones (min)

Zone	*1*	*2*	*3*
1	5	2	3
2	2	6	6
3	3	6	5

Table 12.11 Travel Time versus Friction Factor

Time (min)	*F*
1	82
2	52
3	50
4	41
5	39
6	26
7	20
8	13

Note: F values were obtained from the calibration process.

Table 12.10 and selecting the correct F value from Table 12.11. For example, travel time is 2 min between zones 1 and 2. The corresponding F value is 52.)

Use Eq. 12.3.

$$T_{ij} = P_i \left[\frac{A_j F_{ij} K_{ij}}{\sum_{j=1}^{n} A_j F_{ij} K_{ij}} \right] \qquad K_{ij} = 1 \text{ for all zones}$$

$$T_{1-1} = 140 \times \frac{300 \times 39}{(300 \times 39) + (270 \times 52) + (180 \times 50)} = 47$$

$$T_{1-2} = 140 \times \frac{270 \times 52}{(300 \times 39) + (270 \times 52) + (180 \times 50)} = 57$$

$$T_{1-3} = 140 \times \frac{180 \times 50}{(300 \times 39) + (270 \times 52) + (180 \times 50)} = 36$$

$$P_1 = 140$$

Make similar calculations for zones 2 and 3.

$$T_{2-1} = 188 \quad T_{2-2} = 85 \quad T_{2-3} = 57 \quad P_2 = 330$$
$$T_{3-1} = 144 \quad T_{3-2} = 68 \quad T_{3-3} = 68 \quad P_3 = 280$$

The results summarized in Table 12.12 represent a *singly constrained* gravity model. This constraint is that the sum of the productions in each zone is equal to the number

Table 12.12 Zone-to-Zone Trips: First Iteration, Singly Constrained

Attr.

Prod.

Zone	*1*	*2*	*3*	*Computed P*	*Given P*
1	47	57	36	140	140
2	188	85	57	330	330
3	144	68	68	280	280
Computed *A*	379	210	161	750	750
Given *A*	300	270	180	750	

of productions given in the problem statement. However, the number of attractions estimated in the trip distribution phase differs from the number of attractions given. For zone 1, the correct number is 300, whereas the computed value is 379. Values for zone 2 are 270 versus 210, and for zone 3, they are 180 versus 161.

To create a doubly constrained gravity model where the computed attractions equal the given attractions, calculate the adjusted attraction factors according to the formula

$$A_{jk} = \frac{A_j}{C_{j(k-1)}} A_{j(k-1)} \tag{12.4}$$

where

A_{jk} = adjusted attraction factor for attraction zone (column) j, iteration k
$A_{jk} = A_j$ when $k = 1$
C_{jk} = actual attraction (column) total for zone j, iteration k
A_j = desired attraction total for attraction zone (column) j
j = attraction zone number, $j = 1, 2, \ldots, n$
n = number of zones
k = iteration number, $k = 1, 2, \ldots, m$
m = number of iterations

To produce a doubly constrained gravity model, repeat the trip distribution computations using modified attraction values so that the numbers attracted will be increased or reduced as required. For zone 1, for example, the estimated attractions were too great. Therefore, the new attraction factors are adjusted downward by multiplying the original attraction value by the ratio of the original to estimated attraction values.

$$\text{Zone 1:} A_{12} = 300 \times \frac{300}{379} = 237$$

$$\text{Zone 2:} A_{22} = 270 \times \frac{270}{210} = 347$$

$$\text{Zone 3:} A_{32} = 180 \times \frac{180}{161} = 201$$

Table 12.13 Zone-to-Zone Trips: Second Iteration, Doubly Constrained

Zone	*1*	*2*	*3*	*Computed P*	*Given P*
1	34	68	38	140	140
2	153	112	65	330	330
3	116	88	76	280	280
Computed *A*	303	268	179	750	750
Given *A*	300	270	180	750	

Apply the gravity model (Eq. 12.3) for all iterations to calculate zonal trip interchanges using the adjusted attraction factors obtained from the preceding iteration. In practice, the gravity model becomes

$$T_{ij} = P_i \left[\frac{A_j F_{ij} K_{ij}}{\sum_j A_j F_{ij} K_{ij}} \right]$$

where T_{ijk} is the trip interchange between i and j for iteration k, and $A_{jk} = A_j$ when $k = 1$. Subscript j goes through one complete cycle every time k changes, and i goes through one complete cycle every time j changes. This formula is enclosed in parentheses and subscripted to indicate that the complete process is performed for each trip purpose.

Perform a second iteration using the adjusted attraction values.

$$T_{1-1} = 140 \times \frac{237 \times 39}{(237 \times 39) + (347 \times 52) + (201 \times 50)} = 34$$

$$T_{1-2} = 140 \times \frac{347 \times 52}{(237 \times 39) + (347 \times 52) + (201 \times 50)} = 68$$

$$T_{1-3} = 140 \times \frac{201 \times 50}{(237 \times 39) + (347 \times 52) + (201 \times 50)} = 37$$

$$P_1 = 140$$

Make similar calculations for zones 2 and 3.

$$T_{2-1} = 153 \qquad T_{2-2} = 112 \qquad T_{2-3} = 65 \qquad P_2 = 330$$
$$T_{3-1} = 116 \qquad T_{3-2} = 88 \qquad T_{3-3} = 76 \qquad P_3 = 280$$

The results are summarized in Table 12.13. Note that, in each case, the sum of the attractions is now much closer to the given value. The process will be continued until there is a reasonable agreement (within 5%) between the A that is estimated using the gravity model and the values that are furnished in the trip generation phase.

C) MODAL SPLIT

To determine the number (or %) of trips made between zones using each mode of travel

For the analysis, the following variables might be used:

- Trip characteristics: length, time of day, purpose, …etc.
- Trip maker characteristics: income, auto ownership, employment, …etc.
- Transportation system characteristics: accessibility, parking, travel time, …etc.

Types of Modal Split Models

- (1) Direct Generation of transit trips,
- (2) Trip End models, and
- (3) Trip Interchange Modal Split models.

Trip End Models:

To determine the % of total person or auto trips that will use a mode,

Estimates are made **prior to the trip distribution** phase based on:

- land-use or socioeconomic characteristics of the zone.

This method **does not incorporate the quality of service**.

Example 12.8 Estimating Trip Productions by Transit

The total number of productions in a zone is 10,000 trips/day. The number of households per auto is 1.80, and residential density is 15,000 persons/square mile. Determine the percent of residents who can be expected to use transit.

Solution: Compute the urban travel factor.

$$\text{UTF} = \frac{1}{1000}\left(\frac{\text{household}}{\text{auto}}\right)\left(\frac{\text{persons}}{\text{mi}^2}\right)$$
$$= \frac{1}{1000} \times 1.80 \times 15{,}000 = 27.0$$

Enter Figure 12.9. Transit mode split = 45%.

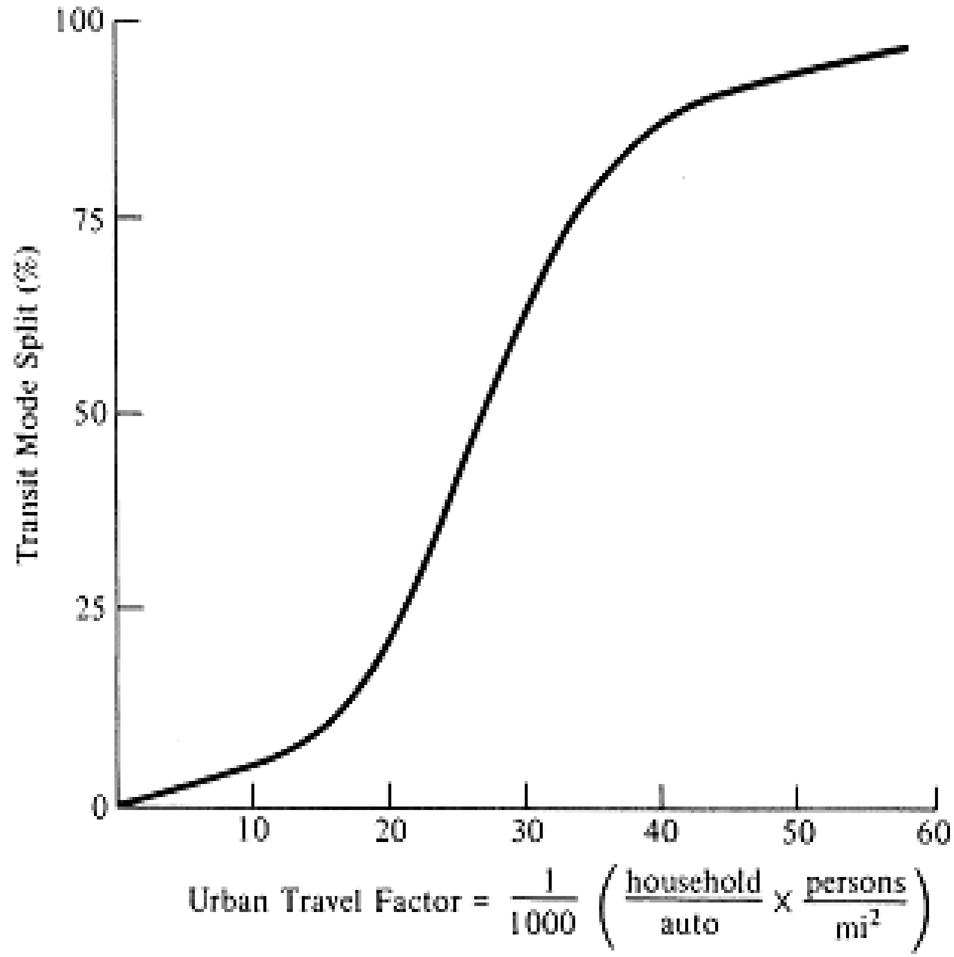


Figure 12.9 Transit Mode Split versus Urban Travel Factor

3. **<u>Trip Interchange Models</u>**:

In this method, system **level-of-service** variables are considered, including:

-relative travel time,

-relative travel cost,

-economic status of the trip maker, and

-relative travel service.

-Estimates are made **after the trip distribution**

- An example of this procedure is illustrated using the **QRS** method which takes account of service parameters in estimating mode choice.
- The QRS method is based on the following relationship:

$$MS_a = \frac{I_{ij}^{b}\ \mathrm{t}}{I_{ijt}^{b} + I_{ija}^{b}} \times 100 \qquad (12.6)$$

$$MS_t = (1 - MS_a) \times 100 \qquad (12.7)$$

where

MS_t = proportion of trips between zone i and j using transit

MS_a = proportion of trips between zone i and j using auto

I_{ijm} = a value referred to as the *impedance* of travel of mode m, between i and j, which is a measure of the total cost of the trip. [*Impedance* = (in-vehicle time min) + (2.5 × excess time min) + (3 × trip cost, \$/ income earned/min).]

b = an exponent, which depends on trip purpose

m = t for transit mode; a for auto mode

- In-vehicle time is time spent traveling in the vehicle, and

- excess time is time spent traveling but not in the vehicle, including waiting for the train or bus and walking to the station.

- The impedance value is determined for each zone pair and represents a measure of the expenditure required to make the trip by either auto or transit.

- The data required for estimating mode choice include

(1) distance between zones by auto and transit,
(2) transit fare,
(3) out-of-pocket auto cost,
(4) parking cost,
(5) Highway and transit speed,
(6) exponent values, b,
(7) median income, and
(8) excess time, which includes the time required to walk to a transit vehicle and time waiting or transferring. Assume that the time worked per year is 120,000 min.

Example 12.9 Computing Mode Choice Using the QRS Model

To illustrate the application of the QRS method, assume that the data shown in Table 12.21 have been developed for travel between a suburban zone *S* and a downtown zone *D*. Determine the percent of work trips by auto and transit. An exponent value of 2.0 is used for work travel. Median income is $24,000 per year.

Table 12.21 Travel Data Between Two Zones, *S* and *D*

	Auto	*Transit*
Distance	10 mi	8 mi
Cost per mile	$0.15	$0.10
Excess time	5 min	8 min
Parking cost	$1.50 (or 0.75/trip)	—
Speed	30 mi/h	20 mi/h

Solution: Use Eq. 12.6.

$$MS_a = \frac{I_{ija}^b}{I_{ijt}^b + I_{ija}^b}$$

$$I_{SDa} = \left(\frac{10}{30} \times 60\right) + (2.5 \times 5) + \left\{\frac{3 \times [(1.50/2) + 0.15 \times 10]}{24{,}000/120{,}000}\right\}$$

$$= 20 + 12.5 + 33.75$$

$$= 66.25 \text{ equivalent min}$$

$$I_{SDt} = \left(\frac{8}{20} \times 60\right) + (2.5 \times 8) + \left[\frac{3 \times (8 \times 0.10)}{24{,}000/120{,}000}\right] = 24 + 20 + 12$$

$$= 56 \text{ equivalent min}$$

$$MS_a = \frac{(56)^2}{(56)^2 + (66.25)^2} \times 100 = 41.6\%$$

$$MS_t = (1 - 0.416) \times 100 = 58.4\%$$

Thus, the mode choice of travel by transit between zones S and D is 68.4%, and by highway the value is 41.6%. These percentages are applied to the estimated trip distribution values to determine the number of trips by each mode. If for example, the number of work trips between zones S and D was computed to be 500, then the number by auto would be $500 \times 0.416 = 208$, and by transit, the number of trips would be $500 \times 0.584 = 292$.

Logit Models:

- An alternative approach used in transportation demand analysis is to consider the relative utility of each mode as a summation of each modal attribute.

- the choice of a mode is expressed as a probability distribution.

- If two modes, auto (*A) and transit (T), are being considered, the probability of* selecting the auto mode *A can be written as:*

$$P(A) = \frac{e^{U_A}}{e^{U_A} + e^{U_T}} \qquad (12.9)$$

This form is called the *logit model*

Example 12.10 Use of Logit Model to Compute Mode Choice

The utility functions for auto and transit are as follows.

$$\text{Auto: } U_A = -0.46 - 0.35T_1 - 0.08T_2 - 0.005C$$
$$\text{Transit: } U_T = -0.07 - 0.05T_1 - 0.15T_2 - 0.005C$$

where

T_1 = total travel time (minutes)
T_2 = waiting time (minutes)
C = cost (cents)

The travel characteristics between two zones are as follows:

	Auto	*Transit*
T_1	20	30
T_2	8	6
C	320	100

Solution: Use the logit model to determine the percent of travel in the zone by auto and transit.

$$U_x = \sum_{i=1}^{n} a_i x_i$$

$$U_A = -0.46 - (0.35 \times 20) - (0.08 \times 8) - (0.005 \times 320) = -9.70$$
$$U_B = -0.07 - (0.35 \times 30) - (0.08 \times 6) - (0.005 \times 100) = -11.55$$

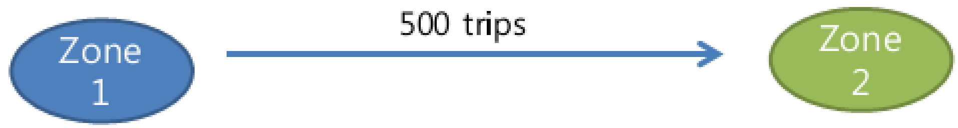
Using Eq.12.9 yields

$$P_A = \frac{e^{U_A}}{e^{U_A} + e^{U_T}} = \frac{e^{-9.70}}{e^{-9.7} + e^{-11.55}} = 0.86$$

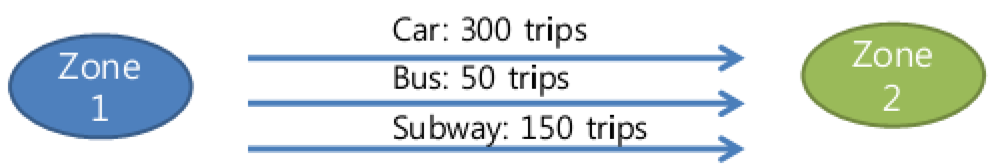
$$P_T = \frac{e^{U_T}}{e^{U_A} + e^{U_T}} = \frac{e^{-11.55}}{e^{-9.7} + e^{-11.55}} = 0.14$$

Route Choice

- Trip Distribution

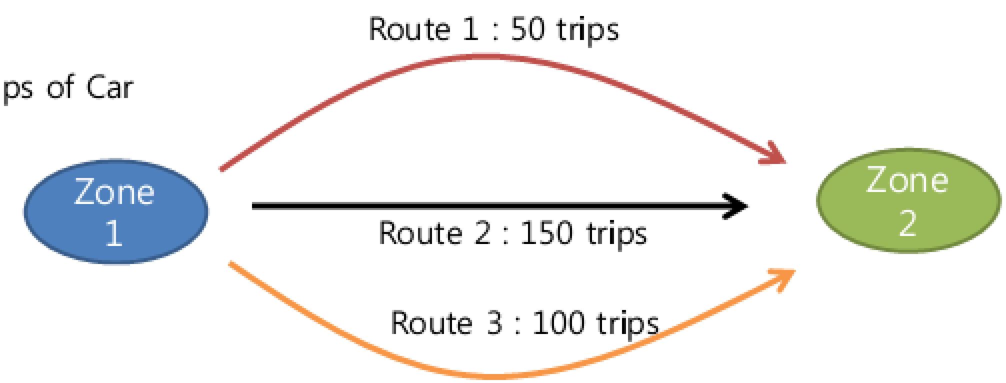


- Mode Choice



- Route Choice

  Among 300 trips of Car



Approaches

(1) Diversion curves,
(2) Minimum time path (all-or-nothing) assignment, and
(3) Minimum time path with capacity restraint.

1. Diversion curves,

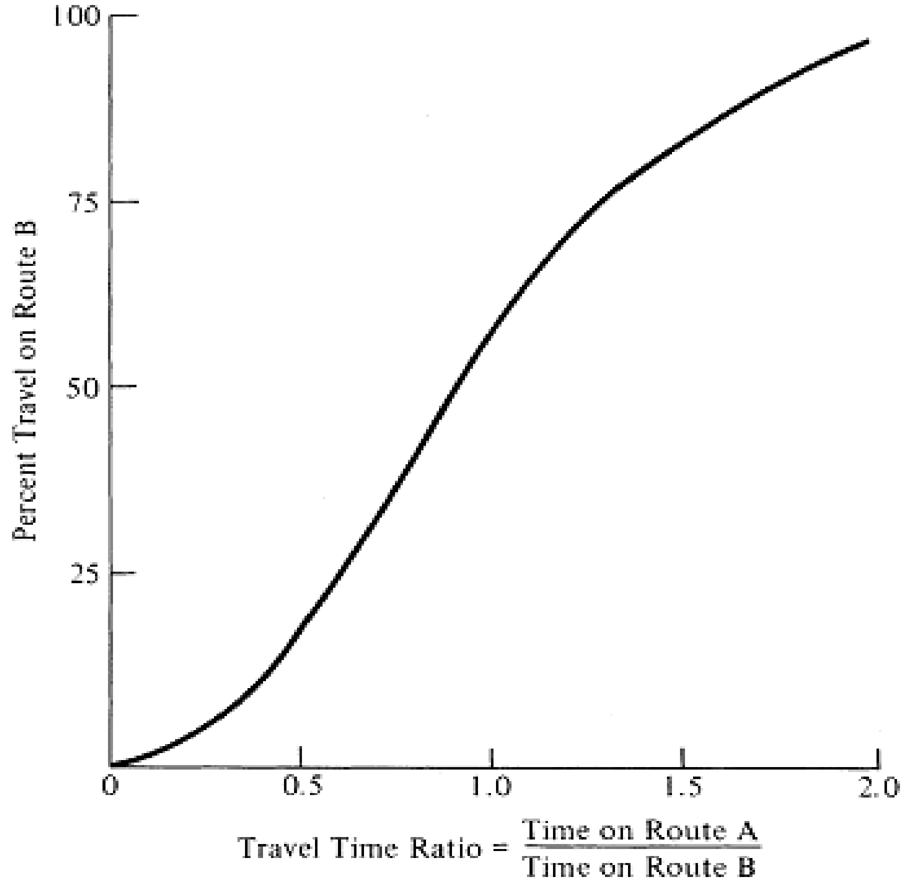


Figure 12.12 Travel Time Ratio versus Percentage of Travel on Route *B*

2. Minimum Path Algorithm

- Why do we need to find the shortest path?

- –In the trip assignment (or route choice), the model assumes that people try to travel the minimum-travel-time paths

- –The problem is finding the minimum-travel-time paths connecting each O-D pair for a given set of link travel time.

All-or-Nothing Assignment

- All trips are assigned on the shortest route which is the minimum travel time or cost between zones
  - Simple and inexpensive to perform
  - Does not take account of congestion effect
    - Assumes there is no travel time change due to increased traffic
    - Flow patterns could be unrealistic
    - Can be used for special cases (significantly under-saturated traffic etc.)

- to determine which route that will be, it is necessary to find the shortest route from the zone of origin to all other destination zones.

- The results can be depicted as a tree, referred to as a **skim tree**.

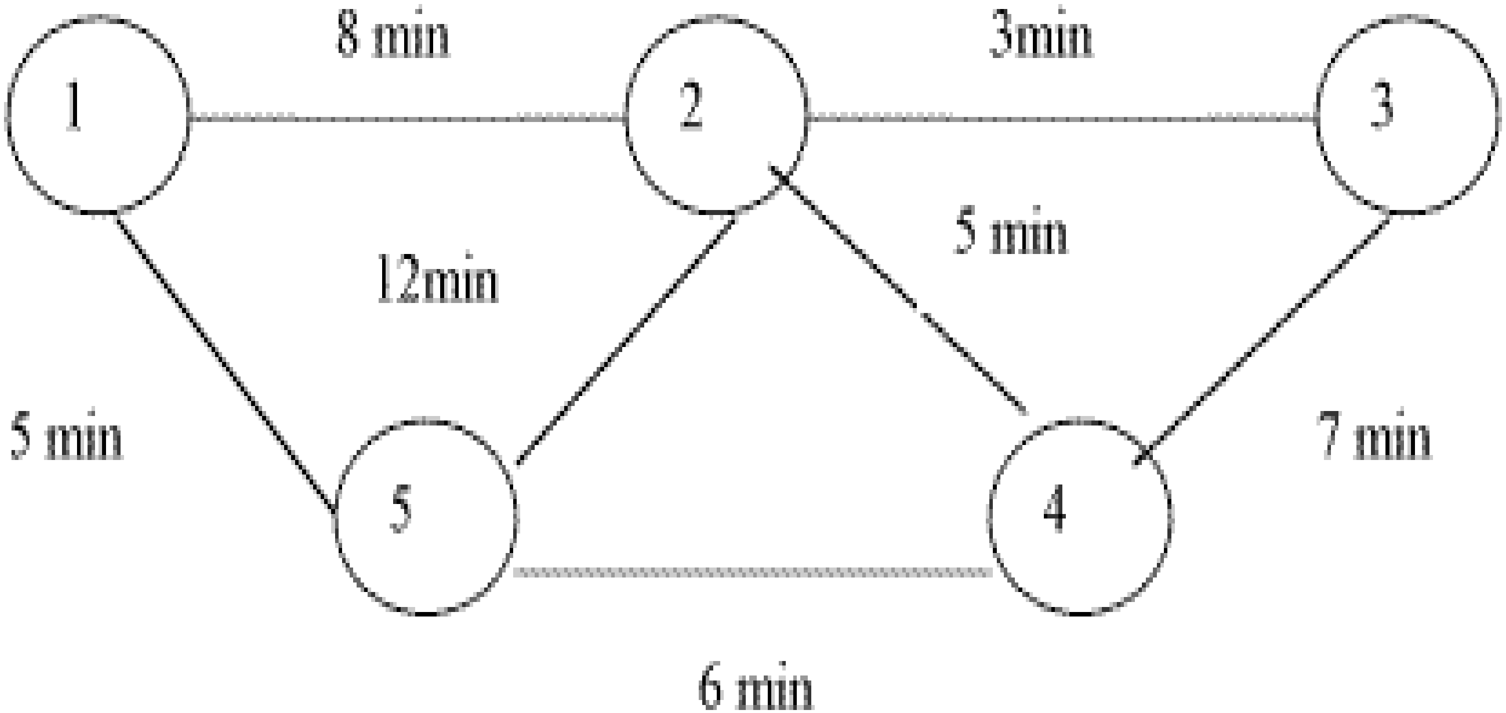
- Each zone is represented by a node in the network which represents the entire area being examined.

Origin-Destination Trip Table:

- Assign the vehicle trips shown in the following O-D trip table to the network, using the all-or-nothing assignment technique. To summarize your results, list all of the links in the network and their corresponding traffic volume after loading.

	Trips between Zones				
From/to	**1**	**2**	**3**	**4**	**5**
1	-	100	100	200	150
2	400	-	200	100	500
3	200	100	-	100	150
4	250	150	300	-	400
5	200	100	50	350	-

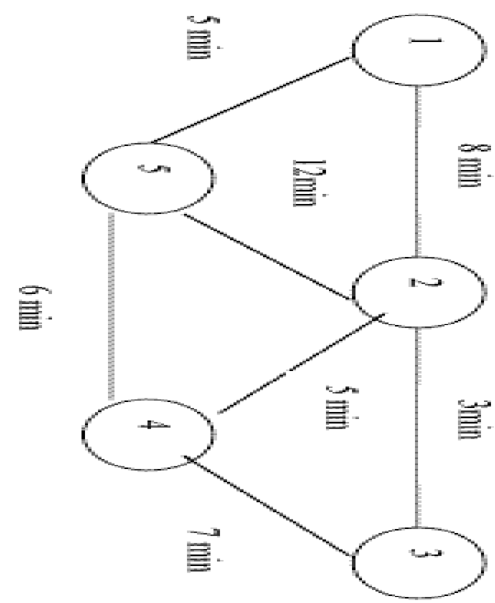
Highway Network:



- The all-or-nothing technique simply assumes that all of the traffic between a particular origin and destination will take the shortest path (with respect to time).

- For example, all of the 200 vehicles that travel between nodes 1 and 4 will travel via nodes 1-5-4.

Nodes		Link	Travel	
From	To	Path	Time	Volume
1	2	1-2	8	100
	3	1-2,2-3	11	100
	4	1-5,5-4	11	200
	5	1-5	5	150
2	1	2-1	8	400
	3	2-3	3	200
	4	2-4	5	100
	5	2-4,4-5	11	500
3	1	3-2,2-1	11	200
	2	3-2	3	100
	4	3-4	7	100
	5	3-4,4-5	13	150
4	1	4-5,5-1	11	250
	2	4-2	5	150
	3	4-3	7	300
	5	4-5	6	400
5	1	5-1	5	200
	2	5-4,4-2	11	100
	3	5-4,4-3	13	50
	4	5-4	6	350



	Trips between Zones				
From/ to	1	2	3	4	5
1	-	100	100	200	150
2	400	-	200	100	500
3	200	100	-	100	150
4	250	150	300	-	400
5	200	100	50	350	-

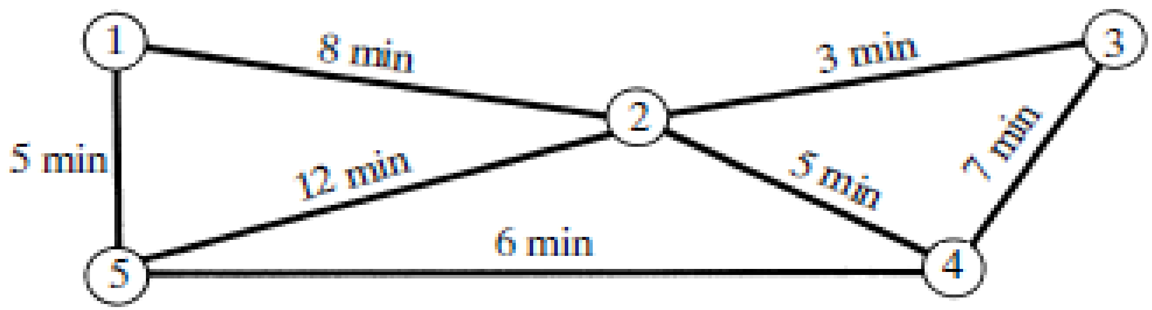
Nodes		Link	Travel	
From	To	Path	Time	Volume
1	2	1-2	8	100
	3	1-2,2-3	11	100
	4	1-5,5-4	11	200
	5	1-5	5	150
2	1	2-1	8	400
	3	2-3	3	200
	4	2-4	5	100
	5	2-4,4-5	11	500
3	1	3-2,2-1	11	200
	2	3-2	3	100
	4	3-4	7	100
	5	3-4,4-5	13	150
4	1	4-5,5-1	11	250
	2	4-2	5	150
	3	4-3	7	300
	5	4-5	6	400
5	1	5-1	5	200
	2	5-4,4-2	11	100
	3	5-4,4-3	13	50
	4	5-4	6	350

Link	Volume	Routes taken	Vol. Calc.	Vol.
1-2	200	1-2 1-2, 2-3	100 100	100+100 =200
2-1	600	2-1 3-2, 2-1	400 200	400+200 =600
1-5	350			
5-1	450			
2-5	0	2-4, 4-5	0	0
5-2	0	5-4, 4-2	0	0
2-3	300			
3-2	300			
2-4	600			
4-2	250			
3-4	250			
4-3	350			
4-5	1300			
5-4	700			

Example:

1. Assign the vehicle trips shown in the O-D trip table to the network shown in Figure below using the all-or-nothing assignment technique.
2. Make a list of the links in the network and indicate the volume assigned to each.
3. Calculate the total vehicle minutes of travel.
4. Show the minimum path and assign traffic for each of the five nodes.

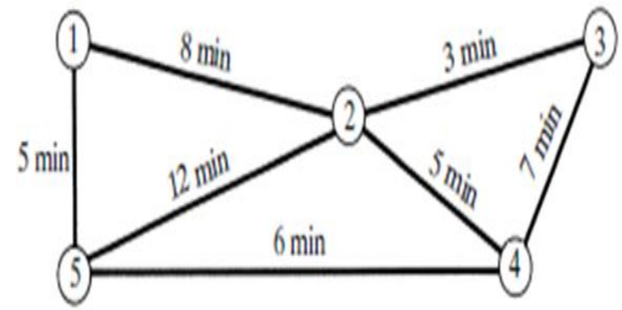
	Trips Between Zones				
From/To	*1*	*2*	*3*	*4*	*5*
1	0	100	100	200	150
2	400	0	200	100	500
3	200	100	0	100	150
4	250	150	300	0	400
5	200	100	50	350	0



Minimum Paths

1: Assignment of trips:

Nodes From - To		Link Path	Nodes From - To		Link Path
1	2	1-2	4	1	4-5, 5-1
1	3	1-2, 2-3	4	2	4-2
1	4	1-5, 5-4	4	3	4-3
1	5	1-5	4	5	4-5
2	1	2-1	5	1	5-1
2	3	2-3	5	2	5-4, 4-2
2	4	2-4	5	3	5-4, 4-3
2	5	2-4, 4-5	5	4	5-4
3	1	3-2, 2-1			
3	2	3-2			
3	4	3-4			
3	5	3-4, 4-5			



Trips Between Zones

From/To	*1*	*2*	*3*	*4*	*5*
1	0	100	100	200	150
2	400	0	200	100	500
3	200	100	0	100	150
4	250	150	300	0	400
5	200	100	50	350	0

2: volume assigned to each link +
3: total vehicle minutes of travel

Link	Volume	Travel Time	Veh-Min of Travel
1 - 2	200	8	1,600
2 - 1	600	8	4,800
1 - 5	350	5	1,750
5 - 1	450	5	2,250
2 - 5	0	12	0
5 - 2	0	12	0
2 - 3	300	3	900
3 - 2	300	3	900
2 - 4	600	5	3,000
4 - 2	250	5	1,250
3 - 4	250	7	1,750
4 - 3	350	7	2,450
4 - 5	1,300	6	7,800
5 - 4	700	6	4,200
TOTAL			32,650

Minimum Paths

Nodes From - To	Link Path	Nodes From - To	Link Path
1 2	1 - 2	4 1	4 - 5, 5 - 1
1 3	1 - 2, 2 - 3	4 2	4 - 2
1 4	1 - 5, 5 - 4	4 3	4 - 3
1 5	1 - 5	4 5	4 - 5
2 1	2 - 1	5 1	5 - 1
2 3	2 - 3	5 2	5 - 4, 4 - 2
2 4	2 - 4	5 3	5 - 4, 4 - 3
2 5	2 - 4, 4 - 5	5 4	5 - 4
3 1	3 - 2, 2 - 1		
3 2	3 - 2		
3 4	3 - 4		
3 5	3 - 4, 4 - 5		

Trips Between Zones

From/To	1	2	3	4	5
1	0	100	100	200	150
2	400	0	200	100	500
3	200	100	0	100	150
4	250	150	300	0	400
5	200	100	50	350	0

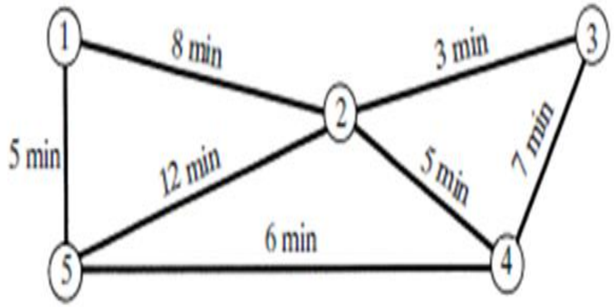
4: assign traffic for each of the five nodes:

Traffic Assigned to Nodes

Node	Volume Assigned
1	1,050
2	750
3	650
4	1,550
5	1,650

Node	Attracted trips	Volume Assigned
1	600+450	1050
2	200+300+250	750
3	300+350	650
4	600+250+700	1550
5	350+1300	1650

4: minimum path (skim trees):

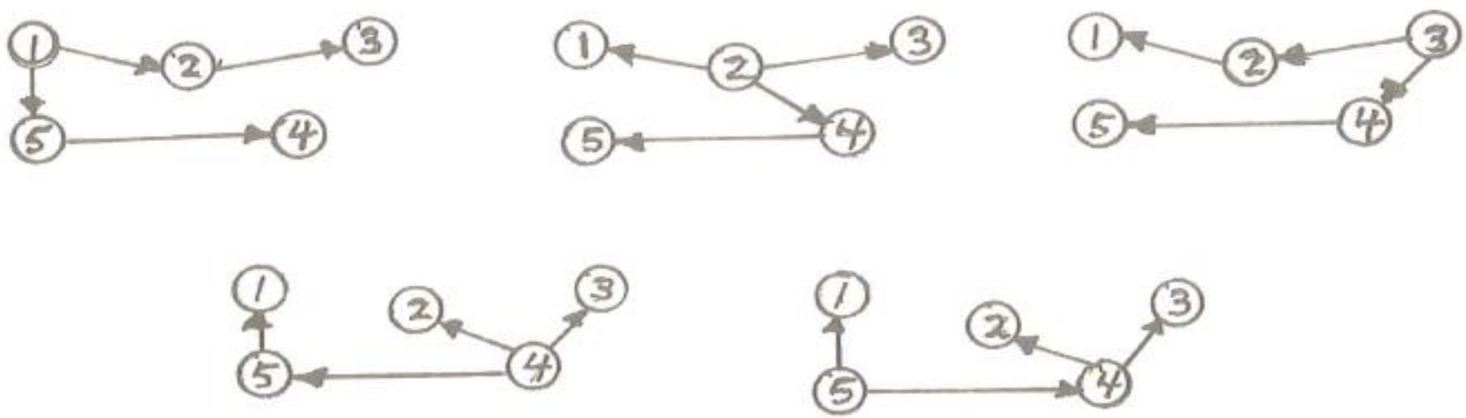


Original Network

Minimum Paths

Nodes From - To		Link Path	Nodes From - To		Link Path
1	2	1 - 2	4	1	4 - 5, 5 - 1
1	3	1 - 2, 2 - 3	4	2	4 - 2
1	4	1 - 5, 5 - 4	4	3	4 - 3
1	5	1 - 5	4	5	4 - 5
2	1	2 - 1	5	1	5 - 1
2	3	2 - 3	5	2	5 - 4, 4 - 2
2	4	2 - 4	5	3	5 - 4, 4 - 3
2	5	2 - 4, 4 - 5	5	4	5 - 4
3	1	3 - 2, 2 - 1			
3	2	3 - 2			
3	4	3 - 4			
3	5	3 - 4, 4 - 5			

Minimum Path Trees



Other models used to Model Demand

TRIP GENERATION

1. Typical Trip Generation Models

- Trip Generation models generally assume a linear form, in which the number of vehicle-based (automobile, bus, or subway) trips is a function of various socioeconomic and/or distributional (residential and commercial) characteristics.

- An example of such a model, for a given trip type is:

$$T_i = b_0 + b_1 Z_{1i} + b_2 Z_{2i} + \ldots + b_k Z_{ki}$$

- Where:

  Ti: no. of vehicle-based trips of a given type(shopping or social\recreational) in some specified time period by household i

  b_k: coefficient estimated from traveler survey data and corresponding to characteristic k,

  Z_{ki}: characteristic k (income, employment in neighborhood, number of household members) of household i.

Example:

- A neighborhood has 205 retail employees and 700 households that can be categorized into four types, with each type having characteristics as follows:

type	Household size	Annual income, $	No. of nonworkers in the peak hour	Workers departing
1	2	40,000	1	1
2	3	50,000	2	1
3	3	55,000	1	2
4	4	40,000	3	1

- There are 100 type 1, 200 type 2, 350 type 3, and 50 type 4 households. Assuming that shopping, social/recreational, and work vehicle-based trips all peak at the same time (for exposition purposes), determine the total number of peak-hour trips (work, shopping, social/recreational) using the following equations:

For vehicle based shopping trips:

- No. of vehicle trips= 0.12+ 0.09 (HH size)+ 0.011 (annual income, 1000)- 0.15 (employment in hundreds)

205 retail employment

Substitute for each type:

- **Type 1:** 0.12+ 0.09 (2)+0.011 (40)-0.15(2.05)=0.4325 trips/HH *100 HH= 43.25 trips
- **Type 2:** 0.12+ 0.09 (3)+0.011 (50)-0.15(2.05)=0.6325 trips/HH *200 HH= 126.5 trips
- **Type 3:** 0.12+ 0.09 (3)+0.011 (55)-0.15(2.05)=0.6875 trips/HH *350 HH= 240.625 trips
- **Type 4:** 0.12+ 0.09 (4)+0.011 (40)-0.15(2.05)=0.6125 trips/HH *50 HH= 30.625 trips

Therefore, there will be a total of 441 vehicle-based shopping trips,

For vehicle-based social/recreational trips:

- No. of social/recreational trips= 0.04 + 0.018 (HH)+ 0.009 (Annual income, 1000) + 0.16 (no. on nonworking HH members)

Substitute for each type:

- **Type 1:** 0.04+0.018(2)+0.009(40)+0.16(1)= 0.596 trips/HH* 100 =59.6 trips
- **Type 2:** 0.04+0.018(3)+0.009(50)+0.16(2)= 0.864 trips/HH*200=172.8 trips
- **Type 3:** 0.04+0.018(3)+0.009(55)+0.16(1)= 0.749 trips/HH*350=262.15 trips
- **Type 4:** 0.04+0.018(4)+0.009(40)+0.16(3)= 0.952 trips/HH*50=47.6 trips

Therefore there will be 542.15 vehicle-based social/recreational trips

For vehicle-based work trips, there will be:

Substitute for each type:

- Type 1: 1*100= 100 trips
- Type 2: 1*200= 200 trips
- Type 3: 2* 350 = 700 trips
- Type 4: 1* 50= 50 trips

In total 1050 vehicle-based work trips

2. Trip Generation with count data models

- There is a problem in the linear regression estimate for trips generation in that the estimated models can produce fractions of trips for a given time period, which is not realistic!

- A Poisson model can be used instead.

- For trip generation (for a given trip type):

$$P(T_i) = \frac{e^{-\lambda_i} \lambda_i^{T_i}}{T_i!}$$

- Ti: no. of vehicle-based trips of a given type (shopping or social/recreational) made in some specified time period by HH I
- P(Ti): probability of HH i making exactly Ti trips (where Ti is a nonnegative integer)
- e: base of the natural logarithm (e= 2.718)
- λ_i: Poisson parameter for HH i, which is equal to HH i's expected number of vehicle-based trips in some specified time period E[Ti]

$$\lambda_i = e^{BZ_i}$$

- B: vector of estimate coefficients
- Z_i: vector of HH characteristics determining trip generation,

Example

- Following the previous example, a Poisson regression is estimated for shopping-trip generation during a shopping-trip peak hour. The estimated coefficients are :

- Bzi: -0.35+0.03 (HH)+0.004(Annual income, 1000)-0.10 (employment in HH’s , 100)

The HH has 6 members, has an annual income of $50,000, retail employment of 150

What is the expected number of peak-hour shopping trips?

What is the probability that the HH will **not make a peak-hour** shopping trip?

E[Ti]= $\lambda_i = e^{BZ_i} = e^{-.035+0.03(6)+0.004(50)-0.1(1.5)} = 0.887\, trips$

Probability of making zero peak-hour shopping trips:

$$P(0) = \frac{e^{-0.887}\, 0.887^0}{0!} = 0.412$$

TRIP DISTRIBUTION

2. Growth Factor Models

1. This method was widely used when O-D data were available but the gravity model and calibrations for F factors had not yet become operational.

2. Growth factor models are used primarily to distribute trips between zones in the study area and zones in cities external to the study area.

3. cannot be used to forecast traffic between zones where no traffic currently exists.

4. the only measure of travel friction is the amount of current travel.

5. cannot reflect changes in travel time between zones, as does the gravity model

- **Fratar Method:** a mathematical formula that proportions future trip generation estimates to each zone as a function of the product of the current trips between the two zones Tij and the growth factor of the attracting zone Gj

$$T_{ij} = (t_i G_i) \frac{t_{ij} G_j}{\sum_x t_{ix} G_x}$$

where

T_{ij} = number of trips estimated from zone i to zone j

t_i = present trip generation in zone i

G_x = growth factor of zone x

$T_i = t_i G_i$ = future trip generation in zone i

t_{ix} = number of trips between zone i and other zones x

t_{ij} = present trips between zone i and zone j

G_j = growth factor of zone j

Example 12.6 Forecasting Trips Using the Fratar Model

A study area consists of four zones (A, B, C, and D). An O-D survey indicates that the number of trips between each zone is as shown in Table 12.17. Planning estimates for the area indicate that in five years the number of trips in each zone will increase by the growth factor shown in Table 12.18 on page 612 and that trip generation will be increased to the amounts shown in the last column of the table.

Determine the number of trips between each zone for future conditions.

Table 12.17 Present Trips between Zones

Zone	*A*	*B*	*C*	*D*
A	—	400	100	100
B	400	—	300	—
C	100	300	—	300
D	100	—	300	—
Total	600	700	700	400

Table 12.18 Present Trip Generation and Growth Factors

Zone	*Present Trip Generation (trips/day)*	*Growth Factor*	*Trip Generation in Five Years*
A	600	1.2	720
B	700	1.1	770
C	700	1.4	980
D	400	1.3	520

Solution: Using the Fratar formula (Eq. 12.5), calculate the number of trips between zones A and B, A and C, A and D, and so forth. Note that two values are obtained for each zone pair (that is, T_{AB} and T_{BA}). These values are averaged, yielding a value for $T_{AB} = (T_{AB} + T_{BA})/2$.

The calculations are as follows.

$$T_{ij} = (t_i G_i) \frac{t_{ij} G_j}{\sum_x t_{ix} G_x}$$

$$T_{AB} = 600 \times 1.2 \frac{400 \times 1.1}{(400 \times 1.1) + (100 \times 1.4) + (100 \times 1.3)} = 446$$

$$T_{BA} = 700 \times 1.1 \frac{400 \times 1.2}{(400 \times 1.2) + (300 \times 1.4)} = 411$$

$$\overline{T}_{AB} = \frac{T_{AB} + T_{BA}}{2} = \frac{446 + 411}{2} = 428$$

Similar calculations yield

$$\overline{T}_{AC} = 141 \qquad \overline{T}_{AD} = 124 \qquad \overline{T}_{BC} = 372 \qquad \overline{T}_{CD} = 430$$

The results of the preceding calculations have produced the first estimate (or iteration) of future trip distribution and are shown in Table 12.19. The totals for each zone do not equal the values of future trip generation. For example, the trip

Table 12.19 First Estimate of Trips between Zones

Zone	*A*	*B*	*C*	*D*	*Estimated Total Trip Generation*	*Actual Trip Generation*
A	—	428	141	124	693	720
B	428	—	372	—	800	770
C	141	372	—	430	943	980
D	124	—	430	—	554	520
Totals	693	800	943	554		

generation in zone A is estimated as 693 trips, whereas the actual value is 720 trips. Similarly, the estimate for zone B is 800 trips, whereas the actual value is 770 trips.

Proceed with a second iteration in which the input data are the numbers of trips between zones as previously calculated. Also, new growth factors are computed as the ratio of the trip generation expected to occur in five years and the trip generation estimated in the preceding calculation. The values are given in Table 12.20.

The calculations for the second iteration are left to the reader to complete and the process can be repeated as many times as needed until the estimate and actual trip generation values are close in agreement.

Table 12.20 Growth Factors for Second Iteration

Zone	*Estimated Trip Generation*	*Actual Trip Generation*	*Growth Factor*
A	693	720	1.04
B	800	770	0.96
C	943	980	1.04
D	554	520	0.94

Average Growth Factor Model.

- A more general form of growth factor model than the Fratar method
- Rather than weighting the growth of trips between zones i and j by the growth across all zones, as is done in the Fratar method,
- the growth rate of trips between any zones i and j is simply the average of the growth rates of these zones.

$$T'_{ij} = T_{ij}\left(\frac{G_i + G_j}{2}\right)$$

Application of the average growth factor method proceeds similarly to that of the Fratar method. As iterations continue, the growth factors converge toward unity.

Example

- Using the average growth factor method, calculate the trip distribution for two iterations:

Present Trips between Zones

Zone	A	B	C	D
A	-	25	50	25
B	25	-	150	75
C	50	150	-	200
D	25	75	200	-
Total	100	250	400	300

First Iteration:

Present Trip Generation and Growth Factors

Zones	Present Totals	Growth Factor	Estimated future totals
A	100	3	300
B	250	4	1000
C	400	2	800
D	300	1	300

T_{AB}= 25* ((3+4)/2)=87.5
T_{AC}= 50* ((3+2)/2)=125
T_{AD}= 25* ((3+1)/2)=50
T_{BC}= 150* ((4+2)/2)=450
T_{BD}= 75* ((4+1)/2)=187.5
T_{CD}= 200* ((2+1)/2)=300

Sum trip ends in each zone and develop the new growth factors:

TA= $T_{AB}+T_{AC}+T_{AD}$= 87.5+125+50= 262.5
TB= $T_{BA}+T_{BC}+T_{BD}$= 87.5+450+187.5= 725
TC= $T_{CA}+T_{CB}+T_{CD}$= 125+450+300= 875
TD= $T_{DA}+T_{DB}+T_{DC}$= 50+187.5+300= 537.5

New Growth Factor for A= 300/262.5= 1.143

New Growth Factor for B= 1000/725= 1.379

New Growth Factor for C= 800/875= 0.914

New Growth Factor for D= 300/537.5= 0.558

Continue Second Iteration

ROUTE CHOICE

Route choice User Equilibrium

- The rule of choice underlying user equilibrium is that travelers will select a route so as to minimize their personal travel time between the origin and destination.

User equilibrium is defined as:

The travel time between a specified origin and destination on all used routes is the same and is less than or equal to the travel time that would be experienced by a traveler on any unused route [Wardrop, 1952].

Example 1:

Peak-hour traffic demand between an origin-destination pair is initially 3500 vehicles. The two routes connecting the pair have performance functions $t_1 = 2 + 3(x_1/c_1)$ and $t_2 = 4 + 2(x_2/c_2)$, where the t's are travel times in minutes, the x's are the peak-hour traffic volumes expressed in thousands, and the c's are the peak-hour route capacities expressed in thousands of vehicles per hour. Initially, the capacities of routes 1 and 2 are 2500 and 4000 veh/h, respectively. A reconstruction project reduces capacity on route 2 to 2000 veh/h. Assuming user equilibrium before and during reconstruction, what reduction in total peak-hour origin-destination traffic flow is needed to ensure that total travel times (summation of all $x_a t_a$'s, where a denotes route) during reconstruction are equal to those before reconstruction?

SOLUTION

First, focusing on the roads before reconstruction, a check to see if both routes are used gives (using performance functions)

$$t_1(3.5) = 6.2 \text{ min}, \qquad t_2(0) = 4 \text{ min}$$
$$t_1(0) = 2 \text{ min}, \qquad t_2(3.5) = 5.75 \text{ min}$$

which, because $t_1(3.5) > t_2(0)$ and $t_2(3.5) > t_1(0)$, indicates that both routes are used. Setting route travel times equal and substituting performance functions gives

$$2 + \frac{3}{2.5}(x_1) = 4 + \frac{2}{4}(x_2)$$

From conservation of flow, $x_2 = 3.5 - x_1$, so that

$$2 + 1.2x_1 = 4 + 0.5(3.5 - x_1)$$

Solving gives $x_1 = 2.206$ and $x_2 = 3.5 - 2.206 = 1.294$. For travel times,

$$t_1 = 2 + 1.2(2.206) = 4.647 \text{ min}$$
$$t_2 = 4 + 0.5(1.294) = 4.647 \text{ min}$$

The total peak-hour travel time before reconstruction will simply be the average route travel time multiplied by the number of vehicles:

$$\text{Total travel time} = 4.647(3500) = 16{,}264.5 \text{ veh-min}$$

During reconstruction, the performance function of route 1 is unchanged, but the performance function of route 2 is altered because of the reduction in capacity to

$$t_2 = 4 + \frac{2}{2}(x_2) = 4 + x_2$$

If it is assumed that both routes are used, $t_1 = t_2$. Also, it is known that the total travel time is

$$\begin{aligned} t_1(q) &= t_2(q) \\ &= 16{,}264.5 \text{ veh-min} \end{aligned}$$

Using the performance function of route 2,

$$(4 + x_2)(q) = 16.2645 \ (\text{using thousands of vehicles})$$

$$q = \frac{16.2645}{4 + x_2}$$

From $t_1 = t_2$, and $x_1 = q - x_2$ (flow conservation),

$$\begin{aligned} 2 + 1.2x_1 &= 4 + x_2 \\ 2 + 1.2(q - x_2) &= 4 + x_2 \\ q &= 1.67 + 1.83x_2 \end{aligned}$$

Equating the two expressions for q gives

$$1.67 + 1.83x_2 = \frac{16.2645}{4 + x_2}$$

$$1.83x_2^2 + 8.99x_2 - 9.5845 = 0$$

which gives $x_2 = 0.901$, $q = 1.67 + 1.83(0.901) = 3.319$, and $x_1 = 3.319 - 0.901 = 2.418$. Because flow exists on both routes, the earlier assumption that both routes would be used is valid, and a reduction of 181 vehicles (3500 − 3319) in peak-hour flow is needed to ensure equality of total travel times.

Example 2:

Two highways serve a busy corridor with a traffic demand that is fixed at 6000 vehicles during the peak hour. The performance functions for the two routes are $t_1 = 4 + 5(x_1/c_1)$ and $t_2 = 3 + 7(x_2/c_2)$, where t's are in minutes, and flows (x's) and capacities (c's) are in thousands of vehicles per hour. Initially, the capacities of routes 1 and 2 are 4400 veh/h and 5200 veh/h, respectively. If a highway reconstruction project cuts the capacity of route 2 to 2200 veh/h, how many additional vehicle hours of travel time will be added in the corridor assuming that user-equilibrium conditions hold?

SOLUTION

To determine the initial number of vehicle hours, first check to see if both routes are used:

$$t_1(6) = 10.82 \text{ min}, \qquad t_2(0) = 3 \text{ min}$$

$$t_1(0) = 4 \text{ min}, \qquad t_2(6) = 11.08 \text{ min}$$

Both routes are used, because $t_2(6) > t_1(0)$ and $t_1(6) > t_2(0)$. At user equilibrium, $t_1 = t_2$, so substituting performance functions gives

$$4+\frac{5}{4.4}(x_1)=3+\frac{7}{5.2}(x_2)$$

With flow conservation, $x_2 = 6 - x_1$, so that

$$4+1.136(x_1)=3+1.346(6-x_1)$$
$$x_1=2.85$$

and

$$x_2=6-2.85$$
$$=3.15$$

The total travel time in hours is $(t_1x_1 + t_2x_2)/60$ or, by substituting,

$$\frac{\{[4+1.136(2.85)]\ 2850+[3+1.346(3.15)]\ 3150\}}{60}=723.88\ \text{veh-h}$$

For the reduced-capacity case, the route usage check is

$$t_1(6) = 10.82\text{ min}, \qquad t_2(0) = 3\text{ min}$$
$$t_1(0) = 4\text{ min}, \qquad t_2(6) = 22.09\text{ min}$$

Again, both routes are used [$t_2(6) > t_1(0)$ and $t_1(6) > t_2(0)$]. Equating performance functions (because travel times are equal) and using flow conservation, $x_2 = 6 - x_1$,

$$4+\frac{5}{4.4}(x_1)=3+\frac{7}{2.2}(x_2)$$
$$4+1.136x_1=3+3.182(6-x_1)$$
$$x_1=4.19$$

and

$$x_2 = 6 - 4.19 = 1.81$$

which gives a total travel time of $(t_1x_1 + t_2x_2)/60$ or, by substituting,

$$\frac{\{[4+1.136(4.19)]\ 4190+[3+3.182(1.81)]\ 1810\}}{60}=875.97\ \text{veh-h}$$

Thus the reduced capacity results in an additional <u>152.09 veh-h</u> (875.97 − 723.88) of travel time.

Mathematical Programming Approach to User Equilibrium

- Equating travel time on all used routes is straight forward approach to user equilibrium, but can become cumbersome when many alternative routes are involved.

- The approach used to solve this computational obstacle is to formulate the user equilibrium as a mathematical program.

- Specifically, user-equilibrium route flows can be obtained by minimizing the following function [Sheffi, 1985]:

$$\min S(x) = \sum_{n} \int_{0}^{x_n} t_n(w)\,dw$$

Where,

n: a specific route, and

$t_n(w)$: performance function corresponding to route n (w denotes flow, x_n's)

This function is subject to the constraints that the flow on all routes is greater than or equal to zero ($x_n \geq 0$) and the flow conservation holds (the flow on all routes between an origin and destination sums to the total number of vehicles, q, travelling between the origin and destination,

$$q = \sum_n x_n$$

Formulating the user equilibrium problem as a mathematical program allows an equilibrium solution to very complex highway networks (many O-Ds)

Solve by formulating user equilibrium problem as a mathematical program.

SOLUTION

From Example 8.10, the performance functions are

$$t_1 = 6 + 4x_1$$
$$t_2 = 4 + x_2^2$$

Substituting these into Eq. 8.8 gives

$$\min S(x) = \int_0^{x_1} (6 + 4w)\,dw + \int_0^{x_2} \left(4 + w^2\right) dw$$

The problem can be viewed in terms of x_2 only by noting that flow conservation implies $x_1 = 4.5 - x_2$. Substituting,

$$S(x) = \int_0^{4.5 - x_2} (6 + 4w)\,dw + \int_0^{x_2} \left(4 + w^2\right) dw$$

$$= 6w + 2w^2 \Big|_0^{4.5 - x_2} + 4w + \frac{w^3}{3} \Big|_0^{x_2}$$

$$= 27 - 6x_2 + 40.5 - 18x_2 + 2x_2^2 + 4x_2 + \frac{x_2^3}{3}$$

To arrive at a minimum, the first derivative is set to zero, giving

$$\frac{dS(x)}{dx_2} = x_2^2 + 4x_2 - 20 = 0$$

which gives x_2 = 2899 veh/h, the same value as found in Example 8.10. It can readily be shown that all other flows and travel times will also be the same as those computed in Example 8.10.

System Optimization

From an idealistic point of view, one can visualize a single route choice strategy that results in the lowest possible number of total vehicle hours of travel for some specified origin-destination traffic flow. Such strategy is known as a system-optimal route choice and is based on the choice rule that travelers will behave such that total system travel time will be minimized even though travelers may be able to decrease their own individual travel times by unilaterally changing routes. From this definition it is clear that system-optimal flows are not stable, because there will always be a temptation for travelers to switch to non–system-optimal routes in order to improve their travel times. Thus system-optimal flows are generally not a realistic representation of actual traffic. Nevertheless, system-optimal flows often provide useful comparisons with the more realistic user-equilibrium traffic forecasts.

The system-optimal route choice rule is made operational by the following mathematical program:

$$\min S(x) = \sum_n x_n t_n(x_n) \tag{8.9}$$

This program is subject to the constraints of flow conservation ($q = \sum_n x_n$) and nonnegativity ($x_n \geq 0$).

Determine the system-optimal travel time for the situation described in Example 3

SOLUTION

Using Eq. 8.9 and substituting the performance functions for routes 1 and 2,

$$S(x) = x_1(6+4x_1) + x_2(4+x_2^2)$$
$$= 6x_1 + 4x_1^2 + 4x_2 + x_2^3$$

From flow conservation, $x_1 = 4.5 - x_2$; therefore,

$$S(x) = 6(4.5-x_2) + 4(4.5-x_2)^2 + 4x_2 + x_2^3$$
$$= x_2^3 + 4x_2^2 - 38x_2 + 108$$

To find the minimum, the first derivative is set to zero, giving

$$\frac{dS(x)}{dx_2} = 3x_2^2 + 8x_2 - 38 = 0$$

which gives $x_2 = 2.467$ and $x_1 = 4.5 - 2.467 = 2.033$. For system-optimal travel times,

$$t_1 = 6 + 4(2.033) = 14.13 \text{ min}$$
$$t_2 = 4 + (2.467)^2 = 10.08 \text{ min}$$

which are not user-equilibrium travel times, because t_1 is not equal to t_2. In Example 3 the total user-equilibrium travel time is computed as 930 veh-h [4500(12.4)/60]. For the system-optimal total travel time [$(t_1x_1 + t_2x_2)/60$],

$$\frac{[2033(14.13) + 2467(10.08)]}{60} = \underline{\underline{893.2 \text{ veh-h}}}$$

Therefore, the system-optimal solution results in a systemwide travel time savings of 36.8 veh-h.

Two roads begin at a gate entrance to a park and take different scenic routes to a single main attraction in the park. The park manager knows that 4000 vehicles arrive during the peak hour, and he distributes these vehicles among the two routes so that an equal number of vehicles take each route. The performance functions for the routes are $t_1 = 10 + x_1$ and $t_2 = 5 + 3x_2$, with the x's expressed in thousands of vehicles per hour and the t's in minutes. How many vehicle-hours would have been saved had the park manager distributed the vehicular traffic so as to achieve a system-optimal solution?

SOLUTION

For the number of vehicle hours, assuming an equal distribution of traffic among the two routes,

$$\textit{Route 1}: \quad \frac{x_1 t_1}{60} = \frac{2000[10+(2)]}{60} = 400 \text{ veh-h}$$

$$\textit{Route 2}: \quad \frac{x_2 t_2}{60} = \frac{2000[5+3(2)]}{60} = 366.67 \text{ veh-h}$$

for a total of 766.67 veh-h. With the system-optimal traffic distribution, the performance functions are substituted into Eq. 8.9, giving

$$S(x) = (10 + x_1)\, x_1 + (5 + 3x_2)x_2$$

With flow conservation, $x_1 = 4.0 - x_2$, so that

$$S(x) = 4x_2^2 - 13x_2 + 56$$

Setting the first derivative equal to zero,

$$\frac{dS(x)}{dx_2} = 8x_2 - 13 = 0$$

gives $x_2 = 1.625$ and $x_1 = 4 - 1.625 = 2.375$. The total travel times are

$$\textit{Route 1:}\quad \frac{x_1 t_1}{60} = \frac{2375\left[10 + 2.375\right]}{60} = 489.84 \text{ veh-h}$$

$$\textit{Route 2:}\quad \frac{x_2 t_2}{60} = \frac{1625\left[5 + 3(1.625)\right]}{60} = 267.45 \text{ veh-h}$$

which gives a total system travel time of 757.27 veh-h or a savings of 9.38 veh-h (766.67 − 757.29) over the equal distribution of traffic to the two routes.

Basics of Engineering Economics

Engineering Economy

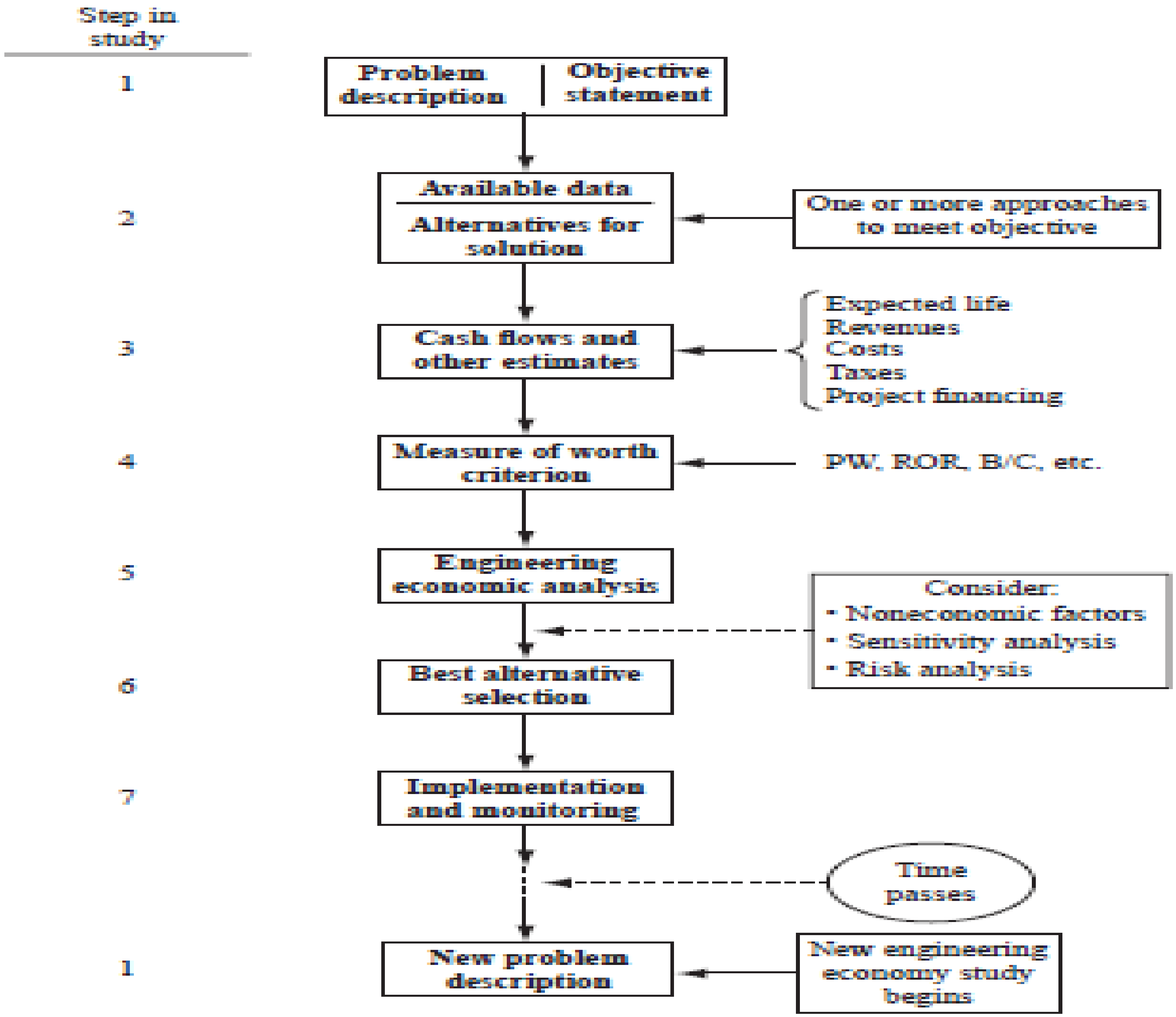
- It deals with the concepts and techniques of analysis useful in evaluating
  - the worth of systems, products, and services in relation to their costs

Engineering Economy

- **It is used to answer many different questions**
  - **Which engineering projects are worthwhile?**
    - Has the civil engineer shown that constructing a new road is worth developing?
  - **Which engineering projects should have a higher priority?**
    - Has the civil engineer shown which transit improvement projects should be funded with the available budget?
  - **How should the engineering project be designed?**
    - Has civil engineer chosen the best alignment for the proposed roadway?

Basic Concepts

- **Cash flow**
- **Interest Rate and Time value of money**
- **Equivalence technique:**
  - Economic equivalence is a combination of interest rate and time value of money to determine the different amounts of money at different points in time that are equal in economic value.



Steps in an engineering economy study.

Cash Flow

- Engineering projects generally have economic consequences that occur over an extended period of time:
  - For example, if an expensive piece of machinery is installed in a plant were brought on credit, the simple process of paying for it may take several years
  - The resulting favorable consequences may last as long as the equipment performs its useful function
- Each project is described as cash receipts or disbursements (expenses) at different points in time

Categories of Cash Flows

- The expenses and receipts due to engineering projects usually fall into one of the following categories:

1. First cost (Capital): expense to build or to buy and install

2. Operations and maintenance (O&M): annual expense, such as electricity, labor, and minor repairs

3. Salvage value: receipt at project termination for sale or transfer of the equipment (can be a salvage cost)

4. Revenues: annual receipts due to sale of products or services

5. Overhaul: major capital expenditure that occurs during the asset's life

Cash Flow diagrams

- The costs and benefits of engineering projects over time are summarized on a cash flow diagram (CFD).

- Specifically, CFD illustrates the size, sign, and timing of individual cash flows, and forms the basis for engineering economic analysis

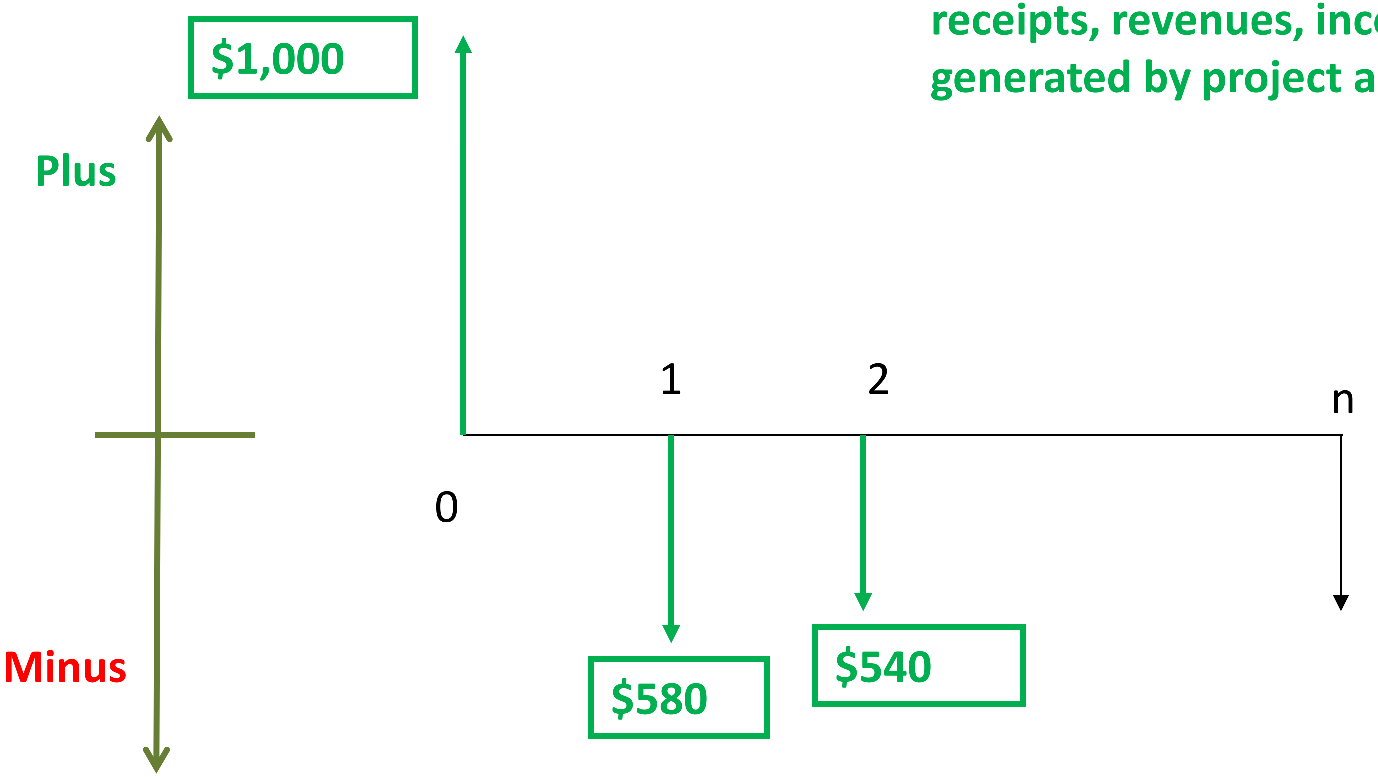
- A CFD is created by first drawing a segmented time-based horizontal line, divided into appropriate time unit.

- Each time when there is a cash flow, a vertical arrow is added – pointing down for costs and up for revenues or benefits. The cost flows are drawn to relative scale

Cash Flow Diagram

Cash inflow:

receipts, revenues, incomes, and savings generated by project and business activity.



Cash outflow:

costs, disbursements, expenses, and taxes caused by projects and business Cash flow activity.

NEW

Cash Inflow Estimates

- Income: JD150,000 per year from sales of solar-powered watches
- Savings: JD24,500 tax savings from capital loss on equipment salvage
- Receipt: JD750,000 received on large business loan plus accrued interest
- Savings: JD150,000 per year saved by installing more efficient air conditioning
- Revenue: JD50,000 to JD75,000 per month in sales for extended battery life iPhones

Cash Outflow Estimates

- Operating costs: JD230,000 per year annual operating costs for software services
- First cost: JD800,000 next year to purchase replacement equipment
- Expense: JD20,000 per year for loan interest payment to bank
- Initial cost: JD1 to JD1.2 million in capital expenditures for a water recycling unit

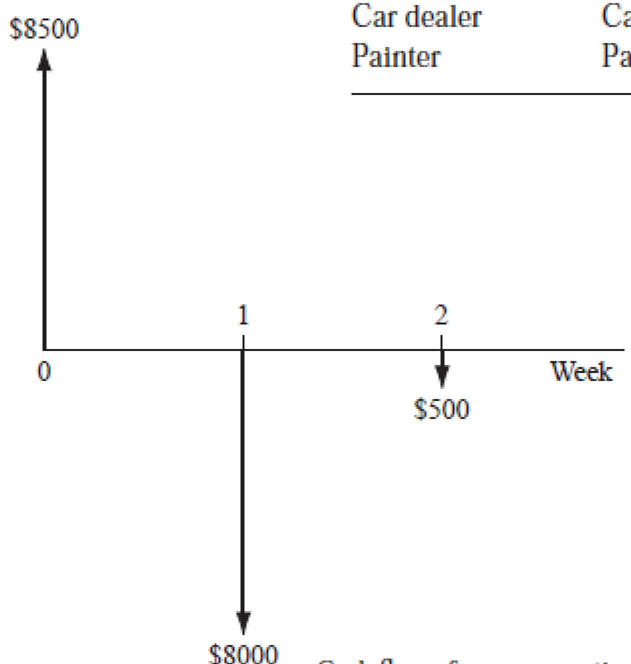
$$\text{Net cash flow} = \text{cash inflows} - \text{cash outflows}$$
$$\text{NCF} = R - D$$

NCF is net cash flow, R is receipts, and D is disbursements.

- Assume you borrow JD8500 from a bank today to purchase an JD8000 used car for cash next week, and you plan to spend the remaining JD500 on a new paint job for the car two weeks from now.

- There are several perspectives possible when developing the cash flow diagram—those of the borrower (that's you), the banker, the car dealer, or the paint shop owner.

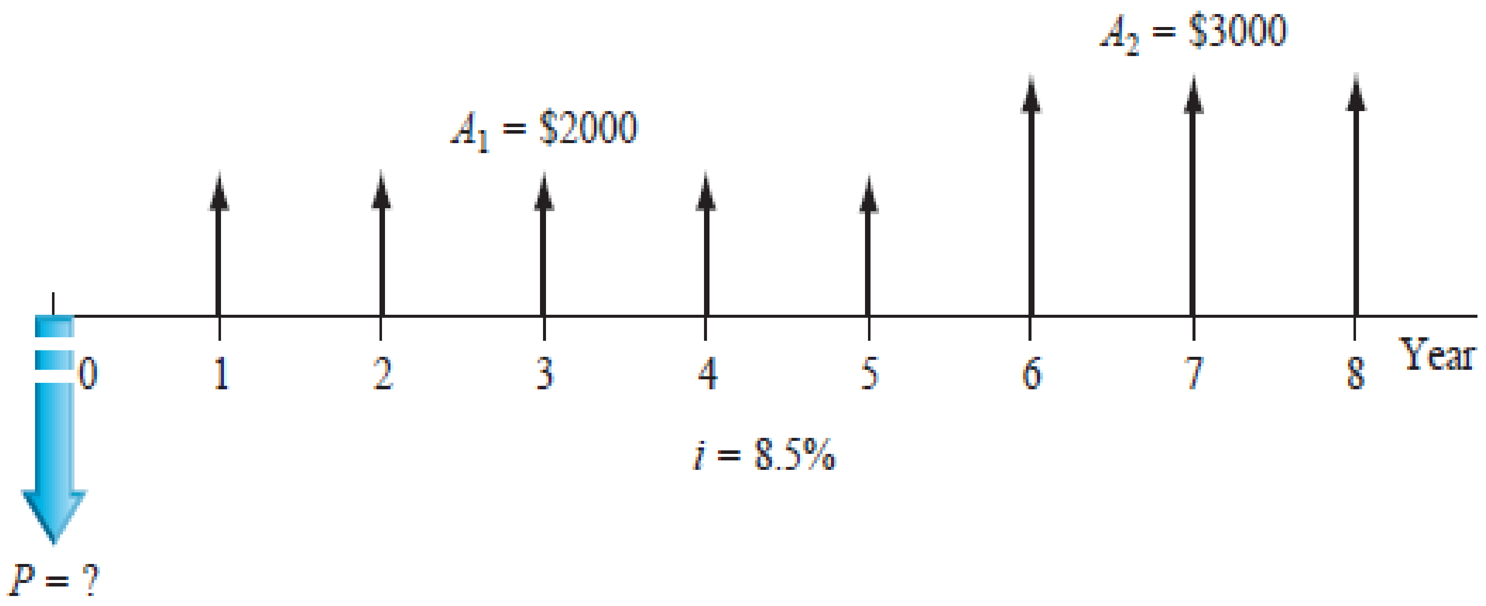
Perspective	Activity	Cash flow with Sign, $	Time, week
You	Borrow	+8500	0
	Buy car	–8000	1
	Paint job	–500	2
Banker	Lender	–8500	0
Car dealer	Car sale	+8000	1
Painter	Paint job	+500	2



One, and only one, of the perspectives is selected to develop the diagram.

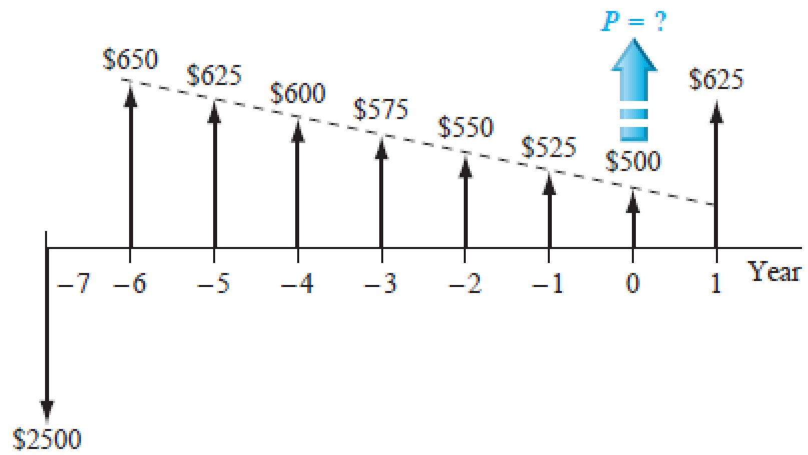
Cash flows from perspective of borrower for loan and purchases.

- An electrical engineer wants to deposit an amount *P* now such that she can withdraw an equal annual amount of ***A1*** **$2000** per year for the **first 5 years**, **starting 1 year after the deposit**, and a different annual withdrawal of ***A2*** **$3000** per year **for the following 3 years**. How would the cash flow diagram appear if ***i*** **8.5% per year**?



- A rental company **spent \$2500 on a new air compressor 7 years ago**. The **annual rental income from the compressor has been \$750**. The **\$100 spent on maintenance the first year** has **increased each year by \$25**. The company plans **to sell the compressor at the end of next year** for **\$150**. Construct the cash flow diagram from the **company's perspective** and indicate where the present worth now is located.

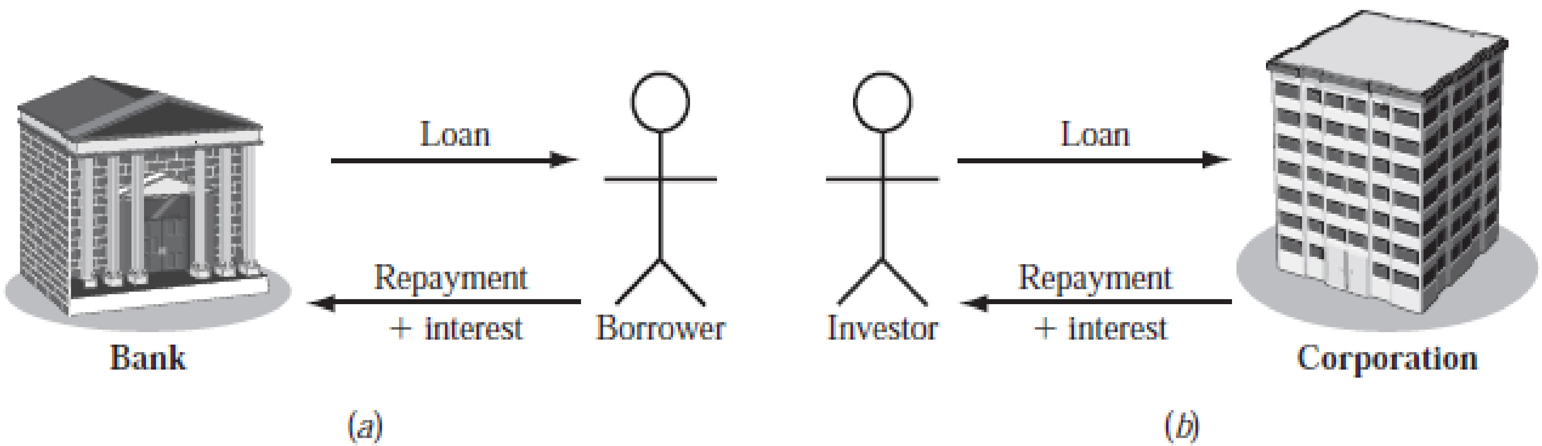
End of Year	Income	Cost	Net Cash Flow
−7	\$ 0	\$2500	\$−2500
−6	750	100	650
−5	750	125	625
−4	750	150	600
−3	750	175	575
−2	750	200	550
−1	750	225	525
0	750	250	500
1	750 + 150	275	625



Interest Rate and Rate of Return

- Computationally, **interest** is the difference between an ending amount of money and the beginning amount. (if diff. is zero or –ve→ no interest)

- There are always two perspectives to an amount of interest—
  - interest paid and interest earned.



(a) Interest paid over time to lender. (b) Interest earned over time by investor.

- **Interest paid** on borrowed funds (a loan) is determined using the original amount, also called the *principal*,

Interest = amount owed now - principal

When interest paid over a *specific time unit* is expressed as a percentage of the principal, the result is called the **interest rate.**

$$\text{Interest rate (\%)} = \frac{\text{interest accrued per time unit}}{\text{principal}} \times 100\%$$

The time unit of the rate is called the **interest period.**

NEW

Example:

- An employee borrows JD10,000 on May 1 and must repay a total of JD10,700 exactly 1 year later. Determine the interest amount and the interest rate paid.

- **Solution**

- The perspective here is that of the borrower since JD10,700 repays a loan.

- To determine the interest paid:

Interest paid = 10,700 - 10,000 = JD 700

- To determine the interest rate paid for 1 year:

$$\textbf{Interest rate} = \frac{700}{10000} \times 100\% = 7\% \; per\ year$$

NEW

Example:

- A company plans to borrow JD 20,000 from a bank for 1 year at 9% interest to buy new equipment.

  Compute the interest and the total amount due after 1 year.

Solution:

Total interest accrued: Interest = JD20,000* (0.09) = JD1,800

The total amount due= 20,000+1,800= JD 21,800

Or: **Total due** = principal * (1 + interest rate) = 20,000*(1.09) = JD 21,800

NEW

From the perspective of a saver, a lender, or an investor, **interest earned** is the final amount minus the initial amount, or principal.

Interest earned = total amount now – principal

Interest earned over a specific period of time is expressed as a percentage of the original amount and is called **rate of return (ROR).**

$$\text{Rate of return (\%)} = \frac{\text{interest accrued per time unit}}{\text{principal}} \times 100\%$$

Example:

NEW

a. Calculate the amount deposited 1 year ago to have JD1000 now at an interest rate of 5% per year.

b. Calculate the amount of interest earned during this time period.

Solution:

a. The total amount accrued (JD1000) is the sum of the original deposit and the earned interest.

If *X* is the original deposit,

- Total accrued = deposit + deposit * (interest rate)
- JD1000 = $X + X\,(0.05) = X*\,(1 + 0.05) = 1.05\,X$
- The original deposit is:

$$X = \frac{1000}{1.05} = JD\ 952.38$$

b. To determine the interest earned:

Interest = 1000 – 952.38 = JD 47.62

NEW

- **inflation** can significantly increase an interest rate, by definition, inflation represents a decrease in the value of a given currency.

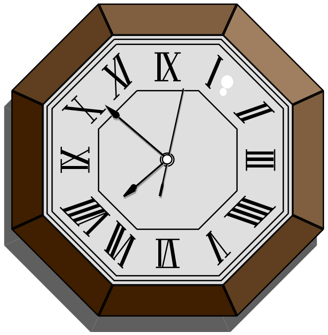
- That is, JD10 now will not purchase the same amount of gasoline for your car (or most other things) as JD10 did 10 years ago. The changing value of the currency affects market interest rates.

> In simple terms, interest rates reflect two things: a so-called real rate of return *plus* the expected inflation rate. The real rate of return allows the investor to purchase more than he or she could have purchased before the investment, while inflation raises the real rate to the market rate that we use on a daily basis.

- The safest investments (such as government bonds) typically have a 3% to 4% real rate of return built into their overall interest rates.

- Thus, a market interest rate of, say, 8% per year on a bond means that investors expect the inflation rate to be in the range of 4% to 5% per year. Clearly, inflation causes interest rates to rise.

Time Value of Money



- Money has value
  - Money can be leased or rented
  - The payment is called interest
  - If you put $100 in a bank at 9% interest for one time period you will receive back your original $100 plus $9

Original amount to be returned = $100
Interest to be returned = $100 x .09 = $9

Interest Rate

Interest Rate: The amount charged, expressed as a percentage of **principal**, by a **lender** to a borrower for the use of **assets**. typically noted on an annual basis,

1. Simple Interest: infrequently used

When the **total interest earned or charged** is **linearly proportional to the initial amount** of the loan (principal), **the interest rate, and the number of interest periods**, the interest and interest rate are said to be ***simple***.

Computation of simple interest

The total interest, **I**, earned or paid may be computed using the formula below.

$$\underline{\mathrm{I}} = (P)(N)(i)$$

P = principal amount lent or borrowed

N = number of interest periods (e.g., years)

i = interest rate per interest period

The total amount repaid at the end of *N* interest periods is *P* + *I*.

Example: If $5,000 were loaned for five years at a simple interest rate of 7% per year, the interest earned would be

$$\underline{\mathrm{I}} = \$5,000 \quad \text{x} \quad 5 \quad \text{x} \quad 0.07 = \$1,750$$

So, the total amount repaid at the end of five years would be the original amount **($5,000) +($1,750) = $6,750**.

2. Compound Interest

- Interest that is computed on the **original unpaid debt** and **the unpaid interest** **(interest on top of interest !!!)**

- Compound interest is most commonly used in practice

- Total interest earned = $\mathbf{I_n = P\,(1+i)^n - P}$

  – Where,
    - P – present sum of money
    - i – interest rate
    - n – number of periods (years)

Future Value of a Loan With Compound Interest

- **Amount of money due at the end of a loan:**
  - **$F = P(1+i)_1(1+i)_2.....(1+i)_n$ or $F = P\,(1 + i)^n$**
  - Where,
    - F = future value and P = present value

If i = 9%, P = $100 and say n= 2. Determine the value of F?

$F = \$100\,(1 + .09)^2 = \$118.81$

Compound interest reflects both the remaining principal and any accumulated interest. **For $1,000 at 10%…**

Period	(1) Amount owed at beginning of period	(2)=(1)x10% Interest amount for period	(3)=(1)+(2) Amount owed at end of period
1	$1,000	$100	$1,100
2	$1,100	$110	$1,210
3	$1,210	$121	$1,331

Compound interest is commonly used in personal and professional financial transactions.

Example:

Assume an engineering company borrows **$100,000 at 10% per year compound interest** and will **pay the principal and all the interest after 3 years**. Compute the **annual interest and total amount due after 3 years**. Graph the interest and total owed for each year, and **compare with the previous example that involved simple interest.**

To include compounding of interest, the annual interest and total owed each year are calculated:

Simple interest:

Year 1: 10,000
Year 2: 10,000
Year 3: 10,000

Sum of interest= 30,000

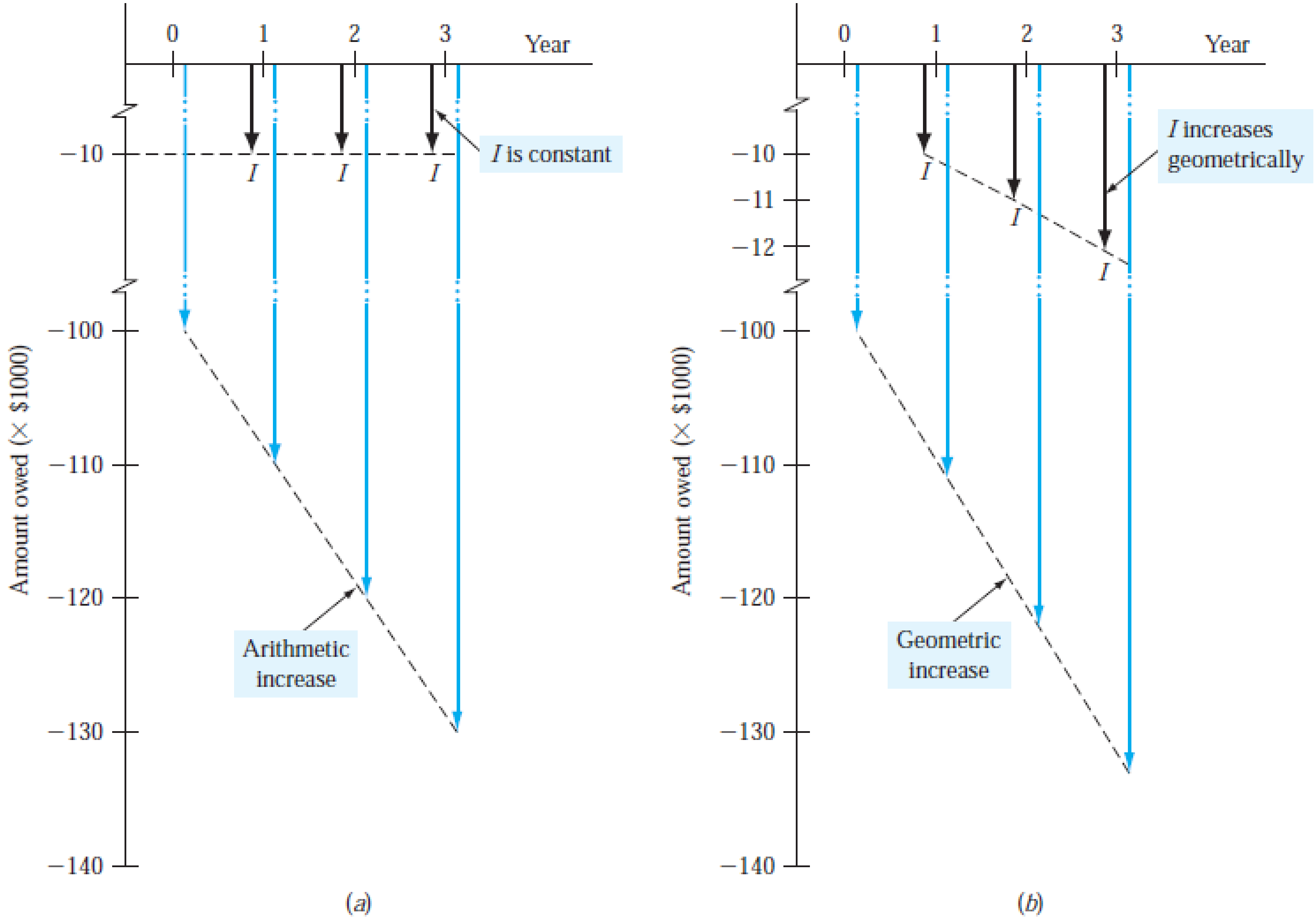
Total due, year 3=

100,000+30,000= 130,000

Compounded interest

Interest, year 1:	$100{,}000(0.10) = \$10{,}000$
Total due, year 1:	$100{,}000 + 10{,}000 = \$110{,}000$
Interest, year 2:	$110{,}000(0.10) = \$11{,}000$
Total due, year 2:	$110{,}000 + 11{,}000 = \$121{,}000$
Interest, year 3:	$121{,}000(0.10) = \$12{,}100$
Total due, year 3:	$121{,}000 + 12{,}100 = \$133{,}100$

NEW



Interest *I* owed and total amount owed for (*a*) simple interest and (*b*) compound interest

An extra $133,100 – 130,000 = $3100 in interest is due for the compounded interest loan.

Due to this **geometric growth** of compound interest, the difference between simple and compound interest **accumulation increases rapidly as the time frame increases.**

For example, **if the loan is for 10 years, not 3,** the **extra paid for compounding interest may be calculated to be $59,374**.

Notation for Calculating a Present Value

We can apply compound interest formulas to "move" cash flows along the cash flow diagram.

Using the standard notation, we find that a **present amount, P**, can **grow into a future amount, F**, in **N time periods** at **interest rate i** according to the formula below:

- $\boldsymbol{F = P(1+i)^N}$
- $\boldsymbol{P = \frac{F}{(1+i)^N}}$ is the *single payment present worth factor*.

- Functional notation:

  P=F(P/F,i,n) P=5000(P/F,6%,10)

Interpretation of (P/F, i, n): a present sum P, given a future sum, F, n interest periods hence at an interest rate i per interest period

It is common to use standard notation for interest factors.

$$(1+i)^N = (F/P, i, N)$$

This is also known as the ***single payment compound amount factor***. The term on the right is read "*F* given *P* at *i* % interest per period for *N* interest periods."

$$(1+i)^{-N} = (P/F, i, N)$$

is called the ***single payment present worth factor***.

We can use these to find economically equivalent values at different points in time.

Example: \$2,500 at time zero is equivalent to how much after six years if the interest rate is 8% per year?

$$F = \$2,500(F/P, 8\%, 6) = \$2,500(1.5869) = \$3,967$$

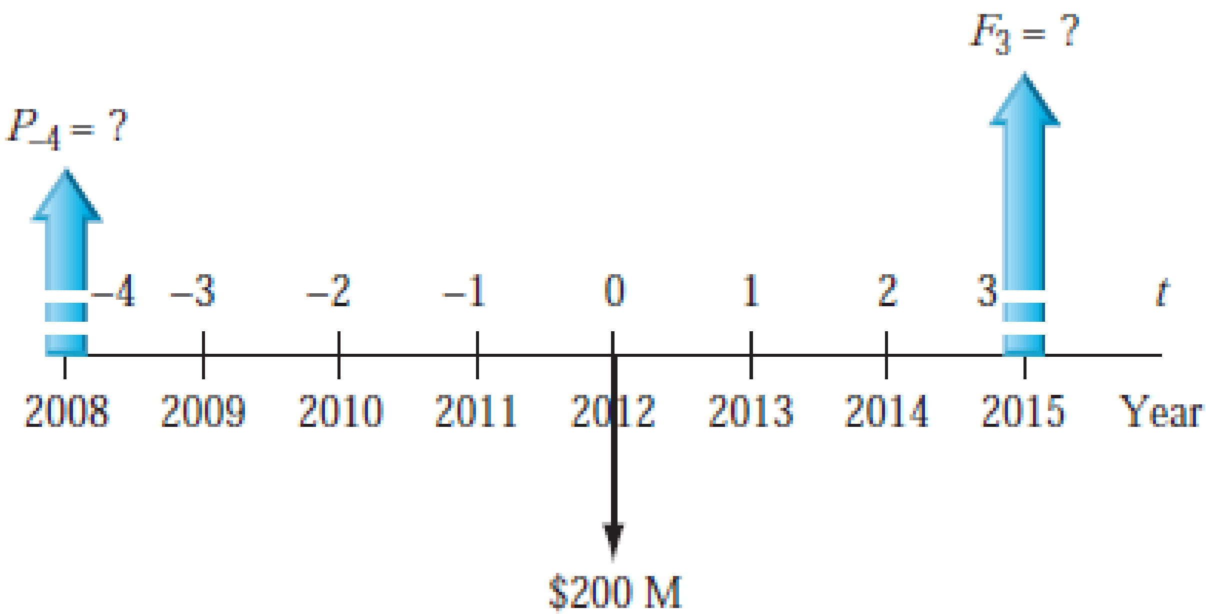
Example: \$3,000 at the end of year seven is equivalent to how much today (time zero) if the interest rate is 6% per year?

$$P = \$3,000(P/F, 6\%, 7) = \$3,000(0.6651) = \$1,995$$

Example:

A Cement factory will require an investment of **$200 million** to construct (year 2012). Delays beyond the anticipated implementation year of 2012 will **require additional money to construct the factory**. Assuming that the **cost of money is 10% per year**, compound interest, determine the following:

(*a*) The equivalent investment needed **if the plant is built in 2015**.
(*b*) The equivalent investment needed had the plant **been constructed in the year 2008.**



(a) To find the equivalent investment required in 3 years, apply the F/P factor. Use $1 million units and the tabulated value for 10% interest.

$F3 = P(F/P,i,n) = 200(F/P,10\%,3) = 200(1.3310)$
$= \$266.2$ (\$266,200,000)

(*b*) The year 2008 is 4 years prior to the planned construction date of 2012. To determine the equivalent cost 4 years earlier, consider the \$200 M in 2012 ($t = 0$) as the future value F and apply the P/F factor for $n = 4$ to find P_{-4}.

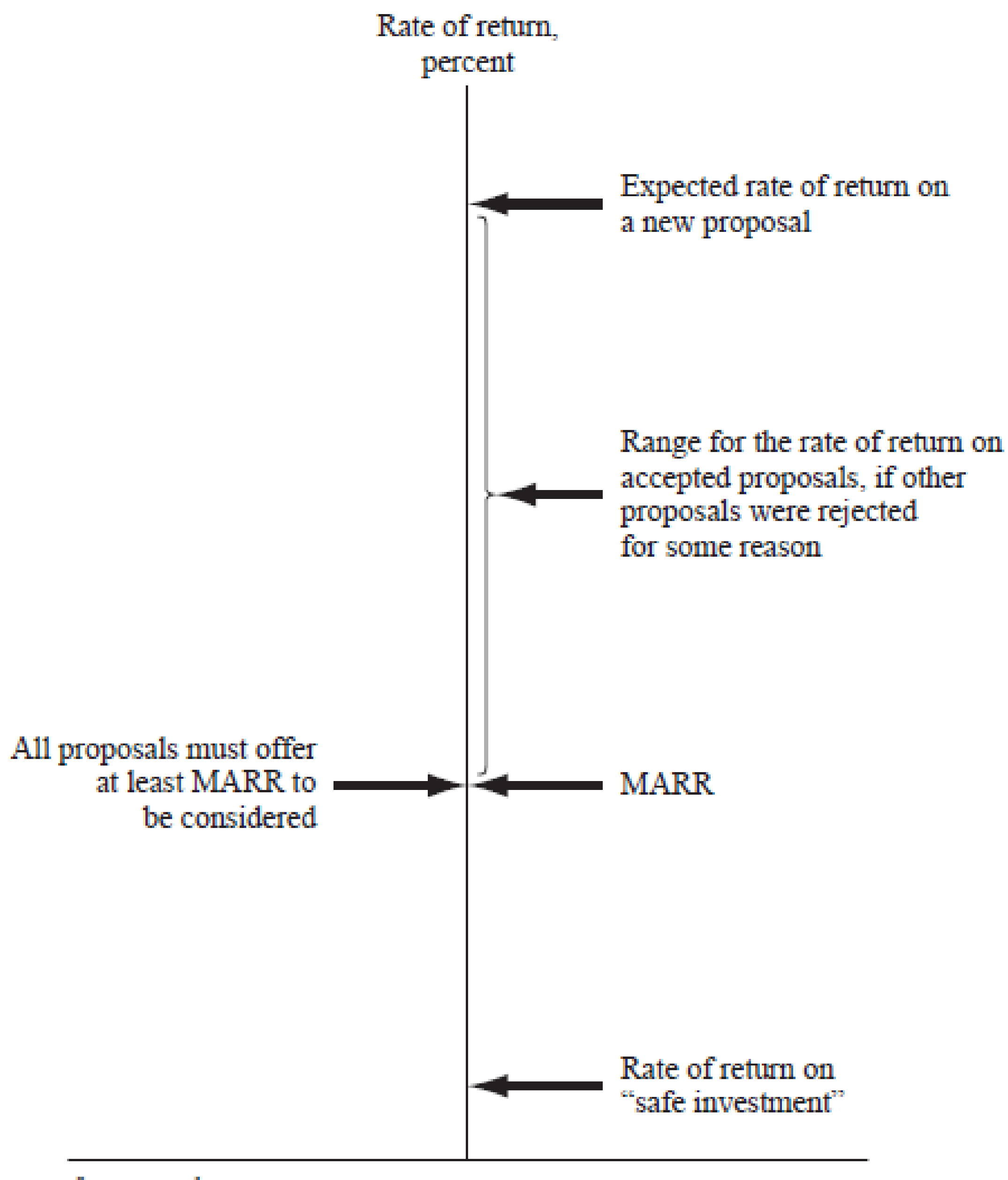
$P_{-4} = F(P/F,i,n) = 200(P/F,10\%,4) = 200(0.6830)$
$= \$136.6$ (\$136,600,000)

3. Minimum Attractive Rate of Return (MARR)

For any investment to be profitable, the investor (corporate or individual) **expects to receive more money than the amount of capital invested**. In other words, a fair ***rate of return,* or *return on investment,*** must be realizable.

> The Minimum Attractive Rate of Return (MARR) is a reasonable rate of return established for the evaluation and selection of alternatives. A project is not economically viable unless it is **expected to return at least the MARR**. MARR is also referred to as the *hurdle rate, cutoff rate, benchmark rate,* and *minimum acceptable rate of return.*

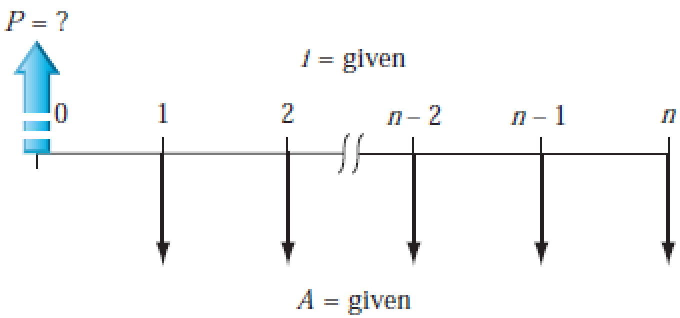
The MARR is not a rate that is calculated as a ROR. **The MARR is established by (financial) managers** and is used as **a criterion against which an alternative's ROR is measured**, when making the **accept/reject investment decision**.



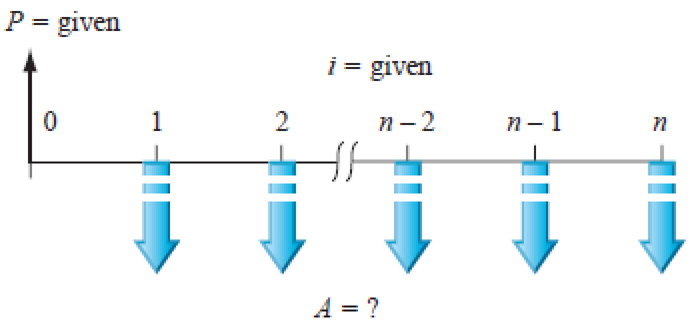
Size of MAAR relative to other rate of return values.

Uniform Series Present Worth Factor and Capital Recovery Factor (*P / A* and *A / P*)

The equivalent present worth *P* of a uniform series *A* of end-of-period cash flows (investments)



(a)



(b)

An expression for the present worth can be determined by considering each A value as a future worth F , calculating its present worth with the P/F factor,

$$P = A\left[\frac{1}{(1+i)^1}\right] + A\left[\frac{1}{(1+i)^2}\right] + A\left[\frac{1}{(1+i)^3}\right] + \cdots + A\left[\frac{1}{(1+i)^{n-1}}\right] + A\left[\frac{1}{(1+i)^n}\right]$$

$$P = A\left[\frac{1}{(1+i)^1} + \frac{1}{(1+i)^2} + \frac{1}{(1+i)^3} + \cdots + \frac{1}{(1+i)^{n-1}} + \frac{1}{(1+i)^n}\right] \qquad \text{---(1)}$$

*** 1/(1+i)**

$$\frac{P}{1+i} = A\left[\frac{1}{(1+i)^2} + \frac{1}{(1+i)^3} + \frac{1}{(1+i)^4} + \cdots + \frac{1}{(1+i)^n} + \frac{1}{(1+i)^{n+1}}\right] \qquad \text{---(2)}$$

(2) - (1)

$$\frac{1}{1+i}P = A\left[\cancel{\frac{1}{(1+i)^2}} + \cancel{\frac{1}{(1+i)^3}} + \cdots + \cancel{\frac{1}{(1+i)^n}} + \frac{1}{(1+i)^{n+1}}\right]$$

$$-\quad P = A\left[\frac{1}{(1+i)^1} + \cancel{\frac{1}{(1+i)^2}} + \cdots + \cancel{\frac{1}{(1+i)^{n-1}}} + \cancel{\frac{1}{(1+i)^n}}\right]$$

$$\frac{-i}{1+i}P = A\left[\frac{1}{(1+i)^{n+1}} - \frac{1}{(1+i)^1}\right]$$

$$P = \frac{A}{-i}\left[\frac{1}{(1+i)^n} - 1\right]$$

$$\boxed{P = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \qquad i \neq 0}$$

Finding the present amount from a series of end-of-period cash flows.

$$P = A\left[\frac{(1+i)^N - 1}{i(1+i)^N}\right] = A(P/A, i\%, N)$$

Example: How much would be needed today to provide an annual amount of $50,000 each year for 20 years, at 9% interest each year?

$$P = \$50,000(P/A, 9\%, N) = \$50,000(9.1285) = \$456,427$$

Finding A when given P.

$$A = P\left[\frac{i(1+i)^N}{(1+i)^N - 1}\right] = P(A/P, i\%, N)$$

Example: If you had \$500,000 today in an account earning 10% each year, how much could you withdraw each year for 25 years?

$$A = \$500,000(A/P, 10\%, 25) = \$500,000(0.1102) = \$55,100$$

Example:

How much money should you be willing to pay now for a guaranteed \$600 per year for 9 years starting next year, at a rate of return of 16% per year?

A =\$600, i = 16%, and n = 9. The present worth is

$P = 600(P/A, 16\%, 9) = 600(4.6065) = \$2763.90$

A Cement plant may generate a **revenue base of $50 million per year**. The president of the company may have reason to be quite pleased with this projection for the simple reason that over **the 5-year planning horizon, the expected revenue would total $250 million**, which is **$50 million more than the initial investment**. With money worth **10% per year**,

- Will the initial investment be recovered over the **5-year horizon** with the time value of money considered?

- If so, by **how much extra in present worth funds**?

- If not, what is the **equivalent annual revenue base required** for **the recovery plus the 10% return** on money?

P = 50(P/A ,10%,5) 50(3.7908)
= $189.54 ($189,540,000)

The present worth value is less than the investment plus a 10% per year return, To determine the minimum required to realize a 10% per year return, use the *A/P* factor.

where **A** starts **1 year after P at t = 0 and n = 5**.

$$A = 200(A/P, 10\%, 5) = 200(0.26380)$$
$$= \$52.76 \text{ per year}$$

The plant needs to generate $52,760,000 per year to realize a 10% per year return over 5 years.

There are interest factors for a series of end-of-period cash flows.

A = end-of-period cash flows in a uniform series continuing for a certain number of periods, starting at the end of the first period and continuing through the last

$$F = A\left[\frac{(1+i)^N - 1}{i}\right] = A(F/A, i\%, N)$$

Example: How much will you have in 40 years if you save \$3,000 each year and your account earns 8% interest each year?

$$F = \$3,000(F/A, 8\%, 40) = \$3,000(259.0565) = \$777,170$$

Finding A when given F.

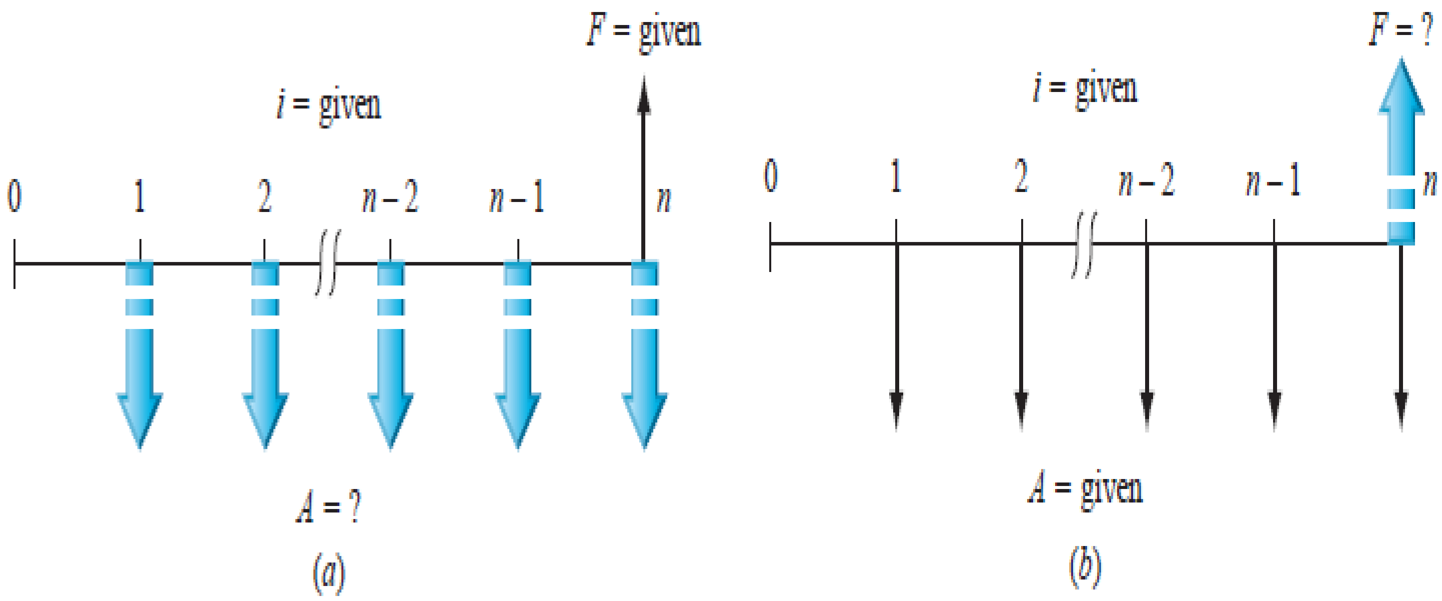
$$A = F\left[\frac{i}{(1+i)^N - 1}\right] = F(A/F, i\%, N)$$

A / F or sinking fund factor

The uniform series *A* begins at the **end of year (period) 1** and continues **through the year of the given *F*.** The last *A* value and *F* occur at the same time.

Example: How much would you need to set aside each year for 25 years, at 10% interest, to have accumulated $1,000,000 at the end of the 25 years?

$$A = \$1,000,000(A/F, 10\%, 25) = \$1,000,000(0.0102) = \$10,200$$

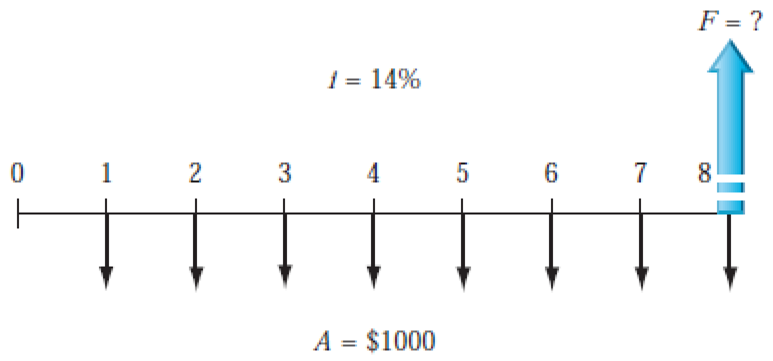


Cash flow diagrams to (*a*) find *A*, given *F*, and (*b*) find *F*, given *A*.

Example:

The president of Ford Motor Company wants to know the equivalent future worth of a $1 million capital investment each year for 8 years, starting 1 year from now. Ford capital earns at a rate of 14% per year.

F = 1000(F/A, 14%,8) = 1000(13.2328) = $13,232.80*1000 = $13,232,800



It can be challenging to solve for N or i.

- We may know P, A, and i and want to find N.
- We may know P, A, and N and want to find i.

Finding *N*

Example: Acme borrowed \$100,000 from a local bank, which charges them an interest rate of 7% per year. If Acme pays the bank \$8,000 per year, how many years will it take to pay off the loan?

$$\$100,000 = \$8,000(P/A, 7\%, N)$$

So,

$$(P/A, 7\%, N) = \frac{\$100,000}{\$8,000} = 12.5 = \frac{(1.07)^N - 1}{0.07(1.07)^N}$$

This can be solved by using the interest tables and interpolation, but we generally resort to a computer solution. N= 30.7 years

Finding *i*

Example: Jill invested $1,000 each year for five years in a local company and sold her interest after five years for $8,000. What annual rate of return did Jill earn?

$$\$8,000 = \$1,000(F/A, i\%, 5)$$

So,

$$(F/A, i\%, 5) = \frac{\$8,000}{\$1,000} = 8 = \frac{(1+i)^5 - 1}{i}$$

Again, this can be solved using the interest tables and interpolation, but we generally resort to a computer solution. i= 23.69%

Basic Analysis Tools

- The evaluation and selection of economic proposals require **cash flow estimates** over a stated period of time, mathematical techniques to calculate the **measure of worth**, and a **guideline for selecting the best proposal.**

The nature of the economic proposals is always one of two types:

Mutually exclusive alternatives: Only one of the proposals can be selected. For terminology purposes, each viable proposal is called an *alternative*.

Independent projects: More than one proposal can be selected. Each viable proposal is called a *project*.

The **do-nothing (DN)** proposal is usually understood to be an option when the evaluation is performed.

The DN alternative or project means that the **current approach is maintained;** nothing new is initiated. No new costs, revenues, or savings are generated.

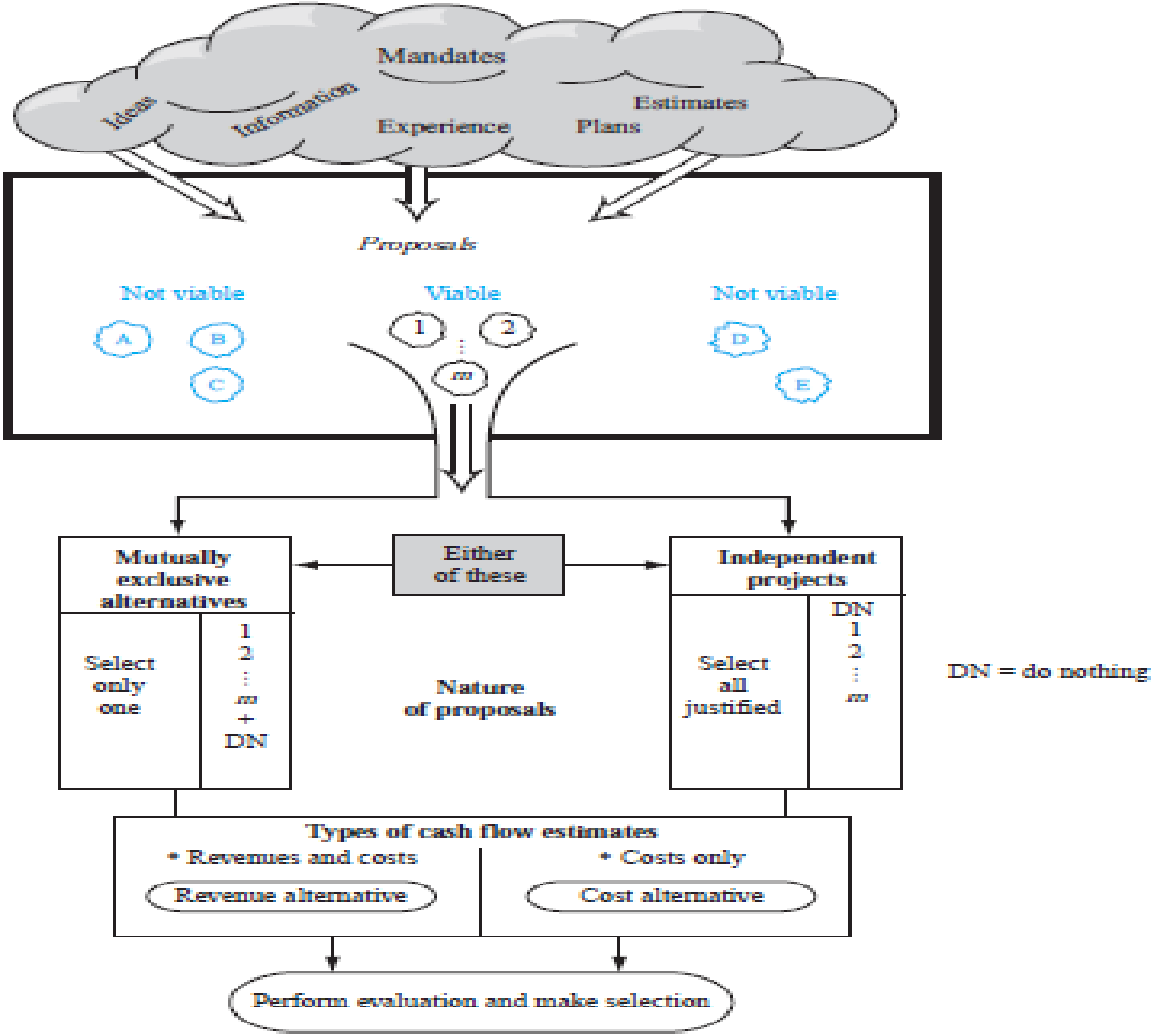
Mutually exclusive alternatives **compete with one another** and are compared pairwise.

Independent projects are evaluated one at a time and **compete only with the DN project.**

it is important to recognize the nature of the cash flow estimates before starting the computation of a measure of worth that leads to the final selection.
Cash flow estimates determine whether the alternatives are revenue- or cost-based. All the alternatives or projects must be of the same type when the economic study is performed. **Definitions for these types follow**:

Revenue: Each alternative generates cost (cash outflow) and revenue (cash inflow) estimates, and possibly savings, also considered cash inflows. Revenues can vary for each alternative.

Cost: Each alternative has only cost cash flow estimates. Revenues or savings are assumed equal for all alternatives; thus they are not dependent upon the alternative selected. These are also referred to as **service alternatives.**



Progression from proposals to economic evaluation to selectior

Economic Analysis Methods

commonly used economic analysis methods are:

- Present Worth Analysis
- Annual Worth Analysis
- Benefit/Cost Analysis
- Rate of Return Analysis

1. Present Worth Analysis

a. Present Worth Analysis of Equal-Life Alternatives

- The present worth method is quite popular in industry because all future costs and revenues are transformed to **equivalent monetary units NOW;** that is, all future cash flows are converted (discounted) to present amounts (e.g., dollars) at a specific rate of return, which is the MARR.

For **mutually exclusive (ME)** alternatives, whether they are revenue or cost alternatives, the following guidelines are applied to justify a single project or to select one from several alternatives.

One alternative: If PW ≥ 0, the requested MARR is met or exceeded and the alternative is economically justified.

Two or more alternatives: Select the alternative with the PW that is **numerically largest,** that is, less negative or more positive. This indicates a lower PW of cost for cost alternatives or a larger PW of net cash flows for revenue alternatives.

PW_A	PW_B	Selected Alternative
$\$-2300$	$\$-1500$	B
-500	$+1000$	B
$+2500$	$+2000$	A
$+4800$	-400	A

For **independent** projects, each PW is considered separately, that is, compared with the DN project, which always has PW = 0. The selection guideline is as follows:

One or more independent projects: Select all projects with PW ≥ 0 at the MARR.

The independent projects must have **positive and negative cash flows** to obtain a **PW value that can exceed zero**; that is, they must be revenue projects.

- **Example:**

- During lab research, three equal-service machines need to be evaluated economically. Perform the present worth analysis with the costs shown below. The MARR is 10% per year.

	Electric-Powered	Gas-Powered	Solar-Powered
First cost, $	−4500	- 3500	−6000
Annual operating cost (AOC), $/year	−900	−700	−50
Salvage value *S*, $	200	350	100
Life, years	8	8	8

- These are cost alternatives. The salvage values are considered a “negative” cost, so a +ve sign precedes them. (If it costs money to dispose of an asset, the estimated disposal cost has a -ve sign.)

- The PW of each machine is calculated at i =10% for n = 8 years. Use subscripts E , G , and S .

$$\text{PW}_E = -4500 - 900(P/A,10\%,8) + 200(P/F,10\%,8) = \$-9208$$
$$\text{PW}_G = -3500 - 700(P/A,10\%,8) + 350(P/F,10\%,8) = \$-7071$$
$$\text{PW}_S = -6000 - 50(P/A,10\%,8) + 100(P/F,10\%,8) = \$-6220$$

b. Present Worth Analysis of Different-Life Alternatives

- When the present worth method is used to compare **mutually exclusive alternatives that have different lives**, the **equal-service requirement must** be met.

- The procedure of (a) is followed, **with one exception:**

The PW of the alternatives must be compared over the **same number of years** and must end at the same time to satisfy the equal-service requirement.

- The **equal-service requirement** is satisfied by using **either** of **two approaches:**

1. **LCM:** Compare the PW of alternatives over a period of time equal to the **least common multiple (LCM)** of their estimated lives.
2. **Study period:** Compare the PW of alternatives using a **specified study period of n years.** This approach does not necessarily consider the useful life of an alternative. The study period is also called the *planning horizon.*

For either approach, **calculate the PW at the MARR** and **use the same selection guideline as that for equal-life alternatives.**

The **LCM approach makes the cash flow estimates extend to the same period**, as required. For example, lives of 3 and 4 years are compared over a 12-year period.

The assumptions when using the LCM approach are that

1. The service provided will be needed over the entire LCM years or more.
2. The selected alternative can be repeated over each life cycle of the LCM in exactly the same manner.
3. Cash flow estimates are the same for each life cycle.

A study period analysis is necessary **if the first assumption about the length of time the alternatives are needed cannot be made.**

2\. For the **study period** approach, a time horizon is chosen over which the economic analysis is conducted, and **only those cash flows which occur during that time period are considered relevant to the analysis.**

All cash flows occurring **beyond the study period are ignored.**

An estimated market value at the end of the study period must be made.

The **time horizon chosen might be relatively short**, especially when short-term business goals are very important.

Example:

- Two manufacturers offered the estimates below.

	Vendor A	Vendor B
First cost, $	−15,000	−18,000
Annual M&O cost, $ per year	−3,500	−3,100
Salvage value, $	1,000	2,000
Life, years	6	9

a. Determine which vendor should be selected on the basis of a present worth comparison, if the **MARR is 15% per year**.

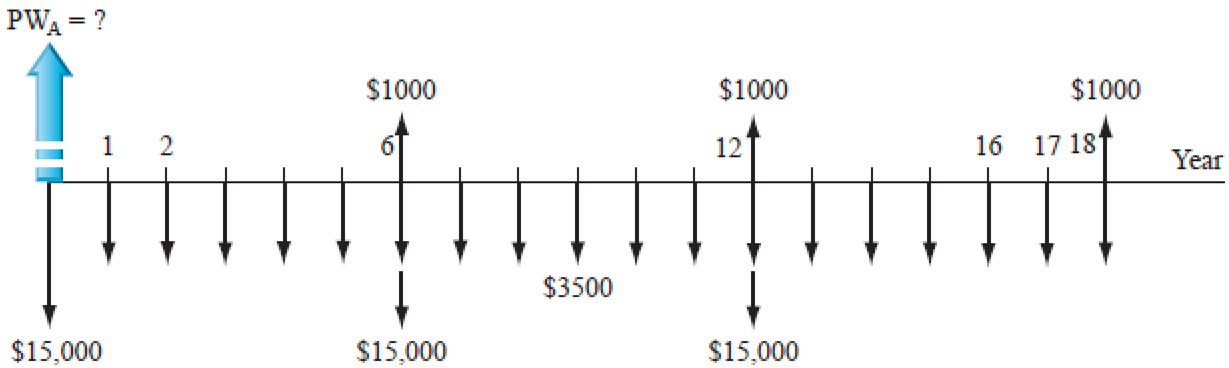
b. The company has a standard practice of evaluating all options **over a 5-year period**. If a study period of **5 years is used and the salvage values are not expected to change**, which vendor should be selected?

a. Since the equipment has different lives, compare them over the LCM of 18 years. For life cycles after the first, the first cost is repeated in year 0 of each new cycle, which is the last year of the previous cycle. These are years 6 and 12 for vendor A and year 9 for B.

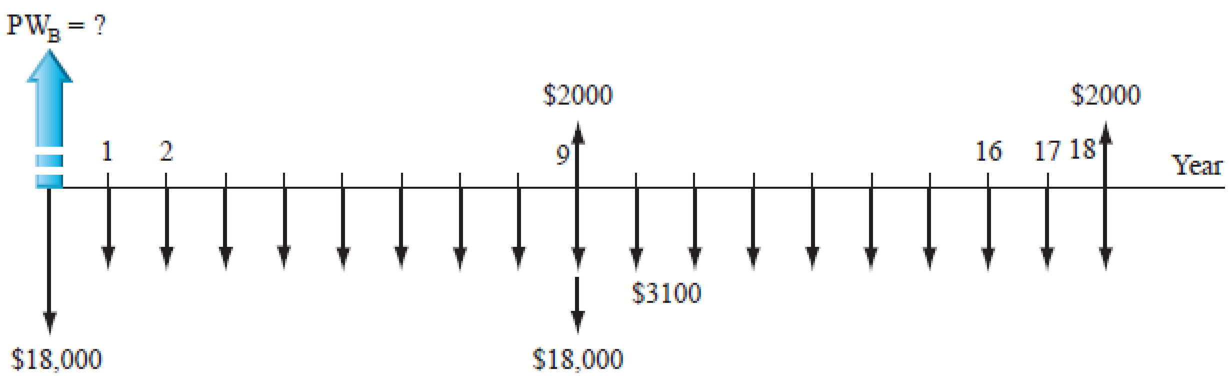
$$\begin{aligned}\mathrm{PW_A} &= -15{,}000 - 15{,}000(P/F,15\%,6) + 1000(P/F,15\%,6)\\ &\quad -15{,}000(P/F,15\%,12) + 1000(P/F,15\%,12) + 1000(P/F,15\%,18)\\ &\quad -3{,}500(P/A,15\%,18)\\ &= \$-45{,}036\end{aligned}$$

$$\begin{aligned}\mathrm{PW_B} &= -18{,}000 - 18{,}000(P/F,15\%,9) + 2000(P/F,15\%,9)\\ &\quad + 2000(P/F,15\%,18) - 3100(P/A,15\%,18)\\ &= \$-41{,}384\end{aligned}$$

- Vendor B is selected, since it costs less in PW terms; that is, the PW B value is numerically larger than PW A .



Vendor A



Vendor B

(*b*) For a 5-year study period, no cycle repeats are necessary. The PW analysis is

$$PW_A = -15{,}000 - 3500(P/A,15\%,5) + 1000(P/F,15\%,5)$$
$$= \$-26{,}236$$

$$PW_B = -18{,}000 - 3100(P/A,15\%,5) + 2000(P/F,15\%,5)$$
$$= \$-27{,}397$$

- study period of 5 years has caused a switch in the economic decision. In situations such as this, the standard practice of using a fixed study period should be carefully examined to ensure that the appropriate approach, that is, LCM or fixed study period, is used to satisfy the equal-service requirement.

- For **independent projects** , use of the LCM approach is **unnecessary** since each project is **compared to the do-nothing alternative**, not to each other, and satisfying the equal-service requirement is not a problem.

- Simply use the MARR to determine the PW over the respective life of each project, and **select all projects with a PW ≥ 0.**

c. Capitalized Cost Analysis

- Many public sector projects such as **bridges, dams, highways and toll roads, railroads, and hydroelectric** and other power generation facilities have very long expected useful lives.
- A **perpetual or infinite life** is the effective planning horizon.
- The **economic worth** of these types of **projects or endowments** is evaluated using the **present worth of the cash flows**.

> Capitalized Cost (CC) is the present worth of a project that has a very long life (more than, say, 35 or 40 years) or when the planning horizon is considered very long or infinite.

- replace the symbols *P* and PW with CC as a reminder that this is a capitalized cost equivalence.

- Since the *A* value can also be termed AW for annual worth, the capitalized cost formula is simply

$$CC = \frac{A}{i} \qquad \text{or} \qquad CC = \frac{AW}{i}$$

- Solving for *A* or AW, the amount of new money that is generated each year by a capitalization of an amount CC is:

$$AW = CC(i)$$

This is the same as the calculation **A = P * (i)** for an infinite number of time periods.

- The cash flows (costs, revenues, and savings) in a capitalized cost calculation are usually of **two types**:

- **recurring**, also called periodic, and **nonrecurring**.

- An annual operating cost of \$50,000 and a rework cost estimated at \$40,000 every 12 years are examples of recurring cash flows.

- Examples of nonrecurring cash flows are the initial investment amount in year 0 and one-time cash flow estimates at future times, for example, \$500,000 in fees 2 years hence.

The procedure to determine the CC for an infinite sequence of cash flows is as follows:

1. Draw a cash flow diagram showing all nonrecurring (one-time) cash flows and at least two cycles of all recurring (periodic) cash flows.
2. Find the present worth of all nonrecurring amounts. This is their CC value.
3. Find the A value through *one life cycle* of all recurring amounts. Add this to all other uniform amounts (A) occurring in years 1 through infinity. The result is the total equivalent uniform annual worth (AW).
4. Divide the AW obtained in step 3 by the interest rate i to obtain a CC value.
5. Add the CC values obtained in steps 2 and 4.

Example:

- A Transportation Authority has just installed new software to charge and track toll fees. The director wants to know the total equivalent cost of all future costs incurred to purchase the software system.

- If the new system will be used for the indefinite future, find the equivalent cost
  a. now, a CC value, and
  b. for each year hereafter, an AW value.

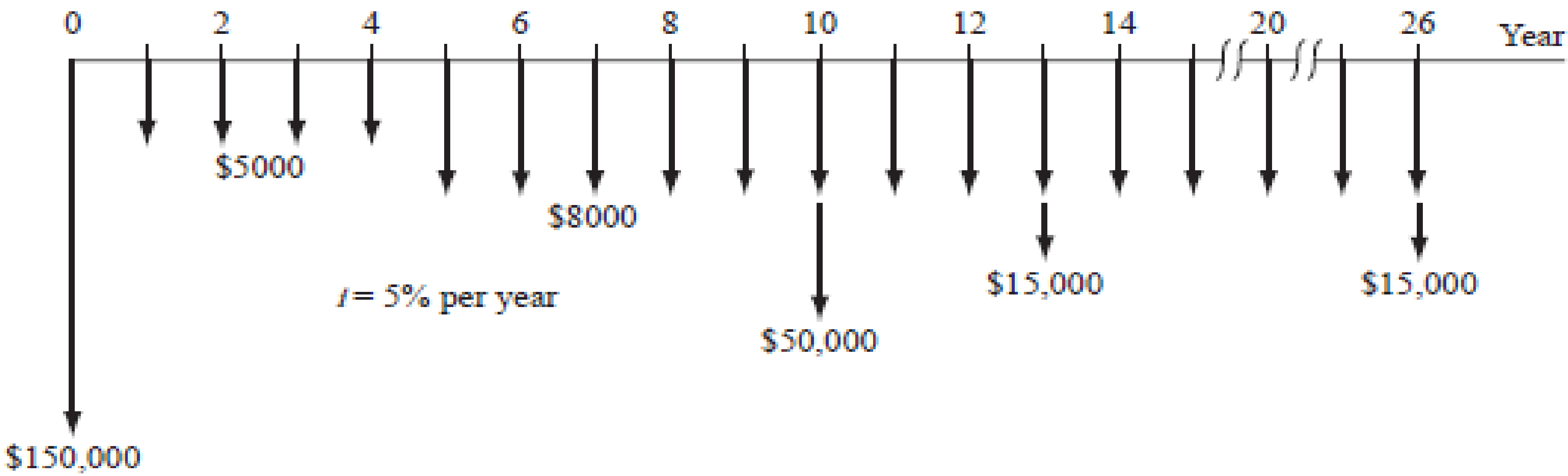
- The system has an **installed cost of $150,000** and an **additional cost of $50,000 after 10 years**.

- The **annual software maintenance** contract cost is **$5000 for the first 4 years and $8000 thereafter**.

- In addition, there is expected to be **a recurring major upgrade cost of $15,000 every 13 years**. Assume that ***i* = 5%** per year for county funds.

a. The five-step procedure to find CC now is applied.

1. Draw a cash flow diagram for two cycles



2. Find the present worth of the nonrecurring costs of $150,000 now and $50,000 in year 10 at i = 5%. Label this CC 1 .

$$CC\ 1 = -150{,}000 - 50{,}000(P/F,5\%,10) = \$\ -180{,}695$$

3 and 4. Convert the $15,000 recurring cost to an *A* value over the first cycle of 13 years, and find the capitalized cost CC 2 at 5% per year

$$A = -15{,}000(A/F{,}5\%{,}13) = \$-847$$
$$CC_2 = -847/0.05 = \$-16{,}940$$

There are several ways to convert the annual software maintenance cost series to A and CC values. A straightforward method is to, first, consider the $−5000 an A series with a capitalized cost of

$$CC_3 = -5000/0.05 = \$-100{,}000$$

Second, convert the step-up maintenance cost series of $−3000 to a capitalized cost CC 4 in year 4, and find the present worth in year 0.

$$CC_4 = \frac{-3{,}000}{0.05}(P/F{,}5\%{,}4) = \$-49{,}362$$

5. The total capitalized cost CC *T* for the Transportation Authority is the sum of the four component CC values.

$$\begin{aligned} CC_T &= -180{,}695 - 16{,}940 - 100{,}000 - 49{,}362 \\ &= \$-346{,}997 \end{aligned}$$

(*b*) To determines the *AW* value forever.

$$AW = Pi = CC_T(i) = \$346{,}997(0.05) = \$17{,}350$$

- Correctly interpreted, this means officials have committed the equivalent of $17,350 forever to operate and maintain the toll management software.

- For the comparison of **two alternatives on the basis of capitalized cost,** use the same procedure to find the *A* value and CC *T* for each alternative.

- Since the capitalized cost represents the total present worth of financing and maintaining a given alternative forever, the alternatives will automatically be compared for the same number of years (i.e., infinity).

- The alternative with the smaller capitalized cost will represent the more economical one.

2. Annual Worth Analysis

- For many engineering economic studies, the **AW method is the best to use**.
- Since the AW value is the equivalent uniform annual worth of all estimated receipts and disbursements during the life cycle of the project or alternative,
- AW is easy to understand by any individual acquainted with annual amounts, for example, dollars per year.

$$AW = PW(A/P,i,n) = FW(A/F,i,n)$$

- The ***n* in the factors is the number of years for equal-service comparison**. This is the **LCM or the stated study period** of the PW or FW analysis.

The annual worth method offers a prime computational and interpretation advantage because the AW value needs to be calculated for **only one life cycle**. The AW value determined over one life cycle is the AW for all future life cycles. Therefore, it is **not necessary** to use the LCM of lives to satisfy the equal-service requirement.

- When **alternatives being compared have different lives**, the **AW** method makes the assumptions that:

1. The services provided are needed for at least the LCM of the lives of the alternatives.
2. The selected alternative will be repeated for succeeding life cycles in exactly the same manner as for the first life cycle.
3. All cash flows will have the same estimated values in every life cycle.

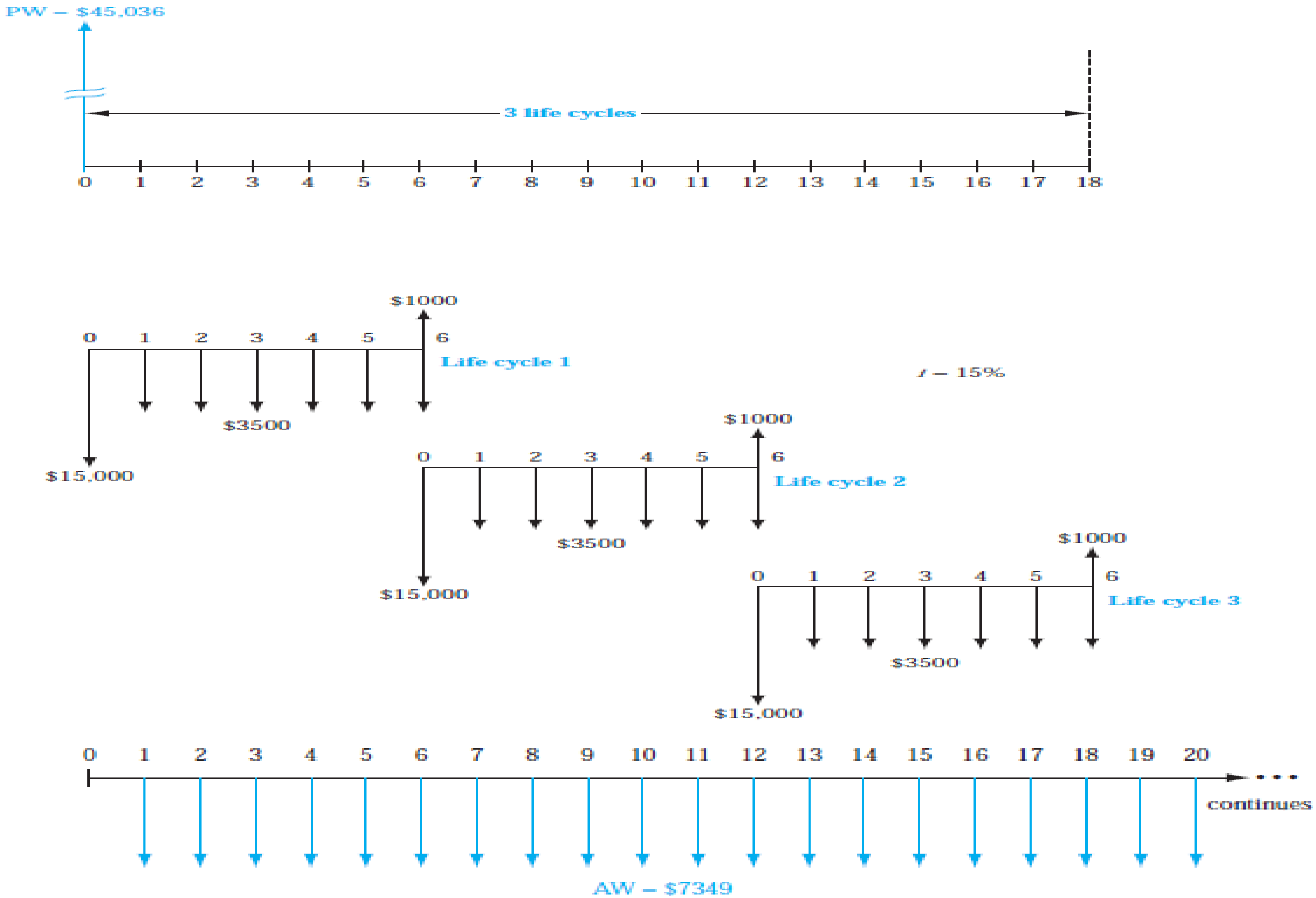
Example:

- **Two manufacturers offered the estimates below.**

	Vendor A	Vendor B
First cost, $	−15,000	−18,000
Annual M&O cost, $ per year	−3,500	−3,100
Salvage value, $	1,000	2,000
Life, years	6	9

- Demonstrate the **equivalence at *i*= 15% of PW over three life cycles and AW over one cycle.**

- present worth for vendor **A** was calculated as **PW = $45,036**.


PW = $45,036
3 life cycles
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
$1000
0 1 2 3 4 5 6
Life cycle 1
$3500
$15,000
i = 15%
Life cycle 2
Life cycle 3
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
continues
AW = $7349

Solution

Calculate the equivalent uniform annual worth value for all cash flows in the first life cycle.

$$AW = -15{,}000(A/P,15\%,6) + 1000(A/F,15\%,6) - 3500 = \$-7349$$

When the same computation is performed on each succeeding life cycle, the AW value is $\$-7349$.

$$AW = -45{,}036(A/P,15\%,18) = \$-7349$$

The one-life-cycle AW value and the AW value based on 18 years are equal.

Evaluating Alternatives by Annual Worth Analysis

- For **MUTUALLY EXCLUSIVE** alternatives, The **AW is calculated over the respective life of each alternative**, and the selection guidelines are the same as those used for the PW method.

- Whether cost- or revenue-based, the guidelines are as follows:

One alternative: If AW ≥ 0, the requested MARR is met or exceeded and the alternative is economically justified.

Two or more alternatives: Select the alternative with the AW that is **numerically largest**, that is, less negative or more positive. This indicates a lower AW of cost for cost alternatives or a larger AW of net cash flows for revenue alternatives.

Example:

- Michele is the general manager of a business unit, and she wishes to choose between two manufacturers of temperature retention units that are mobile and easy to sterilize after each use.
- Use the cost estimates below to select the more economic unit at a MARR of **8%** per year.

	Hamilton (H)	Infinity Care (IC)
Initial cost P, \$	−15,000	−20,000
Annual M&O, \$/year	−6,000	−9,000
Refurbishment cost, \$	0	−2,000 every 4 years
Trade-in value S, % of P	20	40
Life, years	4	12

Solution

The best evaluation technique for these different-life alternatives is the annual worth method, where AW is taken at 8% per year over the respective lives of 4 and 12 years.

$$\begin{aligned}
AW_H &= \text{annual equivalent of } P - \text{annual M\&O} + \text{annual equivalent of } S \\
&= -15{,}000(A/P,8\%,4) - 6000 + 0.2(15{,}000)(A/F,8\%,4) \\
&= -15{,}000(0.30192) - 6000 + 3000(0.22192) \\
&= \$-9{,}863
\end{aligned}$$

$$\begin{aligned}
AW_{IC} &= \text{annual equivalent of } P - \text{annual M\&O} - \text{annual equivalent of refurbishment} \\
&\quad + \text{annual equivalent of } S \\
&= -20{,}000(A/P,8\%,12) - 9000 - 2000[(P/F,8\%,4) + (P/F,8\%,8)](A/P,8\%,12) \\
&\quad + 0.4(20{,}000)(A/F,8\%,12) \\
&= -20{,}000(0.13270) - 9000 - 2000[0.7350 + 0.5403](0.13270) + 8000(0.05270) \\
&= \$-11{,}571
\end{aligned}$$

The Hamilton unit is considerably less costly on an annual equivalent basis.

If the projects are independent, the AW at the MARR is calculated.

All projects with AW ≥ 0 are acceptable.

AW of a Permanent Investment

- Evaluation of public sector projects, such as flood control dams, irrigation canals, bridges, or other large-scale projects, requires the comparison of alternatives that have such long lives that they may be considered **infinite in economic analysis terms.**

- For this type of analysis, the **annual worth of the initial investment is the perpetual annual interest on the initial investment**, that is, $A = Pi = (CC)\,i$.

- Cash flows recurring at regular or irregular intervals are handled exactly as in conventional AW computations; **convert them to equivalent uniform annual amounts *A* for one cycle**.

- This automatically annualizes them for each succeeding life cycle.

Example:

- The U.S. Bureau of Reclamation is considering three proposals for increasing the capacity of the main drainage canal in an agricultural region of Nebraska. i= 5%

	Proposal A	Proposal B	Proposal C
Initial cost $	650,000	4 million	6 million
O & M $ Annual	120,000 + 50,000	5000	3000
Other Fixed costs	-	Every five years= 30,000	-
S $	17,000	-	-
N	10	Permanent	50

- Since this is an investment for a permanent project, compute the AW for one cycle of all recurring costs.

Proposal A	
CR of dredging equipment:	
$-650{,}000(A/P{,}5\%{,}10) + 17{,}000(A/F{,}5\%{,}10)$	\$ −82,824
Annual cost of dredging	−50,000
Annual cost of weed control	−120,000
	\$−252,824
Proposal B	
CR of initial investment: −4,000,000(0.05)	\$−200,000
Annual maintenance cost	−5,000
Lining repair cost: $-30{,}000(A/F{,}5\%{,}5)$	−5,429
	\$−210,429
Proposal C	
CR of pipeline: $-6{,}000{,}000(A/P{,}5\%{,}50)$	\$−328,680
Annual maintenance cost	−3,000
	\$−331,680

Proposal B, which is a permanent solution, is selected due to its lowest AW of costs.

Evaluating Transportation Alternatives

EVALUATION BASED ON MULTIPLE CRITERIA

Many problems associated with economic methods limit their usefulness. Among these are:

- Converting criteria values directly into dollar amounts.
- Choosing the appropriate value of interest rate and service life.
- Distinguishing between the user groups that benefit from a project and those that pay.
- Considering all costs, including external costs.

Discusses evaluation methods that seek to include measurable criteria that are not translated just in monetary terms.

Before construction

1. Rating and Ranking:

Numerical scores are helpful in comparing the relative worth of alternatives in cases where criteria values cannot be transformed into monetary amounts.

$$S_i = \sum_{j=1}^{N} K_j V_{ij}$$

where

S_i = total value of score of alternative i
K_j = weight placed on criteria j
V_{ij} = relative value achieved by criteria j for alternative i

The application of this method is illustrated by the following example.

Example 13.2 Evaluating Light-Rail Transit Alternatives Using the Rating and Ranking Method

A transportation agency is considering the construction of a light-rail transit line from the center of town to a growing suburban region. The transit agency wishes to examine five alternative alignments, each of which has advantages and disadvantages in terms of cost, ridership, and service provided. The alternatives differ in length of the line, location, types of vehicles used, seating arrangements, operating speeds, and numbers of stops. Estimated values achieved by each criterion for each of the five alternatives are shown in Table 13.5. The agency wants to evaluate each alternative using a ranking process. Determine which project should be selected.

Table 13.5 Estimated Values for Measures of Effectiveness

		Alternatives				
Number	*Measure of Effectiveness*	*I*	*II*	*III*	*IV*	*V*
1	Annual return on investment (%)	13.0	14.0	11.0	13.5	15.0
2	Daily ridership (1000s)	25	23	20	18	17
3	Passengers seated in peak hour (%)	25	35	40	50	50
4	Length of line (mi)	8	7	6	5	5
5	Auto drivers diverted (1000s)	3.5	3.0	2.0	1.5	1.5

Solution:

Step 1. Identify the goals and objectives of the project. The transit agency has determined that five major objectives should be achieved by the new transit line.

1. Net revenue generated by fares should be as large as possible with respect to the capital investment.
2. Ridership on the transit line should be maximized.
3. Service on the system should be comfortable and convenient.
4. The transit line should extend as far as possible to promote development and accessibility.
5. The transit line should divert as many auto users as possible during the peak hour in order to reduce highway congestion.

Step 2. Develop the alternatives that will be tested. In this case five alternatives have been identified as feasible candidates. These vary in length from 5 to 8 miles. The alignment, the amount of the system below-, at-, and above-grade; vehicle size; headways; number of trains; and other physical and operational features of the line are determined in this step.

Step 3. Define an appropriate measure of effectiveness for each objective. For the objectives listed in step 1, the following measures of effectiveness are selected.

Objective	*Measure of Effectiveness*
1	Net annual revenue divided by annual capital cost
2	Total daily ridership
3	Percent of riders seated during the peak hour
4	Miles of extension into the corridor
5	Number of auto drivers diverted to transit

Step 4. Determine the relative weight for each objective. This step requires a subjective judgment on the part of the group making the evaluation and will vary among individuals and vested interests. One approach is to allocate the weights on a 100-point scale (just as would be done in developing final grade averages for a course). Another approach is to rank each objective in order of importance and then use a formula of proportionality to obtain relative weights. In this example, the objectives are ranked as shown in Table 13.6. The weighting factor is determined by assigning the value n to the highest ranked alternative, $n - 1$ to the next highest (and so forth), and computing a relative weight as

$$K_j = \frac{W_j}{\sum_{j=1}^{n} W_j} \tag{13.10}$$

where

K_j = weighting factor of objective j
W_j = relative weight for objective j

Table 13.6 Ranking and Weights for Each Objective

Objective	*Ranking*	*Relative Weight* (W_j)	*Weighting Factor** (× 100) Kj
1	1	5	30
2	2	4	24
3	3	3	17
4	3	3	17
5	4	2	12
Total		17	100

*Rounded to whole numbers to equal 100.

Step 5. Determine the value of each measure of effectiveness. In this step, the measures of effectiveness are calculated for each alternative. Cost estimates are developed based on the length of line, number of vehicles and stations, right of way costs, electrification, and so forth. Revenues are computed, and ridership volumes during the peak hour are estimated. In some instances, forecasts are difficult to make, so a best or most likely estimate is produced. Since it is the comparative performance of each alternative that is of interest, relative values of effectiveness measures can be used.

Step 6. Compute a score and ranking for each alternative. The score for each alternative is computed by considering each measure of effectiveness and awarding the maximum score to the alternative with the highest value and a proportionate amount to the other alternatives. Consider the first criterion, return on investment. Table 13.5 shows that Alternative V achieves the highest value and is awarded 30 points. The value for Alternative I is calculated as (13/15)(30) = 26. The results are shown in Table 13.7. (An alternative approach is to award the maximum points to the highest valued alternative and zero points to the lowest.)

The total point score indicates that the ranking of the alternatives in order of preference is I, II, V, IV, and III. Alternatives I and II are clearly superior to the others and are very similar in ranking. These two will bear further investigation prior to making a decision.

Table 13.7 Point Score for Candidate Transit Lines

		Alternatives				
Measure of Effectiveness		*I*	*II*	*III*	*IV*	*V*
1	Vij	26.0	28.0	22.0	27.0	30.0
2		24.0	22.1	19.2	17.3	16.3
3		8.5	11.9	13.6	17.0	17.0
4		17.0	14.9	12.8	10.6	10.6
5		12.0	10.3	6.9	5.1	5.1
Si Total		87.5	87.2	74.5	77.0	79.0

2. Cost Effectiveness:

- Attempts to be comprehensive in its approach while using the best attributes of economic evaluation.
  - The project criteria are considered to be measures of its effectiveness, and
  - The costs are considered as the investment required if that effectiveness value is to be achieved.
  - **Data from economic analysis** is used + **measured environmental** consequences

Example 13.3 Evaluating Metropolitan Transportation Plans using Cost Effectiveness

Five alternative system plans are being considered for a major metropolitan area. They are intended to provide added capacity, improved levels of service, and reductions in travel time during peak hours. Plan A retains the status quo with no major improvements, Plan B is an all-rail system, Plan C is all highways, Plan D is a mix of rail transit and highways, and Plan E is a mix of express buses and highways. An economic evaluation has been completed for the project, with the results shown in Table 13.8.

Plan B, the all-rail system, and Plan D, the combination rail and highway system, have an incremental BCR of less than 1, whereas Plan C, all highways, and Plan E, highways and express buses, have an incremental BCR greater than 1. These results would suggest that the highway–bus alternative (Plan E) is preferable to the highway–rail transit alternatives (Plans B and D).

To examine these options more fully, noneconomic impacts have been determined for each and are displayed as an evaluation matrix in Table 13.9. Among the measures of interest are numbers of persons and businesses displaced, number of fatal and personal-injury accidents, emissions of carbon monoxide and hydrocarbons, and average travel speeds by highway and transit.

Solution: An examination of Table 13.9 yields several observations. In terms of number of transit passengers carried, Plan E ranks highest, followed by Plan B. The relationship between annual cost and transit passengers carried is illustrated in Figure 13.4. This cost-effectiveness analysis indicates that Plan B produces a significant increase in transit passengers over Plan A. Although Plans C, D, and E are much more costly, they do not produce many more transit riders for the added investment.

Community impacts are reflected in the number of homes and businesses displaced and the extent of environmental pollution. Figure 13.5 illustrates the results for number of businesses displaced, and Figure 13.6 depicts the results for emissions of hydrocarbons.

Table 13.9 Measure of Effectiveness Data for Alternative Highway–Transit Plans

	Plan A	*Plan B*	*Plan C*	*Plan D*	*Plan E*
Measure of Effectiveness	*Null*	*All Rail*	*All Highway*	*Rail and Highway*	*Bus and Highway*
Persons displaced	0	660	8000	8000	8000
Businesses displaced	0	15	183	183	183
Annual total fatal accidents	159	158	137	136	134
Annual total personal injuries	6767	6714	5596	5544	5517
Daily emissions of carbon monoxide (tons)	2396	2383	2233	2222	2215
Daily emissions of hydrocarbons (tons)	204	203	190	189	188
Average door-to-door auto trip speed (mi/h)	15.9	16.2	21.0	21.2	21.5
Average door-to-door transit trip speed (mi/h)	6.8	7.6	6.8	7.6	7.8
Annual transit passengers (millions)	154.2	161.7	154.2	161.7	165.2
Total annual cost ($ millions)	2.58	31.16	106.72	129.38	123.44
Interest rate (%)	8.0	8.0	8.0	8.0	8.0

SOURCE: Adapted from *Alternative Multimodal Passenger Transportation Systems,* NCHRP Report 146, Transportation Research Board, National Research Council, Washington, D.C., 1973.

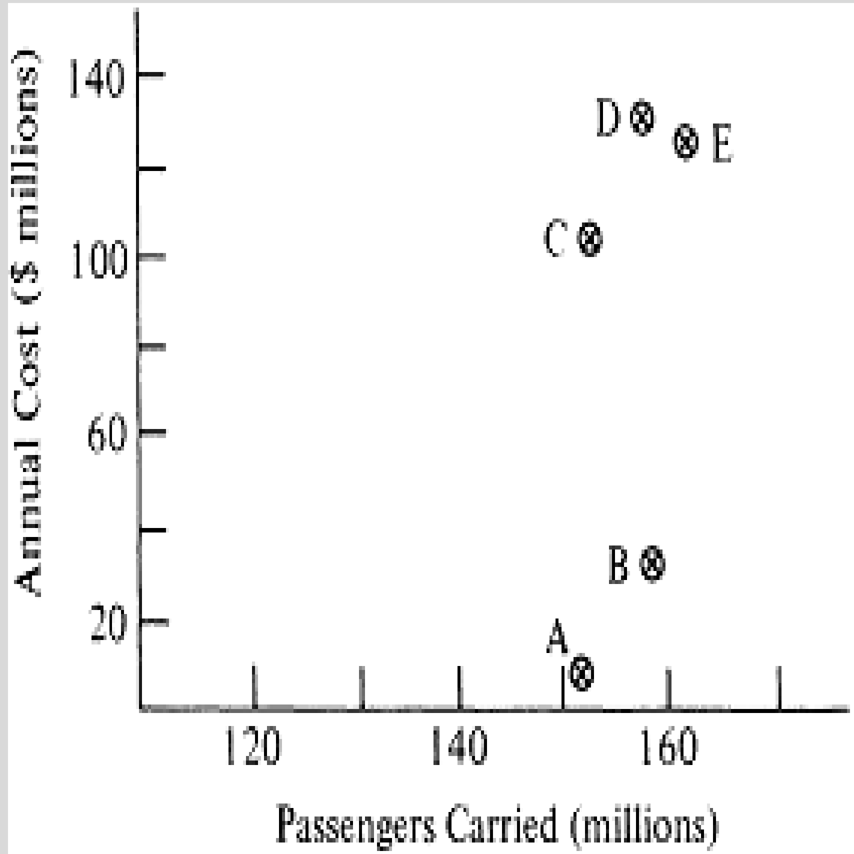


Figure 13.4 Relationship between Annual Cost and Passengers Carried

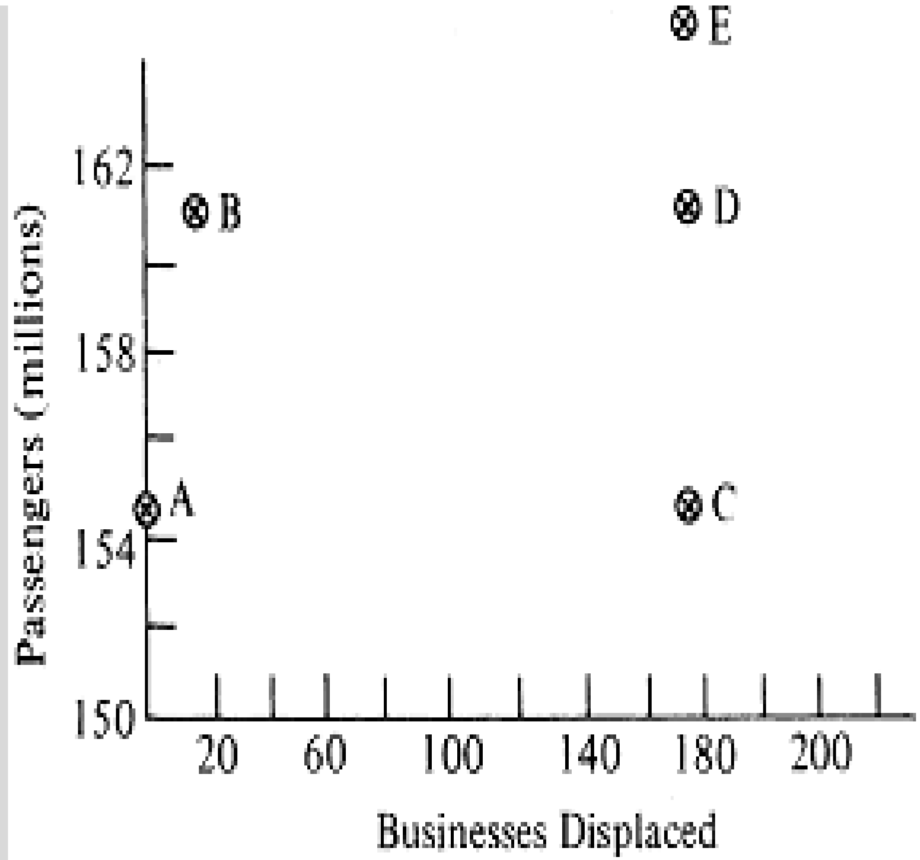


Figure 13.5 Relationship between Passengers Carried and Businesses Displaced

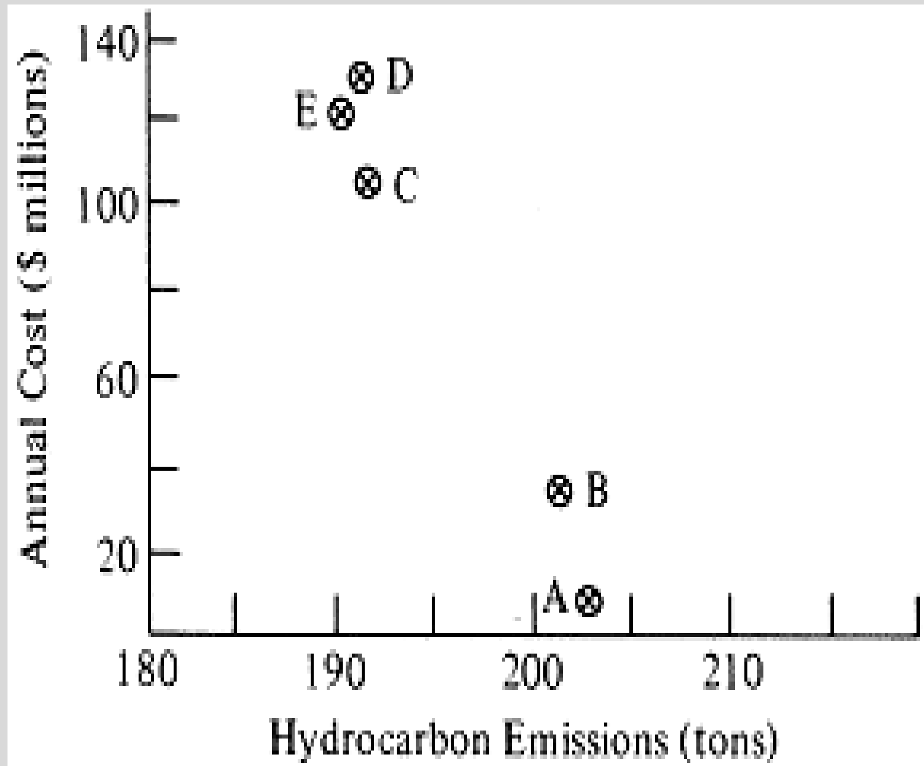


Figure 13.6 Annual Cost versus Hydrocarbon Emissions

In terms of businesses displaced versus transit passengers carried, Plans C and D require considerable disruption with very little increase in transit patronage over Plan B, which is clearly preferred if the impact on the community is to be minimized. On the other hand, Plan C, which is considerably more costly than Plan B, results in a significant reduction in pollution levels, whereas the other two plans, D and E, although more expensive than C, have little further impact on pollution levels.

Finished Projects: After construction

3. Evaluation of Completed Projects

(1) how effective it has been in accomplishing its objectives,

(2) what can be learned that is useful for other project decisions,

(3) what changes should be made to improve the current situation, or

(4) if the project should be continued or abandoned.

Example 13.4 Evaluating the Effect of Bus Shelters on Transit Ridership

A transit authority wishes to evaluate the effectiveness of new bus shelters on transit ridership as well as acceptance by the community. A series of new shelters was built along one bus route but not on the other lines. Do the shelters affect ridership?

Solution: Bus ridership has been measured before and after the shelters had been installed on the test line and on a control line where nothing new had been added. Both lines serve similar neighborhoods. The ridership results are shown in Table 13.10. The line with new shelters increased ridership by 13.3%, whereas the line without shelters increased by only 2.5%. It should be stressed that only in the absence of any other factors can we conclude that the effect of the new shelters was to increase ridership by $(13.3 - 2.5) = 10.8\%$.

Table 13.10 Transit Ridership

	Before	*After*	*Change (%)*
Line A: new shelters	1500	1700	13.3
Line B: no shelters	1950	2000	2.5

Example 13.5 Comparing the Effectiveness of Bus and Rail Transit

Compare the effectiveness of rail and bus based on the experience with a rail transit line serving downtown Philadelphia and a suburb of New Jersey with an express bus line connecting downtown Washington, D.C., with the Virginia suburbs. The rail line, known as the Lindenwold Line, serves 12 stations with 24-hour service per day, whereas the busway, known as the Shirley Highway, extends for 11 miles, with no stations along the way and with bus service provided on exclusive lanes only during the peak hour. Both systems serve relatively low-density, auto-oriented residential areas with heavy travel during the peak hours.

Solution: To determine the relative effectiveness, a comparative analysis of each project was made after they had been in operation for several years. Measures of effectiveness were considered from the viewpoint of the passenger, the operator, and the community. Data were collected for each system and for each measure of effectiveness. A detailed evaluation for each parameter was prepared that both described how each system performed and discussed its advantages and disadvantages. To illustrate, consider the evaluation of one service parameter—*reliability*—expressed as schedule adherence. The variance from scheduled travel times may result from traffic delays, vehicle breakdowns, or adverse weather conditions. It depends mostly on the control that the operator has over the entire system. By far, the most significant factor for reliability is availability of exclusive rights of way.

- *Lindenwold:* That year 99.15% of all trains ran less than 5 minutes late, and the following year the figure was 97%.
- *Shirley:* Surveys conducted over a 4-day period indicated that 22% arrived before schedule time, 32% were more than 6 minutes late, and only 46% arrived at the scheduled time within a 5-minute period.
- *Comparison:* The Lindenwold Line (rail) is superior to the Shirley Highway (bus) with respect to reliability.

A summary of the comparative evaluations of the two systems is shown in Table 13.11.

A detailed analysis of the results would indicate that each system has advantages and disadvantages. The principal reasons why the rail system appears more attractive than the bus is because it provides all-day service, is simpler to understand and use, and produces a higher quality of service.

Table 13.11 Comparative Evaluation of Completed Rail and Bus Transit

Measure of Effectiveness	*Lindenwold (Rail)*	*Shirley (Bus)*	*Higher Rated System*
Investment cost	Very poor	Fair	Bus
Operating cost	Good	Fair	Rail
Capacity	Good	Poor	Rail
Passenger attraction	Very good	Good	Rail
System impact	Very good	Good	Rail

SOURCE: Adapted from V. R. Vuchic and R. M. Stanger, "Lindenwold Rail Line and Shirley Busway: A Comparison," *Highway Research Record* 459, Transportation Research Board, National Research Council, Washington, D.C.

4. Evaluating Effects of Transportation on Social and Natural Systems

Step 1: Assess the Need for the Project. Addresses the question: Why do it at all?

That is, how does the proposed project advance the stated goals and objectives and does the project represent the best use of funds when compared with other options?

Step 2: Conduct a Feasibility Analysis of the Alternatives. Addresses the question:

- Why do it this way? That is, has the project been demonstrated to be a feasible one
- from an engineering perspective? What are the costs involved in the project?
- Are there other methods or approaches that could achieve a similar result at a lower cost in time and money?
- Should the project be included as a budget item for implementation or deferred to a later date?

Step 3: Analyze the Impact of the Project. Addresses the question:

If the project is feasible, what will be its impact on affected groups? These include the users of the transportation improvement, the community, and other stakeholders who will be impacted by the construction of the project. These effects are categorized into three major effects.

a. Transportation system effects
b. Social and economic effects
c. Natural systems effects

Step 3 (a): **Transportation System Effects.**

These are effects experienced by the travelers who use the transportation facility, such as motorists, transit riders, and commercial vehicles. They comprise the following elements.

- Changes in travel time
- Changes in safety
- Changes in vehicle operating costs

Step 3 (b): **Social and Economic Effects.**

These are analyzed to determine the impact that a transportation project could have on the community and its residents. These studies are also conducted to meet federal and state requirements regarding environmental impact, civil rights, and environmental justice. They comprise the following elements.

– Accessibility
– Community cohesion
– Economic development
– Traffic noise
– Visual quality
– Property values

Step 3 (c): **Natural Systems Effects.**

These refer to those impacts of transportation projects that are related to the environment within which the project will be located.

- Among the natural elements that may be affected are
  - Air and water quality
  - Endangered species
  - Wildlife
  - Greenhouse gas emissions
  - Archeological sites
  - Energy conservation
  - Areas of cultural or historic significance

Design of Railway and Guideway Systems

Service Characteristics of Rail Transportation

1. Service safety
2. Travel speed
3. Performance reliability
4. Comfort and convenience
5. Travel cost

Passenger trains

A passenger train is one which includes passenger-carrying vehicles which can often be very long and fast. It may be a self-powered multiple unit or railcar, or else a combination of one or more locomotives and one or more unpowered trailers known as coaches, cars or carriages.

1. High-speed rail: speeds above 200 km/h

2. Maglev: over 500 km/h

3. Inter-city trains: connecting cities in the fastest time possible, bypassing all intermediate stations

    a) Regional trains: calling at all intermediate stations between cities, serving all line-side communities

    b) Higher-speed rail: can operate at top speeds that are higher than conventional inter-city trains but the speeds are not as high as those in the high-speed rail services.

4. Short-distance trains
   a) Commuter trains: serving the city and its suburbs.

5. Long-distance trains: travel between many cities and/or regions of a country, and sometimes cross several countries.

6. Within cities
   a) Rapid transit: Large cities often have a metro system, also called underground, subway or tube. Their railroads are separate from other traffic, usually without level crossings. Usually they run in tunnels in the city center and sometimes on elevated structures in the outer parts of the city. They can accelerate and decelerate faster than heavier, long-distance trains.

   b) Tram: A tram (also known as tramcar; and in North America known as streetcar, trolley or trolley car), is a rail vehicle which runs on tracks along public urban streets (called street running), and also sometimes on separate rights of way.

   c) Light rail: (LRT) is typically an urban form of public transport often using rolling stock similar to a tramway, but operating primarily along exclusive rights-of-way and having vehicles capable of operating as a single tramcar or as multiple units coupled together to form a train

   d) Monorail: to meet medium-demand traffic in urban transit, is a railway in which the track consists of a single rail, typically elevated.

Alta Velocidad Española (*AVE*):
up to 310 km/h

The Shanghai Maglev Train:
a top speed of 430km/h

Source: Wikipedia

An InterCity 125 passes Ealing Broadway on its way to Swansea. This is the world's fastest diesel train and is used on various intercity services in Great Britain.

Source: Wikipedia

The New York City Subway is the world's largest rapid transit system by track length and by number of stations, at 468.

Trams in Vienna, one of the largest existing networks in the world

Source: Wikipedia

The METRO Blue Line light rail in Minneapolis, Minnesota, United States

The high capacity Tokyo Monorail.

Source: Wikipedia

Route Selection

- Decisions made during the location selection process not only determine the cost and operational efficiency of the facility but also influence the disbenefits to or negative impact on nearby communities and the environment.

- By means of aerial or ground surveys, topographic maps are prepared that serve as a basis for the selection of a preliminary and final location.

Examples of criteria to be used in facility location decisions

Criteria	Influencing Factors
Construction costs	Functional classification/ design type; topography and soil conditions; current land use
User costs	Traffic volume; facility design features (e.g., gradients, intersections); operating conditions (e.g., speeds, traffic control systems)
Environmental impact	Proximity to sensitive areas; design features to mitigate impacts
Social impacts	Isolation or division of neighborhoods; aesthetics of design; fostering of desired development patterns
Acceptance by various interest groups	Government agencies; private associations and firms; neighborhood groups and the general public

Geometric Design Elements

1. Alignment (Horizontal/Plan & Vertical/Profile)

2. Cross section

3. Other (Sight distance: SSD, PSD, DSD)

Horizontal Alignment of Highway and Railway

- Consists of a series of tangents connected by circular curves

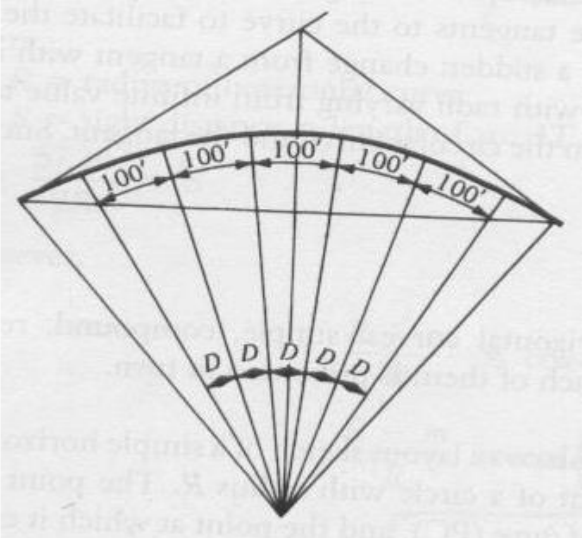
- The alignment must be continuous, without sudden changes which may be dangerous to drivers

- In the design of curves, it is necessary to consider:
    1. Design speed
    2. Degree of curvature (or radius)
    3. Superelevation

Circular Curves

- Circular curves are described by giving either the radius (metric system) or degree of curvature.

- In highway design, degree of curve is defined as the central angle subtended by a 100 ft arc (arc definition)



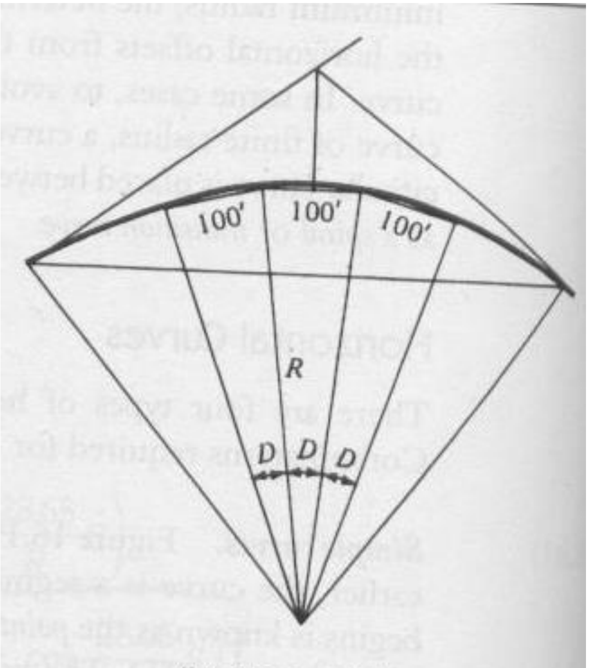
(a) Arc definition

$$\boxed{\frac{2\pi R}{360} = \frac{100}{D}}$$

$$\mathrm{D} = \frac{5729.58}{R}, \text{ ft}$$

$$\mathrm{D} = \frac{1718.87}{R}, \text{ m}$$

- Historical railroad practice defined the degree of curve as the central angle subtended by a 100 ft chord (chord definition)



(b) Chord definition

$$\boxed{\sin\frac{1}{2}D = \frac{50}{R}}$$

Layout of a Simple Horizontal Curve

R = Radius of Circular Curve

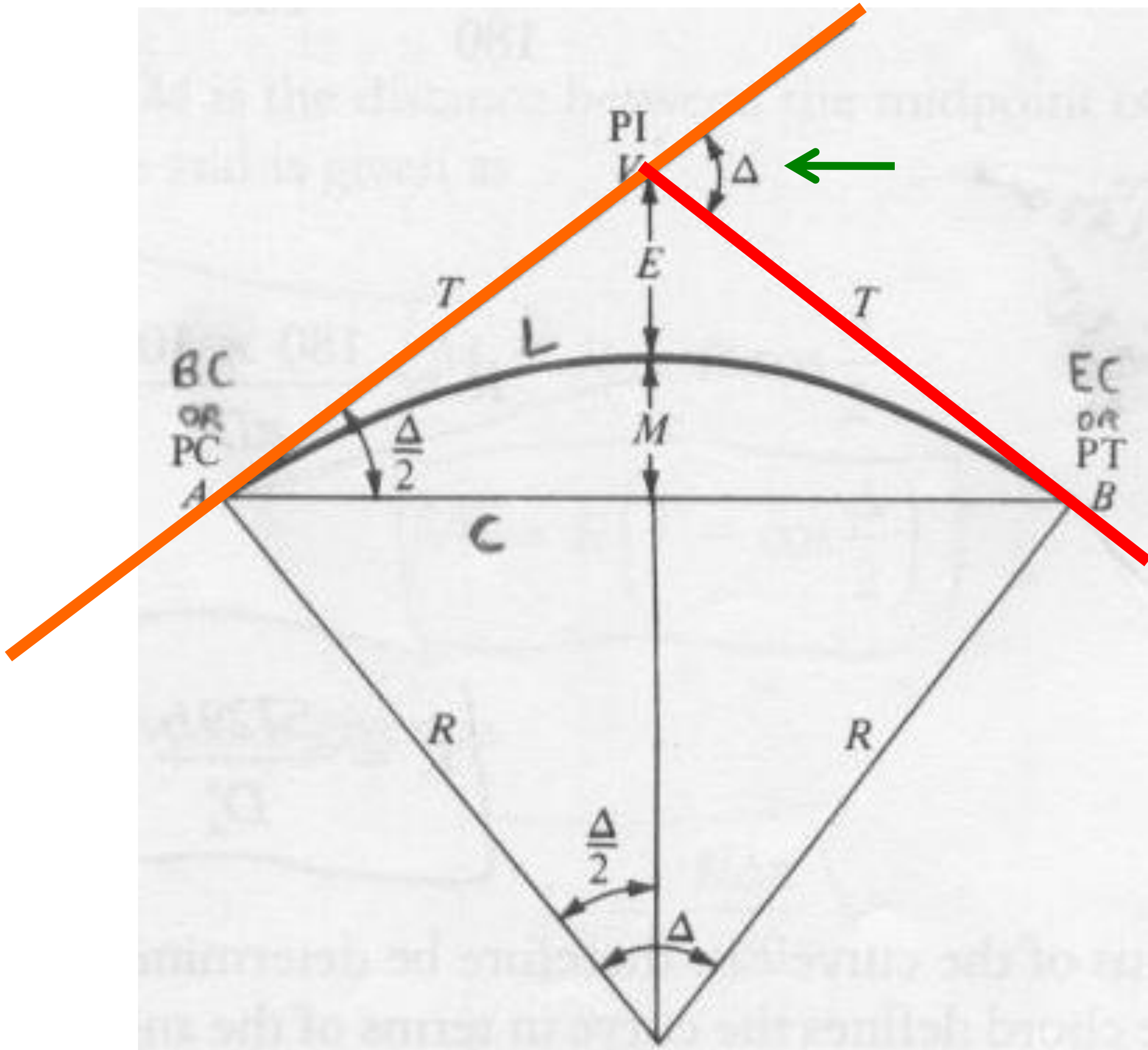
BC = Beginning of Curve
(or PC = Point of Curvature)

EC = End of Curve
(or PT = Point of Tangency)

PI = Point of Intersection
T = Tangent Length
(T = PI – BC = EC - PI)

L = Length of Curvature
(L = EC – BC)

M = Middle Ordinate
E = External Distance
C = Chord Length
Δ = Deflection Angle



Properties of Circular Curves

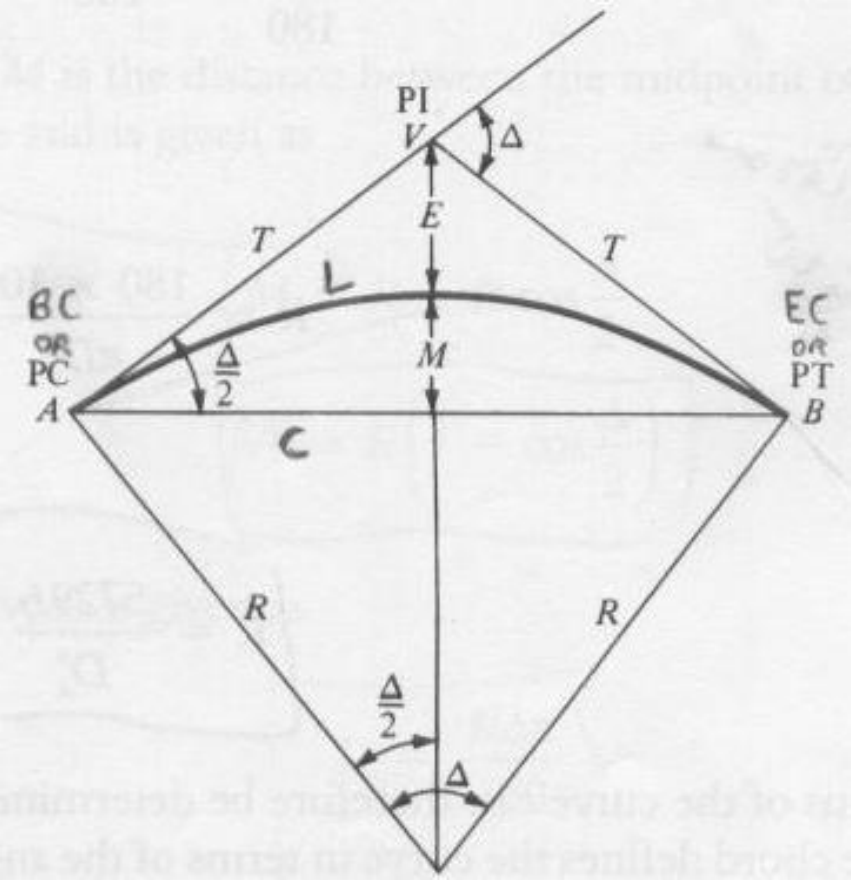
Other Formulas…

Tangent: $T = R\tan(\Delta/2)$

Chord: $C = 2R\sin(\Delta/2)$

Mid Ordinate: $M = R - R\cos(\Delta/2)$

External Distance: $E = R\sec(\Delta/2) - R$



- The expression for the external distance **E**, which is the distance from the point of intersection to the curve on a radial line is

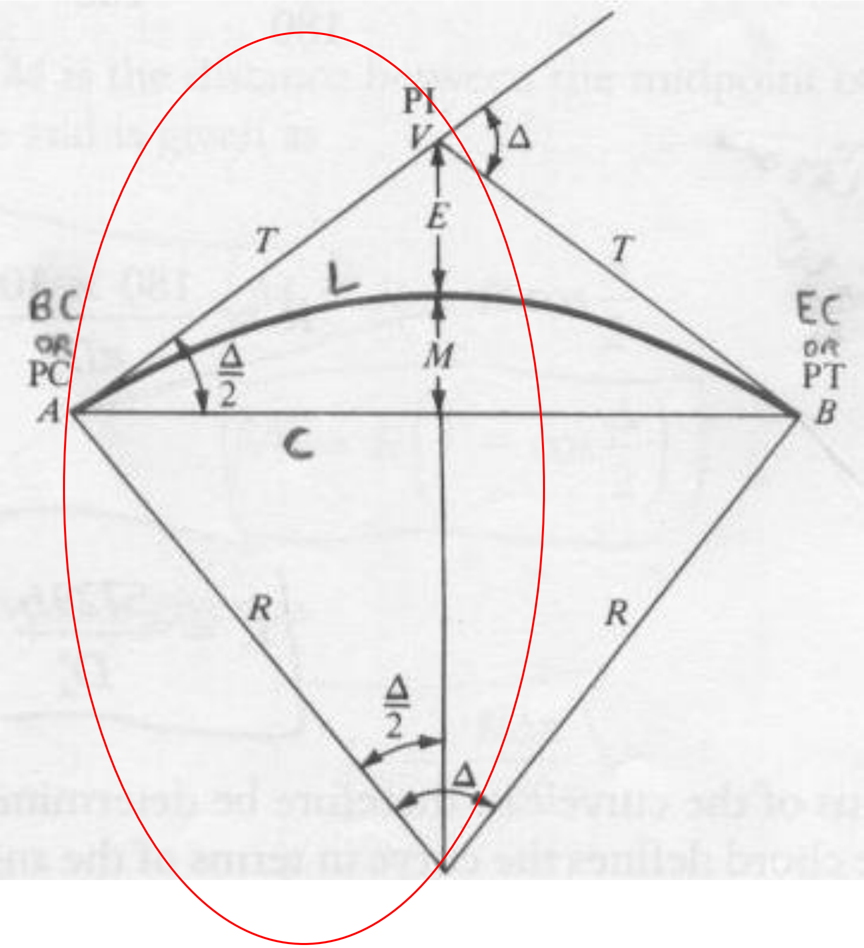
$$\cos\frac{\Delta}{2} = \frac{R}{E+R}$$

$$\cos\frac{\Delta}{2}(E+R) = R$$

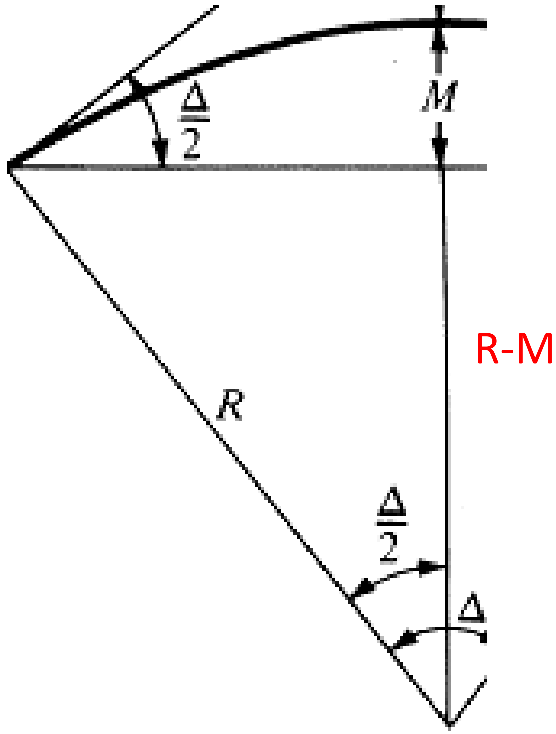
$$E+R = \frac{R}{\cos\frac{\Delta}{2}}$$

$$E+R = R\sec\frac{\Delta}{2}$$

$$E = R\sec\frac{\Delta}{2} - R$$



- The expression for the middle ordinate **M**, which is the distance between the mid-point of the long chord and the midpoint of the curve is:



$$Cos\frac{\Delta}{2} = \frac{R - M}{R}$$

$$R - M = RCos\frac{\Delta}{2}$$

$$M = R - RCos\frac{\Delta}{2}$$

- The expression for the length of the curve **L** is:

Δ/360 = L/2.Pi.R

$$L = \frac{R\Delta\pi}{180}$$

Example

Given:

Simple Curve, $\Delta = 27^{\circ}\ 34'\ 40''$, $D = 2^{\circ}\ 30'$

Full Station= 100ft

St. Of PI= 25+00

Required: R, T, E, Lc, M, L, St. Of P.C, St. of P.T

$$Da = \frac{5729.5}{R}$$

$$R = \frac{5729.5}{2.5} = 2291.83\ ft$$

$$T = R\tan\frac{\Delta}{2} = 2291.83\tan\frac{27^{o}34'40''}{2} = 562.46\ ft$$

$$E = R\sec\frac{\Delta}{2} - R = 2291.83\sec\frac{27^{o}34'40''}{2} - 2291.83 = 68.01\ ft$$

$$M = R - R\cos\frac{\Delta}{2} = 2291.83 - 2291.83\cos\frac{27^{o}34'40''}{2} = 66.05\ ft$$

$$Lc = 2R\sin\frac{\Delta}{2} = 2 * 2291.83\sin\frac{27°34'40''}{2} = 1092.50\ ft$$

$$L = \frac{R\pi\Delta}{180} = \frac{2291.83 * \pi(27°34'40'')}{180} = 1103.11\ ft$$

- St. PC=St. PI-T
- =25+00-(5+62.46)
- =(2500-562.46)
- =1937.54
- =19+37.54

- St. PT=St. PC+L
- =(19+37.54+1103.11)
- =1937.54+1103.11
- =3040.65
- =3+40.65

Horizontal Alignment Design Criteria for Railways and Guideways

Because rail and guideways can not shift laterally, main line tracks and guideways cannot be designed with sudden changes in horizontal alignment.

Horizontal curvature limits the speed of rail vehicles and increase the risk of derailments and overturning accidents.

Generally speaking,

For main railroad lines (curvature Dc):

Flat curves→ 1°- 3°

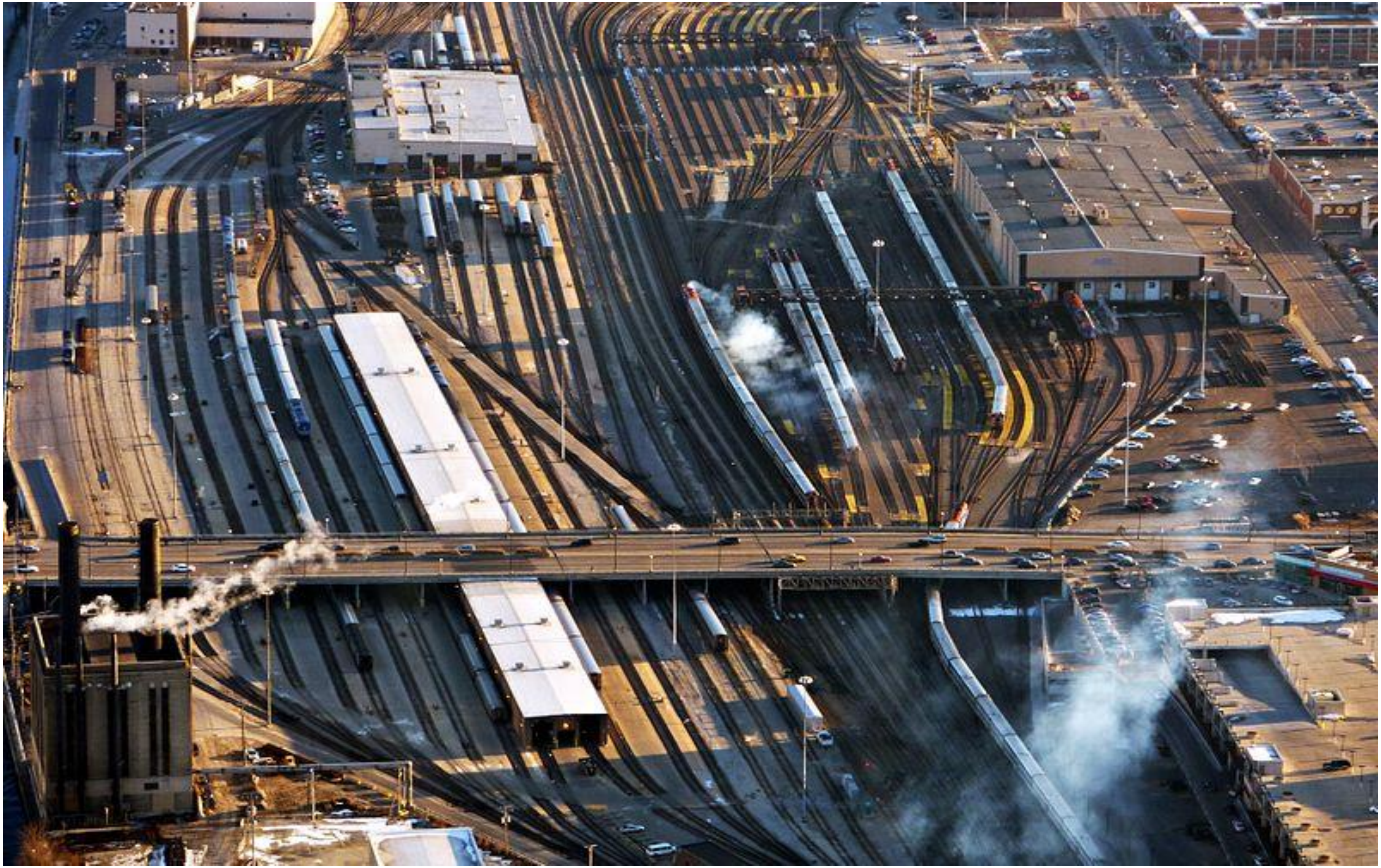
Sharp curves→ 8°- 10°

> 10° seldom used

16° or even 24° curves have been utilized in mountainous areas, or on low-speed approaches to terminals in urban areas

40° curves have been used in railroad yards



Minimum recommended curve radii for urban passenger systems

System/ Criteria Source	Main Lines, m (ft)	Yards and Secondary Tracks, m (ft)
Metropolitan Atlanta Rapid Transit Authority (MARTA)	229 (750)	107 (350)
Montreal Bureau de Transport Metropolitan	140 (459)	52 (170)
Italian Transport Organization (UNIFER)	150 (492)	75 (246)

Superelevation of railway and transit guideway curves

- Difference in height between the inner and outer rail on a curve
- Provided by gradually lifting the outer rail above the level of the inner rail

Track level in place indicating 5" of superelevation on the outside rail of a curve.

- When a train rounds a curve, it has a tendency to want to travel in a straight direction and the track must resist this movement, and force the train to turn.

- The opposing movement of the train and the track result in a number of different forces being at play:

  – Weight
  – Resisting forces excreted by the rails
  – Centrifugal force

$$F = \frac{mv^2}{R} = \frac{Wv^2}{gR}$$

m= mass of car, kg (lb)

v= velocity, m/sec (ft/sec)

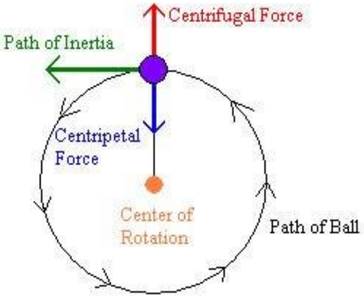
R= radius of curve, m (ft)

g= acceleration of gravity, 9.08 m/sec^2 (32.2 ft/sec^2)

Radial Force and Design Speed

Radial forces act on a vehicle as it travels around a curve and this is why transition curves are necessary

A vehicle of mass **m**, travelling at a constant speed **v**, along a curve of radius **r**, is subjected to a radial force **P** (centripetal) such that:



$$P = \frac{mv^2}{r}$$

This force acting on the vehicle is trying to push the vehicle back on a straight course. On a straight road where r = infinity , P = 0.

Roads are designed according to a 'design speed' which is constant for a given stretch of roadway.

Thus a vehicle must be able to comfortable and safely travel the length of a given stretch of road at the design speed regardless of bends etc.

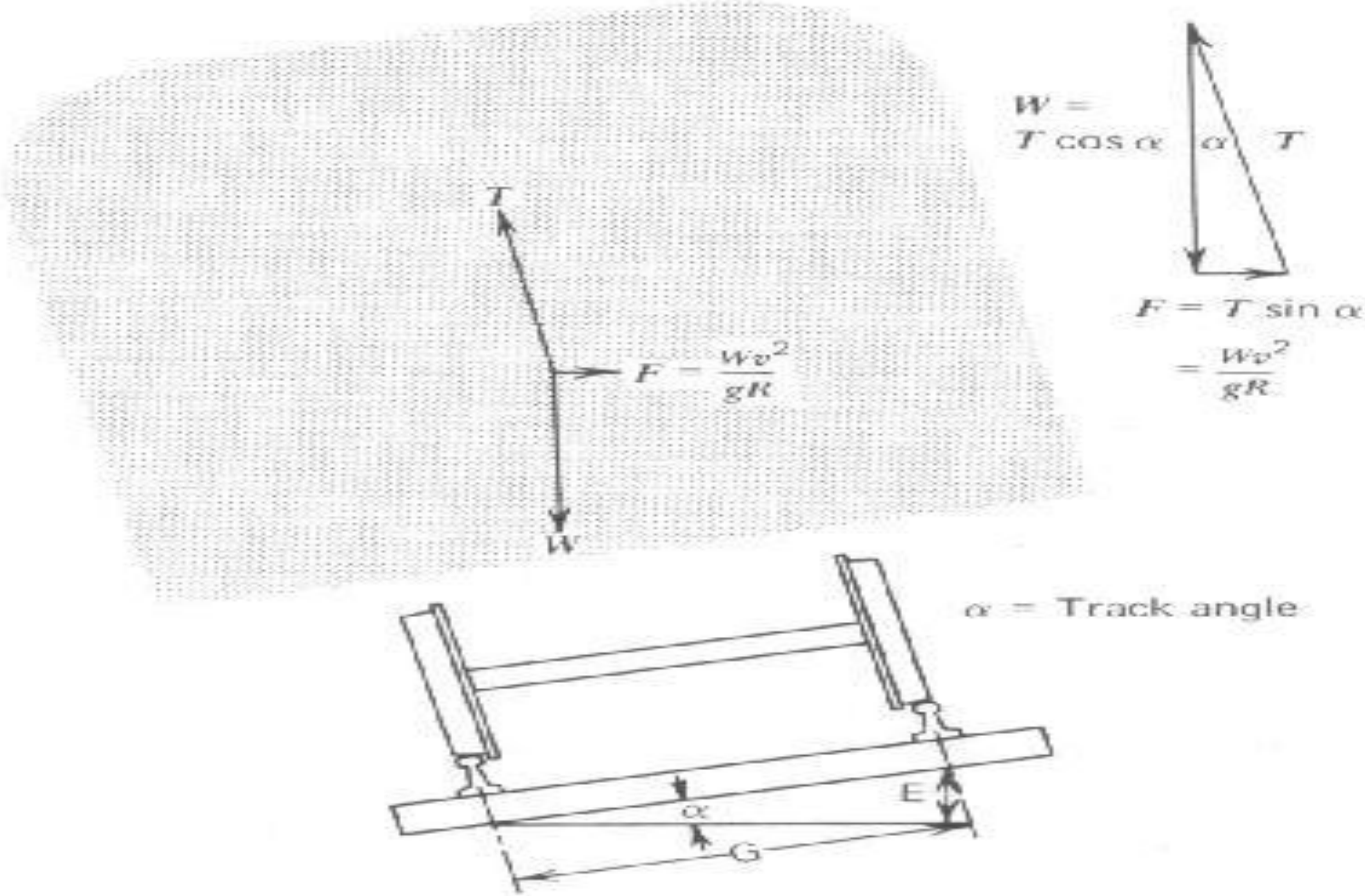
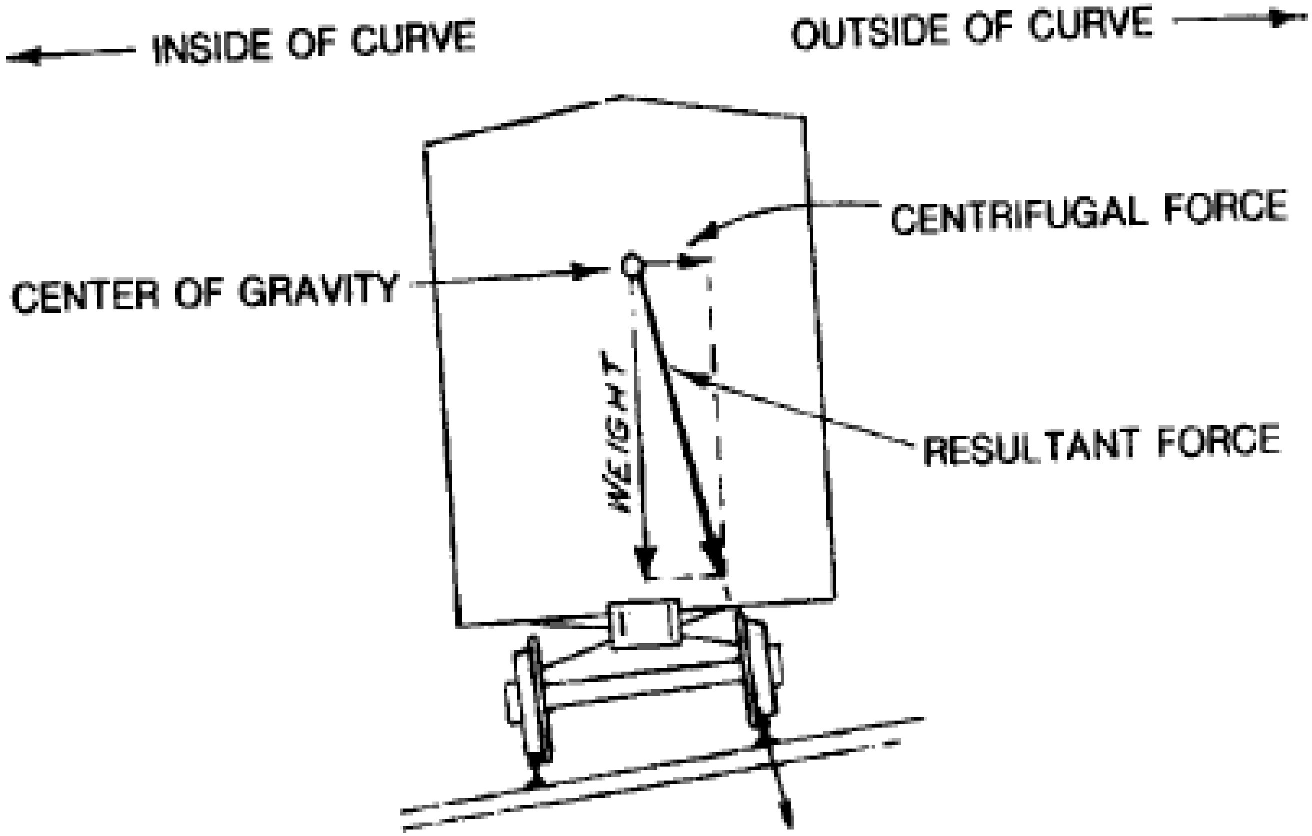


Figure 12-7 Forces on a car body traversing a curve at equilibrium speed. (Source: *Proceedings*, American Railway Engineering Association, Vol. 56, 1955.)



. Effect of Centrifugal Force

- A state of equilibrium is said to exist when both wheels bear equally on the rails.

- Under these conditions, **E**, the equilibrium elevation, is just sufficient to cause the resultant force, T, to be perpendicular to the plane of the top of the rails. By similar triangles, it can be shown that:

$$\frac{E}{G} = \frac{F}{T}$$

For small angles where sines and tangents are approximately equal, the following relationship is essentially correct:

$$\frac{E}{G} = \frac{F}{T} = \frac{v^2}{gR}$$

Where, G: is the distance between center to center of rails

- Using G= 1511 mm (59.5 ft):

$$E = \frac{1511\ v^2\left({}^{1000}\!/_{3600}\right)^2}{9.8\ R} = {}^{11.9v^2}\!/_R$$

$$E = \frac{59.5\ v^2\left({}^{5280}\!/_{3600}\right)^2}{32.2\ R} = {}^{3.97v^2}\!/_R$$

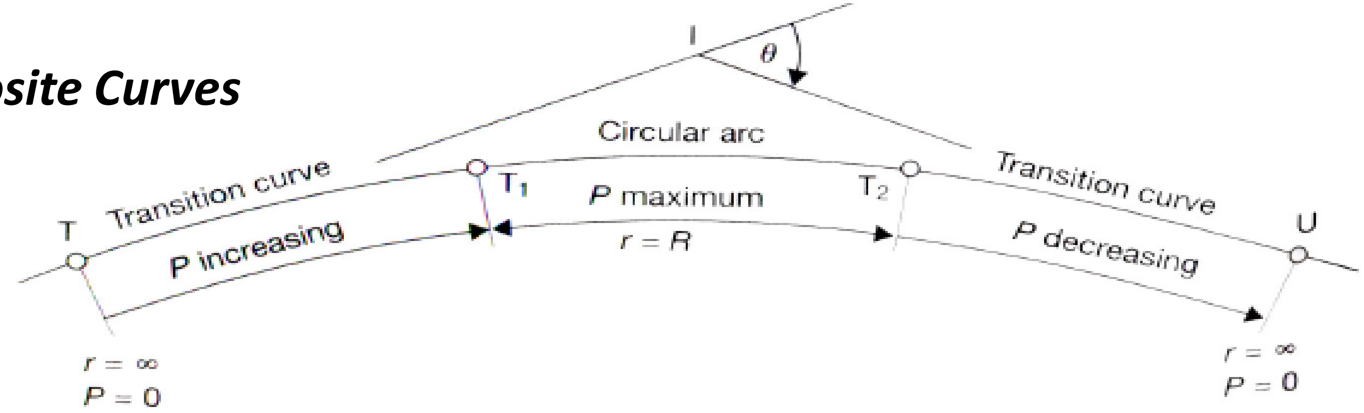
- V= speed, km/h (mph)
- R= radius of curve, m (ft)

- A rail car will ride comfortably and safely around a curve at a speed that requires an elevation about 3 in. higher than that for equilibrium

The use of Transition Curves

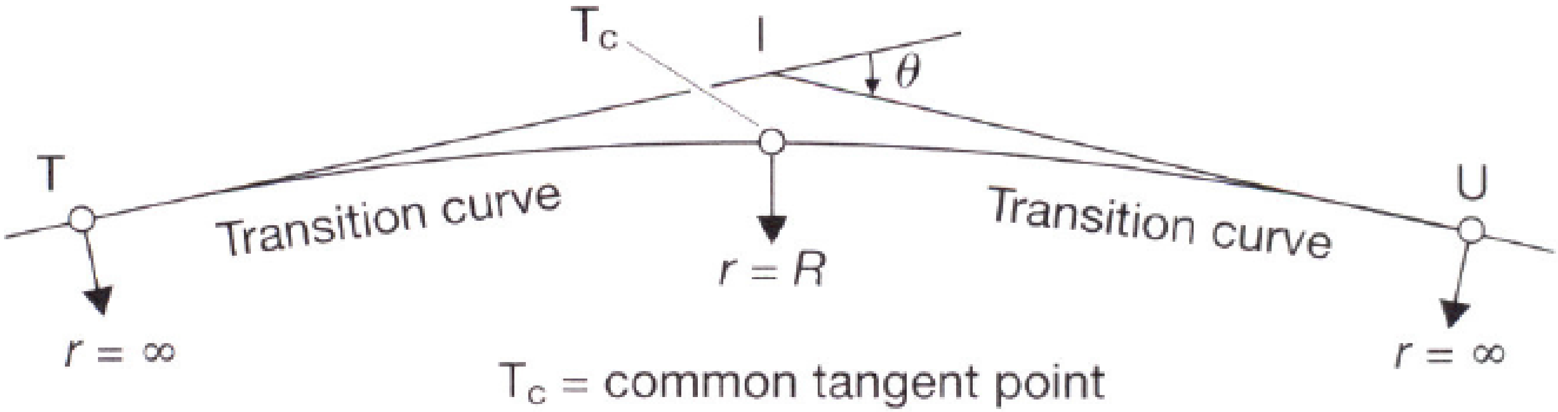
Transition curves can be used to join two straights in one of two ways:
- Composite curves
- Wholly transitional curves

Composite Curves



Here transition curves of equal length are used on either side of a central circular arc of radius R.

Wholly Transitional Curves



A wholly transitional curve consists of two transitional curves of equal length with no central arc. The radius of this curve is constantly changing and therefore the force is constantly changing.

There is only one point Tc (the common tangent point) at which P is a maximum.

This means wholly transitional curves are safer than composite curves.
However, they cannot always be fitted between two straight due to minimum radius requirements.

Spirals or Transition Curves for Railways and Transit Guideways

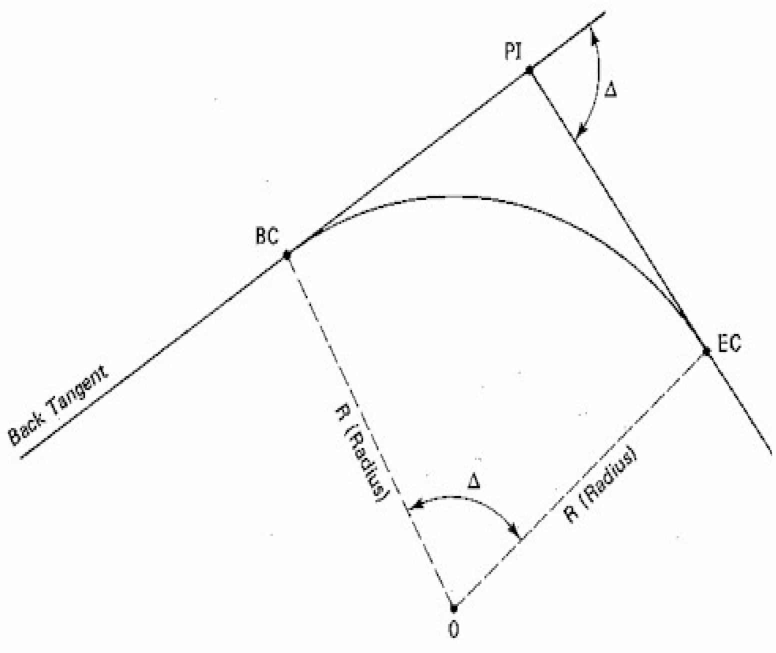
Railroad cars or guideways are restrained by their tracks or guideways and cannot shift laterally.

For this reason, spiral transition curves are used extensively in mainline railroad design.

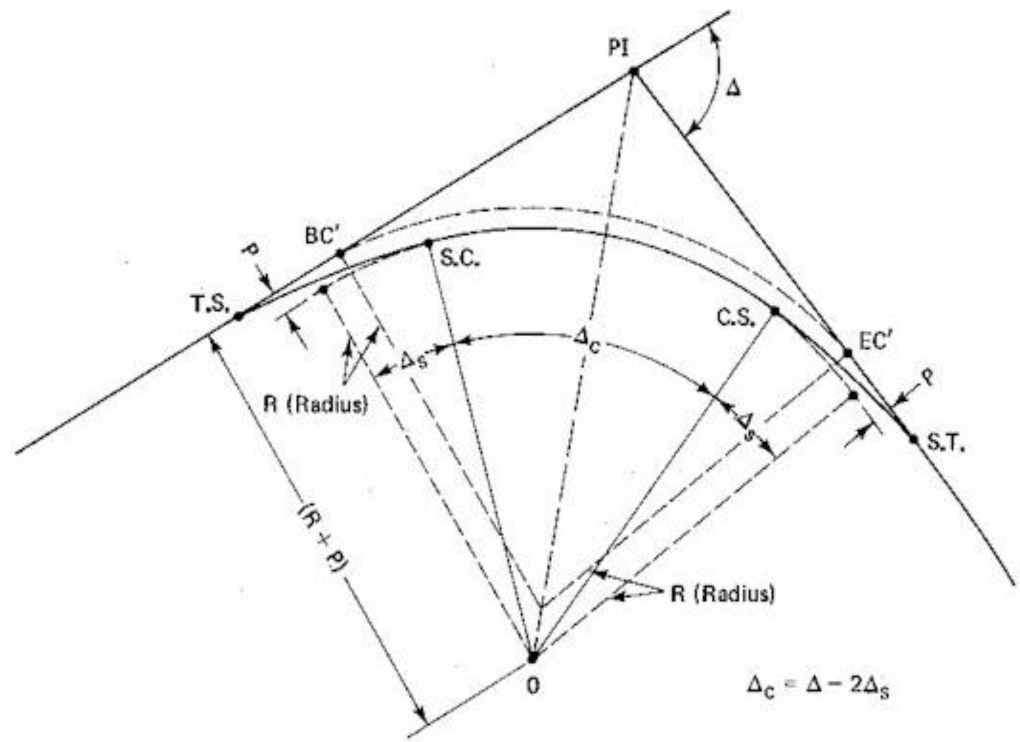
American Railway Engineering Association (AREA) recommends using spiral curves on all mainline tracks between tangent and curve and between different degrees of curvature where compound curves are used.

Spiral Curve

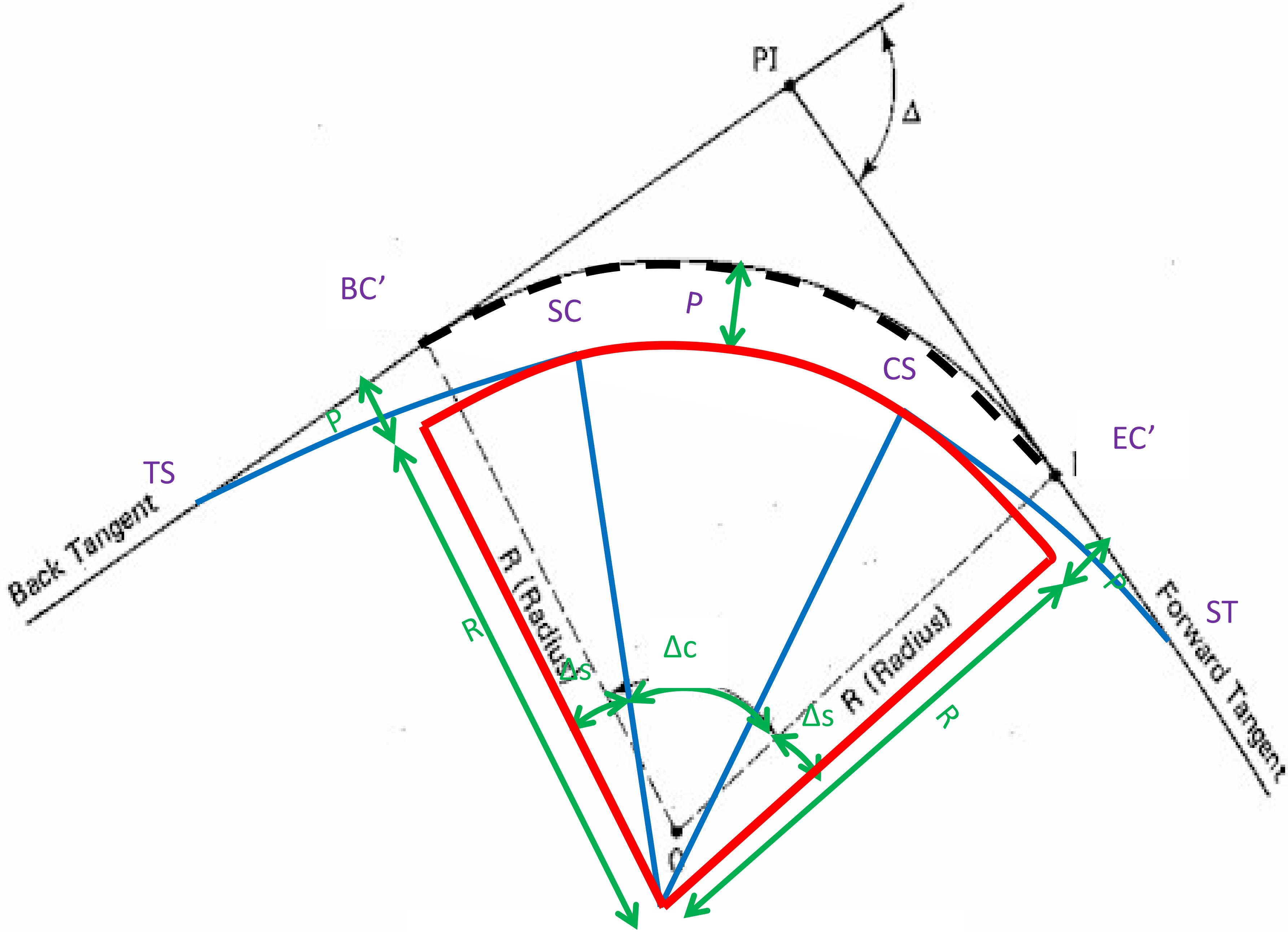
A transition curve is sometimes used in horizontal alignment design
It is used to provide a gradual transition between tangent sections and circular curve sections.
Different types of transition curve may be used but the most common is the **Euler Spiral.**



(a) Circular Curve Joining Two Tangents



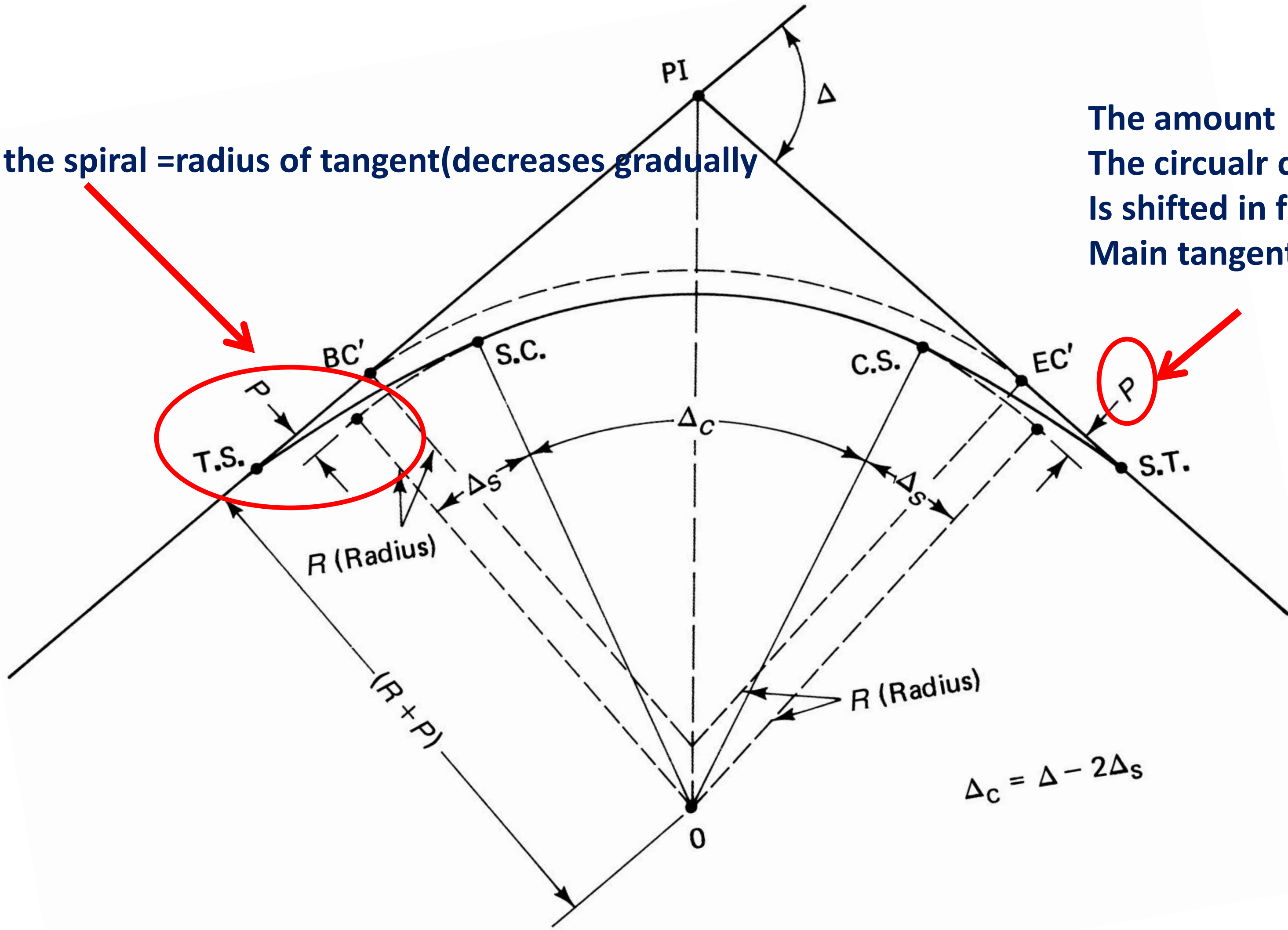
Properties of Euler Spiral
(reference: **Surveying: Principles and Applications, Kavanagh and Bird, Prentice Hall**]



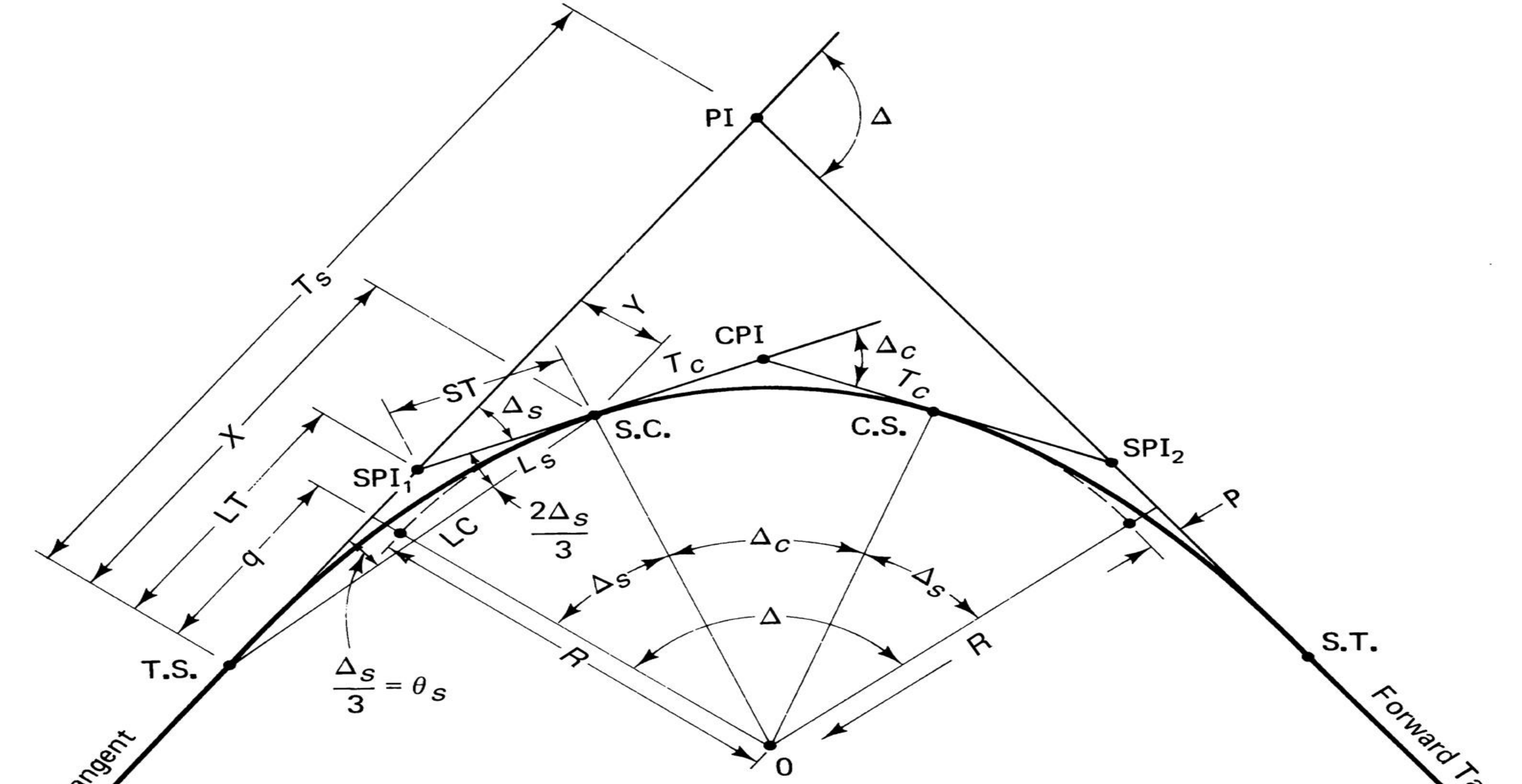
PI
Δ
BC'
SC
P
CS
EC'
I
TS
Back Tangent
P
R (Radius)
R
Δc
Δs
Δs
R (Radius)
R
P
ST
Forward Tangent
O

Radius of the spiral =radius of tangent(decreases gradually

The amount that
The circualr curve
Is shifted in from the
Main tangent



(b)



Symbols

T.S. — Tangent to Spiral
S.C. — Spiral to Curve
C.S. — Curve to Spiral
S.T. — Spiral to Tangent
T_s — Spiral Tangent
X — Distance along Tangent from T.S. to Point at Right Angle to S.C.
Y — Right Angle Distance from Tangent to S.C.
LT — Long Tangent (Spiral)
ST — Short Tangent (Spiral)
L_s — Length of Spiral (Arc)

LC — Long Chord
q — Distance along Tangent to a Point at Right Angle to Ghost BC (Marginally Less than $L_s/2$)
P — Distance from Tangent That the Curve (Ghost BC) Has Been Offset
T_c — Circular Curve Tangent
CPI — **Circular Curve PI**
SPI — Spiral Curve PI
PI — Point of Intersection of Curve Tangents
L_c — Length of Circular Curve
L — Length of Curve System — TS to ST

According to AREA, the recommended formula for the minimum length of the spiral is:

In metric system:

$$L = 0.01216 E_u V \qquad L = 0.744 E_a$$

In traditional U.S. units:

$$L = 1.63 E_u V \qquad L = 62 E_a$$

L: desired minimum length of spiral, m(ft)

Eu: unbalanced elevation, mm (in.)

Ea: actual elevation, mm (in.)

V: maximum train speed, km/h (mph)

- In locations where obstructions make it impossible to provide a spiral of desired length or where the cost of realignment would be prohibitive, the short spiral as defined by:

$$\mathbf{L_{(min)} = 1.22\,E_u\,V} \text{ may be used.}$$

Where

$L_{(min)}$ = desirable length of the spiral in feet

E_u = unbalanced elevation in inches

V = maximum train speed in miles per hour

- **The Transportation Research Board (TRB) recommends an additional formula for spiral length for light rail vehicles:**

- The desired minimum main line spiral length is the greater of the lengths as determined by the following:

$$L = 31\ Ea$$

$$L = 0.82\ E\ u\ V$$

$$L = 1.10\ E\ a\ V$$

Where $L_{(min)}$ = desirable length of the spiral in feet
E_u = unbalanced elevation in inches
V = maximum vehicle speed in miles per hour

- It should be noted that the length of spiral to be used is the maximum computed by both formulas:

$$L = 0.01216EuV \qquad L = 0.744Ea$$

- **Note that maximum superelevation**: Freight: 6-7”   Light Rail: 6”

Avoid Reversed Curves

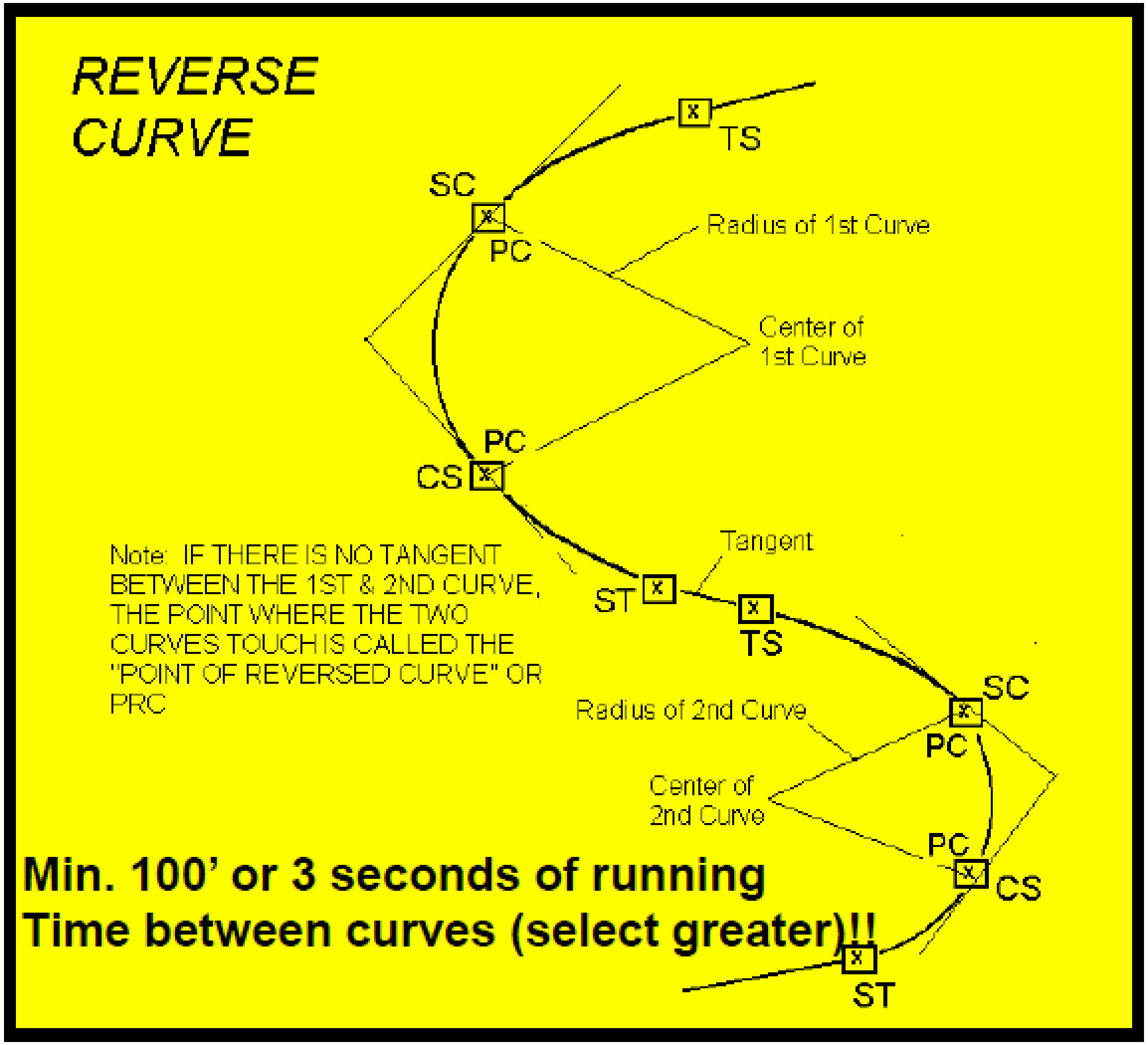


Table 12-6 Equilibrium Elevation for Various Speeds on Curves (mm)

Curve Radius (m)	Degree of Curve[a]	48 km/hr (30 mph)	64 km/hr (40 mph)	80 km/hr (50 mph)	96 km/hr (60 mph)	112 km/hr (70 mph)
3493	0° 30'	8	14	22	31	43
1746	1° 00'	16	28	44	63	86
1164	1° 30'	24	42	65	94	128
873	2° 00'	31	56	87	126	171
699	2° 30'	39	70	109	157	214
582	3° 00'	47	84	131	188	256
499	3° 30'	55	98	153	220	
437	4° 00'	63	112	174	251	
349	5° 00'	79	140	218		
291	6° 00'	94	168	262		
250	7° 00'	110	195			
218	8° 00'	126	224			
194	9° 00'	141	251			
175	10° 00'	157	279			
159	11° 00'	172				
146	12° 00'	188				

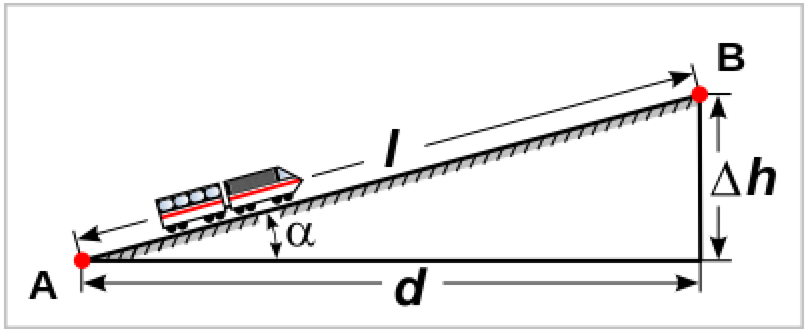
[a]Degree of curve applies to traditional U.S. units.

Source: Equation 12-8.

Using chord length = 30.48 m

Vertical Alignment of railways and guideways

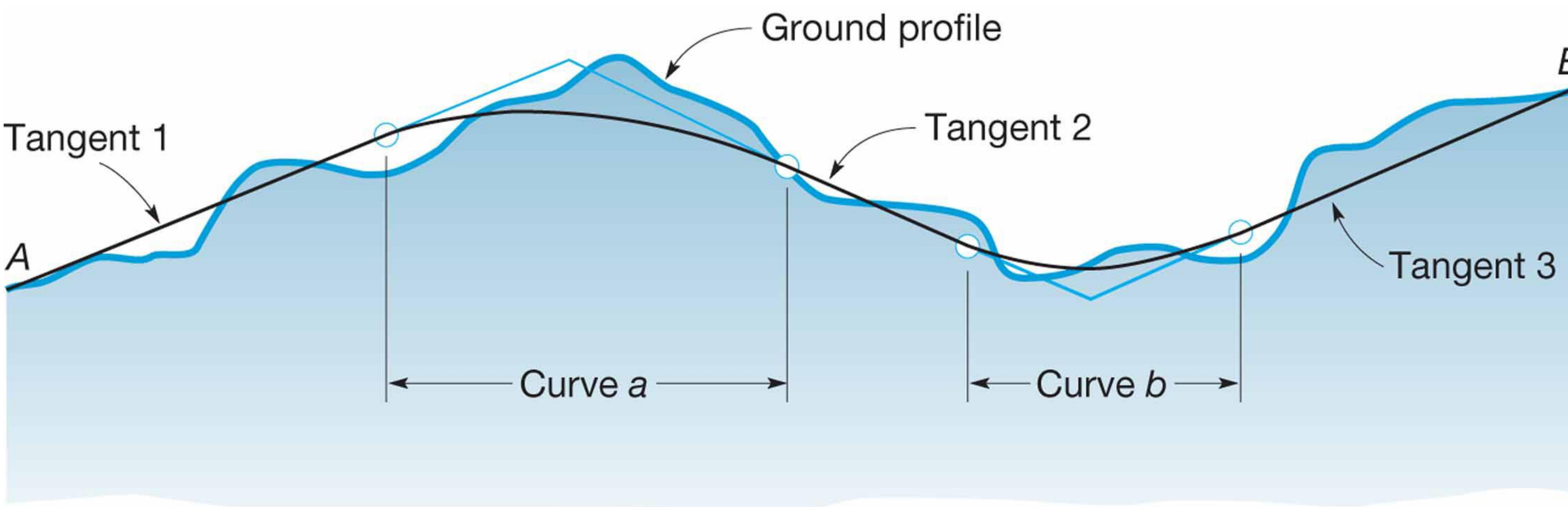
- Vertical parabolic curves are used to connect intersecting railroads gradelines.



- Curves are needed to provide smooth transitions between straight segments (tangent) of grade lines for highways and railroads.

- In addition to horizontal curves that go to the right or left, roads also have vertical curves that go up or down.

- These curves are used to join tangents (eg: tangent 1, 2 and 3 Figure 1) in order to provide a gradual change in grade from the initial (back) tangent to the grade of the second (forward) tangent.



Vertical curves at the top of a hill are called crest curves and vertical curves at the bottom of a hill or dip are called sag curves.

<u>Factors to be Considered</u>

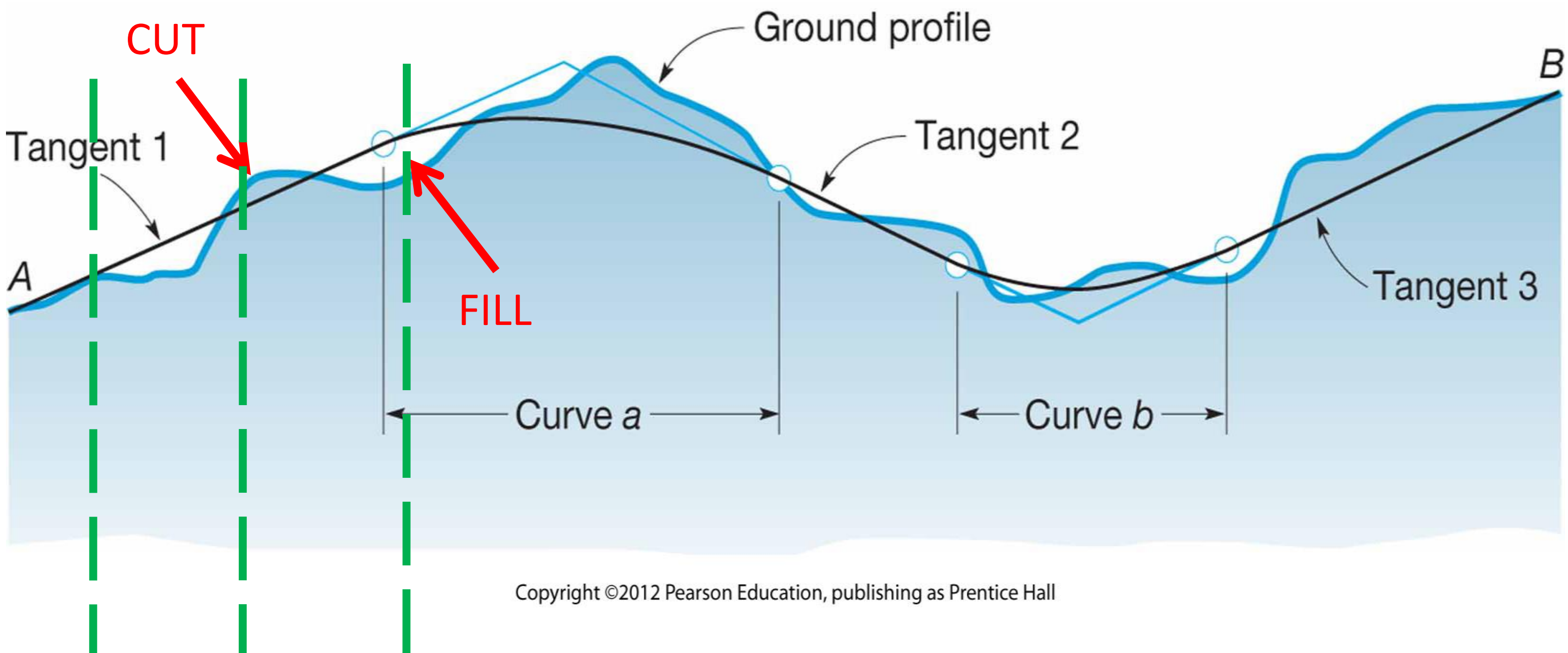
- Providing a good fit with the existing ground profile, thereby minimizing depths of cuts and fills.

- Balancing the volume of cut materials against fill.

- Maintaining adequate drainage.

- Not exceeding maximum specified grades (g) and meeting fixed elevations such as intersections with other roads.

- *<u>In addition, the curves must be designed to:</u>*
  - fit the grade lines they connect
  - have lengths sufficient to meet specifications covering a maximum rate of change of grade (which affects the comfort of vehicle occupants)
  - provide sufficient sight distance for safe vehicle operation.



STATION	0+00	0+200	0+400						
RL	500	520	530						
GL	500	550	510						
HT. Cut	0	30	0						
HT. Fill	0	0	20						

Design of Vertical Curves

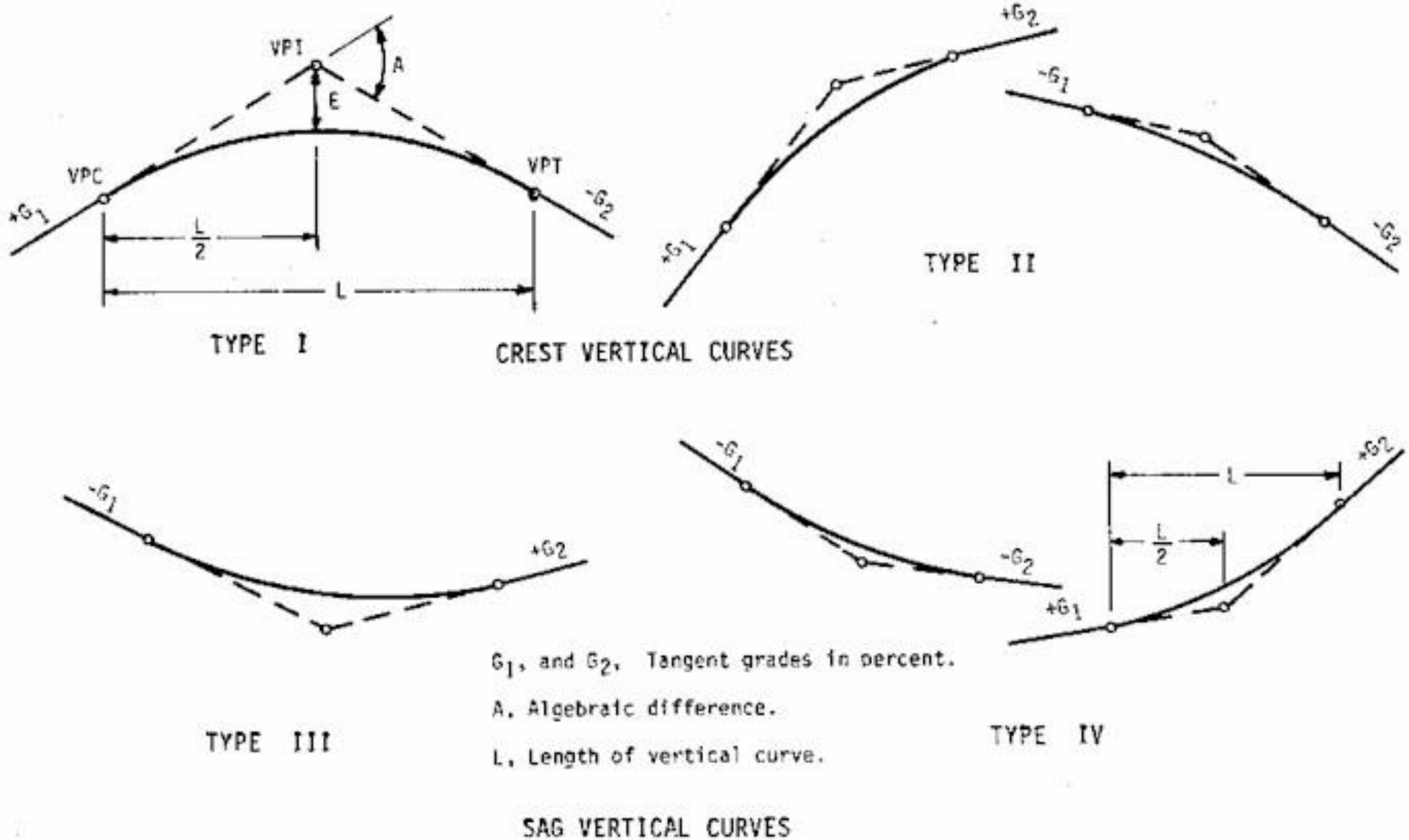


Figure III-38. Types of vertical curves.

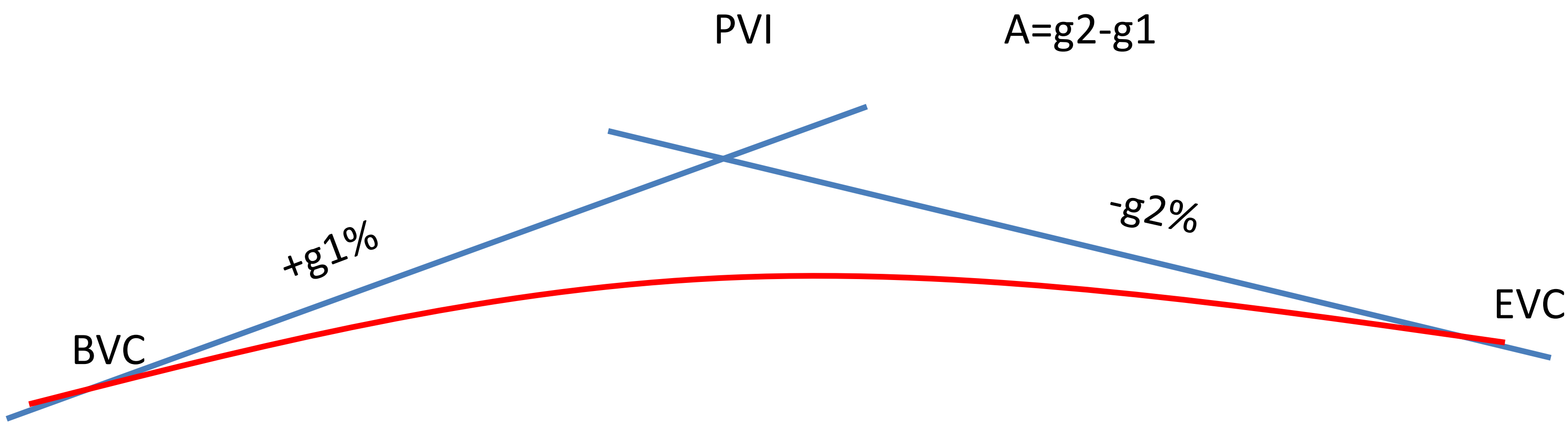
Vertical curve terminology

Change in grade: $A = G_2 - G_1$

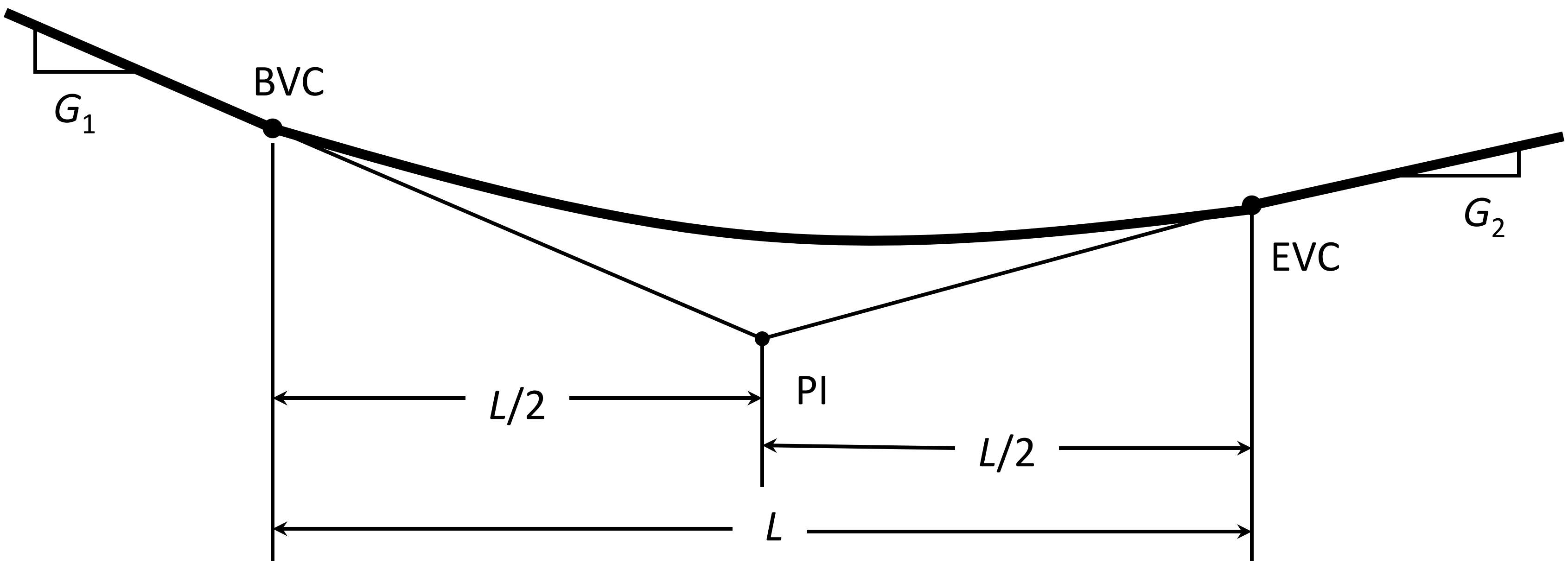
where G is expressed as % (positive /, negative \)

For a crest curve**, *A* is negative**.

For a sag curve**, *A* is positive**.



Properties of Vertical Curves



Characterizing the curve:

Rate of change of grade: $r = (g_2 - g_1) / L$ where,

g is expressed as a ratio (positive /, negative \)

L is expressed in feet or meters

Vertical Curve Geometry

- Parabolas provide a constant rate of change of grade, they are ideal and almost always applied for vertical alignments used by vehicular traffic.

- The general mathematical expression of a parabola:

$$y = ax^2 + bx \cdots + c \cdots (1)$$

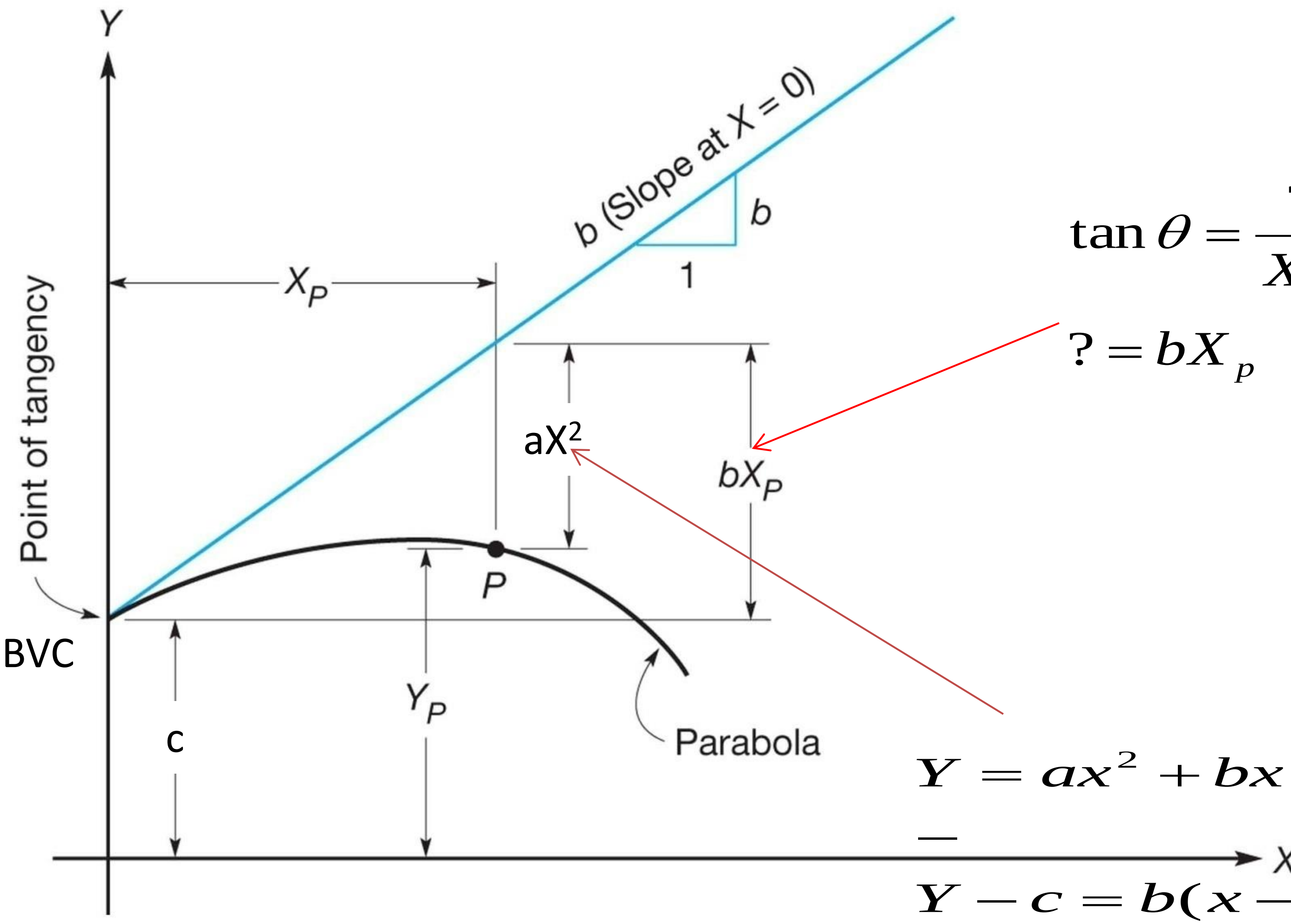
y = the ordinate at any point of the parabola at a distance x from the origin of the curve

ax^2= the parabola's departure from the tangent (tangent offset) in distance x

b = the slope of the tangent to the curve (X = 0)

bX = the change in ordinate along the tangent over distance X

c= the ordinate at the beginning of the curve (X = 0)



$$\tan\theta = \frac{?}{X_p} = b$$

$$? = bX_p$$

$$Y = ax^2 + bx + c$$

$$-$$

$$Y - c = b(x - 0)$$

$$= ax^2 + bx + c - bx - c$$

$$= ax^2$$

The slope of the curve at any point is given by the first derivative

$$\frac{dy}{dx} = 2ax + b$$

The rate of change of slope is given by the second derivative:

$$\frac{d^2y}{dx^2} = 2a$$

Which is constant, **2 a** can also be written as:

$$r = 2a = \frac{g_2 - g_1}{L} = \frac{A}{L}$$

(for an equal tangent parabolic curve)

- **<u>If for convenience, the axes is placed at BVC, equation 1 becomes:</u>**

$$y = ax^2 + bx$$

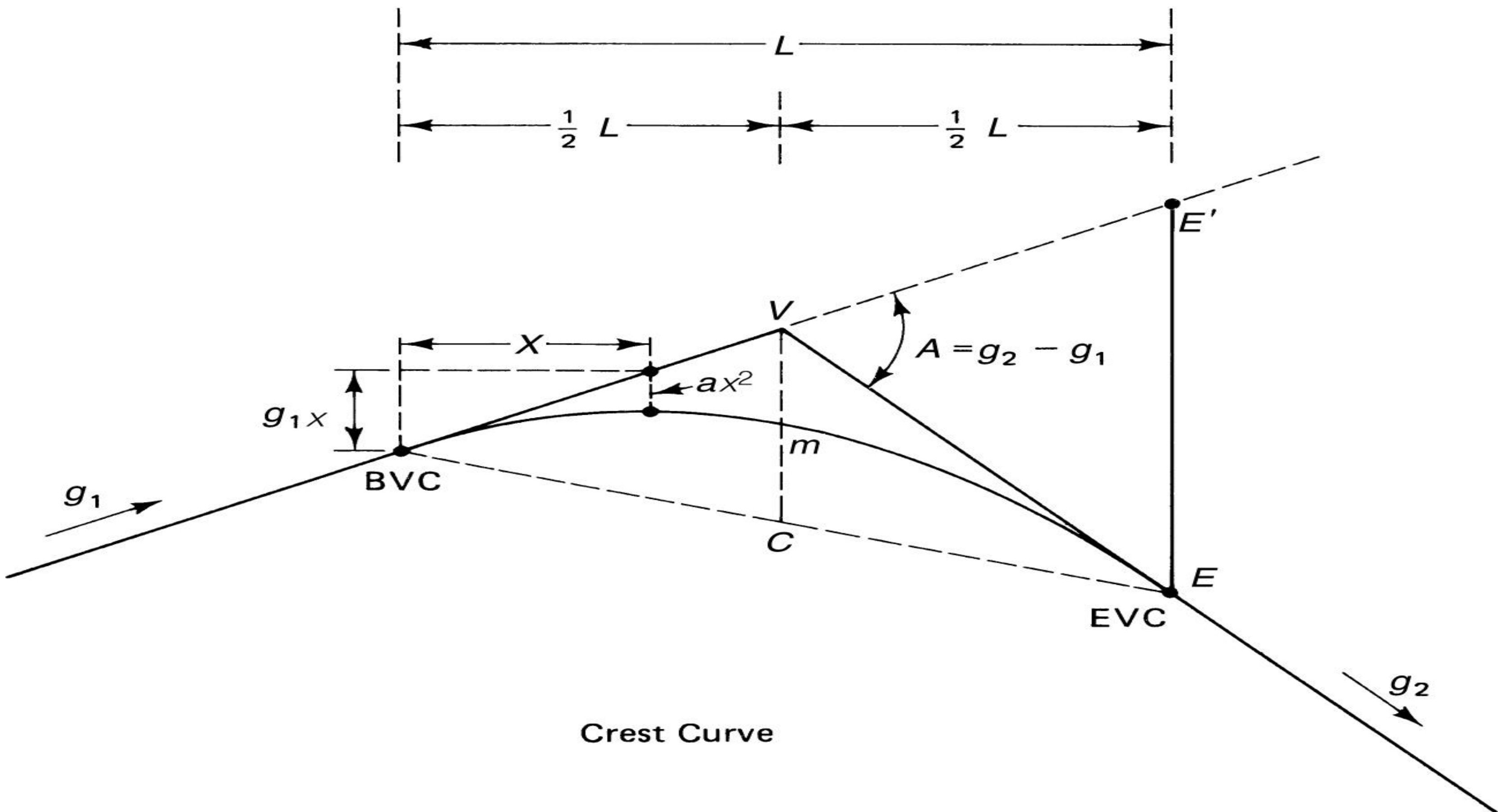
$$\frac{dy}{dx} = slope = 2ax + g_1$$

$$\frac{dy}{dx} = 2\left(\frac{g2 - g1}{2L}\right)x + g_1$$

$$now, y = ax^2 + bx:$$

$$y = \left(\frac{g2 - g1}{2L}\right)x^2 + g1x$$

Geometric properties of the parabola



Crest Curve

Elements of Vertical Curve

- **<u>Equal Tangent Vertical Parabolic curve</u>**

<u>Terms used by surveyors and Engineers:</u>

BVC = beginning of vertical curve OR
VPC = vertical point of curvature
V = the vertex, often called VPI
VPI = vertical point of intersections
EVC = end of vertical curve OR
VPT = vertical point of tangency
g1 = grade of the back tangent (%)
g2 = grade of the forward tangent (%)
L = horizontal distance (BVC to EVC)

An equal tangent vertical parabolic curve means the vertex occurs at a distance X = L/2 from the BVC

- Railroads vertical alignment **design differs significantly in several aspects from the profile grade design of highways**.

- These differences arise from inherent vehicle differences and results in more stringent design criteria for railroads, this is **attributed to two considerations**:

1. The **much longer and heavier railroad** vehicle
2. The relatively **low coefficient of friction between the driver wheels** and the rails.

- Railroads are characterized by **much smaller maximum grades and much longer vertical curves** than are highways.

- Generally, **steep grades cannot be tolerated** in railroad design.

- Maximum grade for most **main lines** is about **1%**
- On **mountainous** terrain up to **2.5%**
- Slightly greater grades can be tolerated for railroads that accommodate **freight trains**, e.g., in Atlanta conventional rail transit system a grade of **3.0%** was used
- **LRT** – maximum **4 to 6% Up to 10%** for short sections
- **Minimum** grade of about **0.3%** maybe required in underground and on aerial line structures to accommodate the **drainage**

<u>Railway vertical curves – old formula:</u> Old railway formula developed in 1880's for "hook and pin" couplers in those days

$$L = A / R$$

- A = algebraic difference of grade (ft. per 100-ft. station)
- R = rate of change per 100-ft. station

Table 12-12 Vertical Curve Criteria for Railroads

	Maximum Rate of Change of Gradient, Percent per Station[a]	
	In Sags	On Crests
High-speed main tracks	0.05	0.10
Secondary main tracks	0.10	0.20
Metric Units		
	Maximum Rate of Change of Gradient, Percent per Meter	
	In Sags	On Crests
High-speed main tracks	0.00164	0.00328
Secondary main tracks	0.00328	0.00656

[a]1 station = 100 ft.

Source: Adapted from *Manual for Railway Engineering*, Vol 1. American Railway Engineering Association, 1995.

<u>New formula developed in recent years:</u>

$$\mathbf{L = 2.15\ V^2\ A\ /\ a}$$

Where,

V = train speed in mph

A = algebraic difference of grade in decimal

a = vertical acceleration in ft./sec2

0.1 ft./ sec^2 for freight,

0.6 ft./ sec^2 for passenger or transit

Example:

A +0.8 % grade intersects a -0.3% grade on a high-speed main track. What minimum length of vertical curve in feet should be used?

- The curve is crest. The total change in Grade is $|-0.3-0.8| = 1.1\%$
- R= 0.1 (Table 12-12)

Length of vertical curve= L = A / R= 1.1/0.1= 11 stations or 1100 ft

Example:

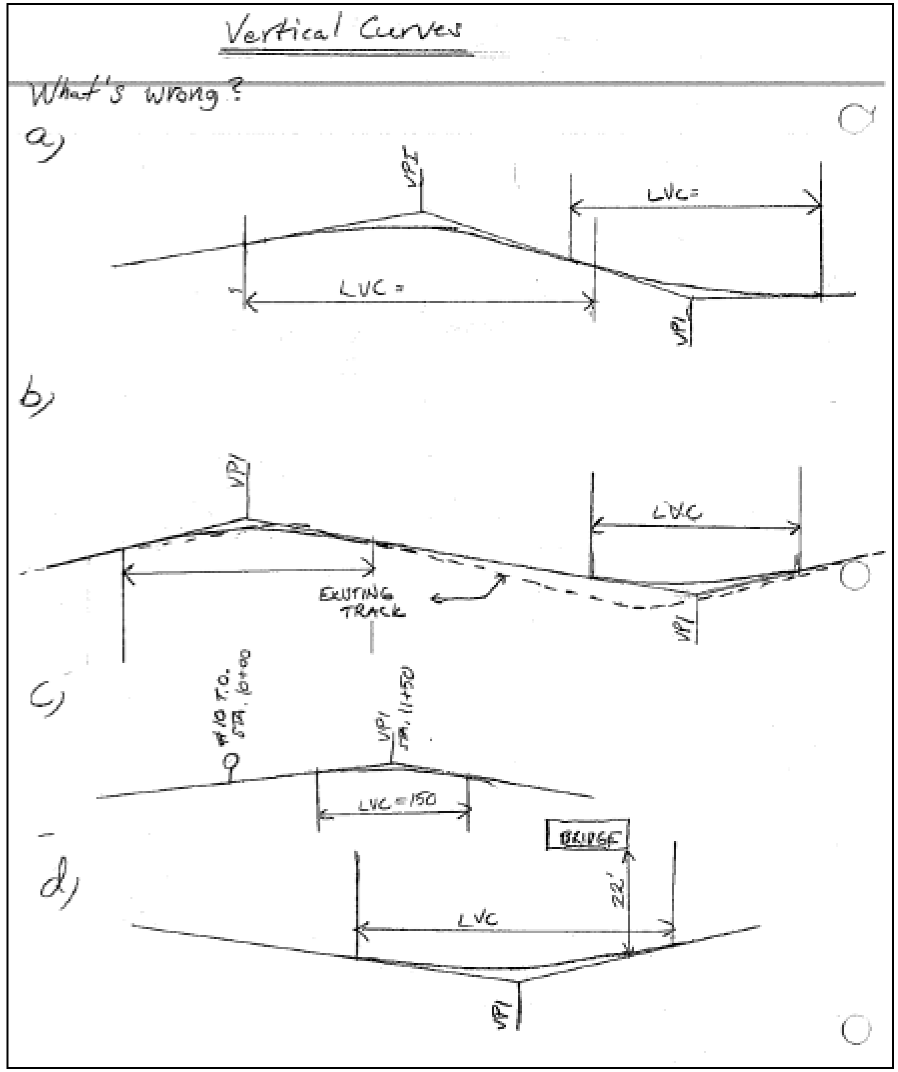
A -0.4 % grade intersects a +1.2% grade on a high-speed main track. What minimum length of vertical curve in feet should be used?

- The curve is sag. The total change in Grade is $|1.2 + 0.4| = 1.6\%$
- R= 0.05 (Table 12-12)

Length of vertical curve= L = A / R= 1.6/0.05= 32 stations or 3200 ft

Critical issues with Vertical Curves

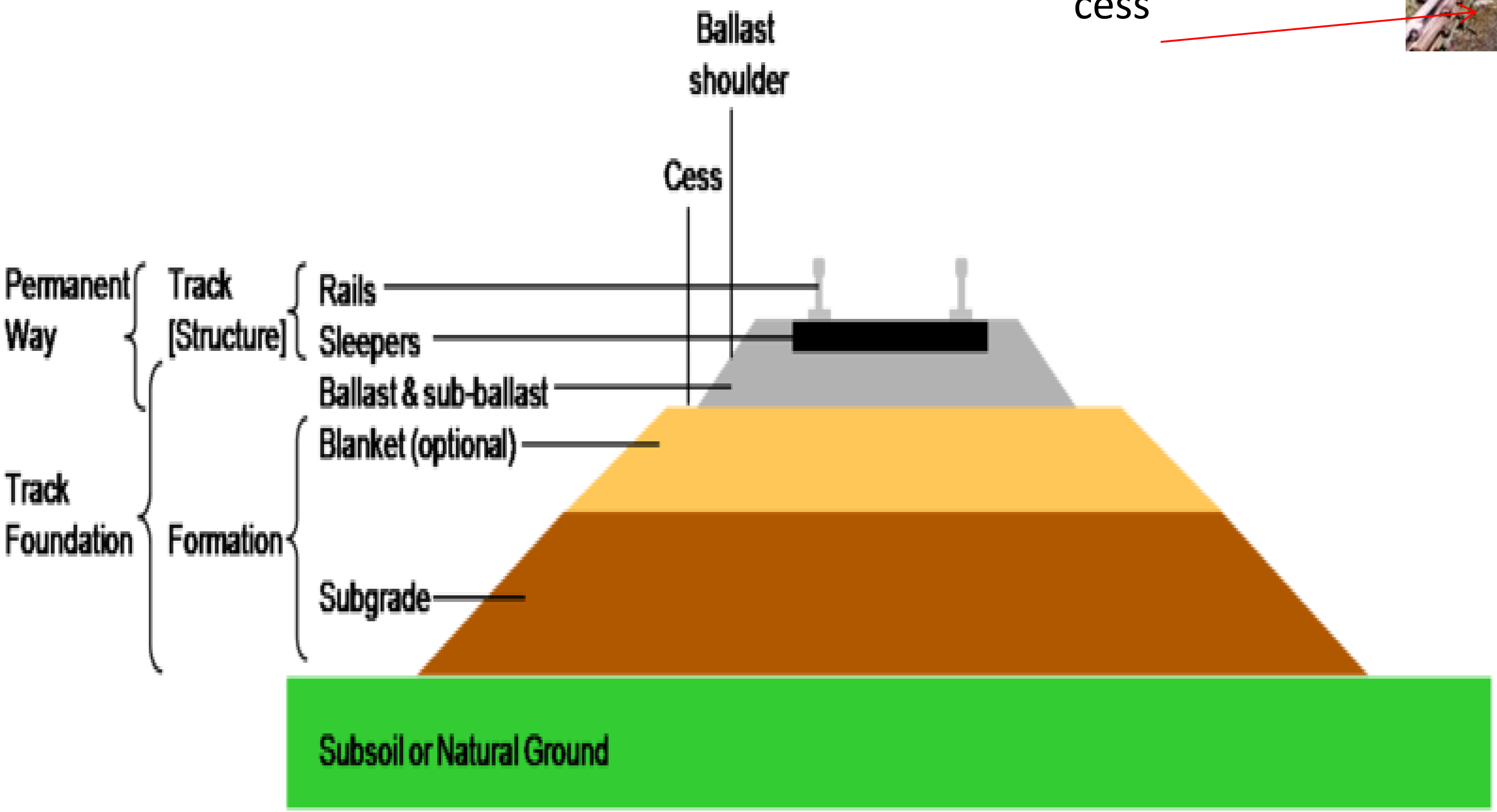
a) Overlapping vertical curves
b) Avoid lowering existing tracks
c) No vertical curves within turnouts
d) Provide additional clearance in sag curves
e) No vertical curves within horizontal spirals



Turnouts

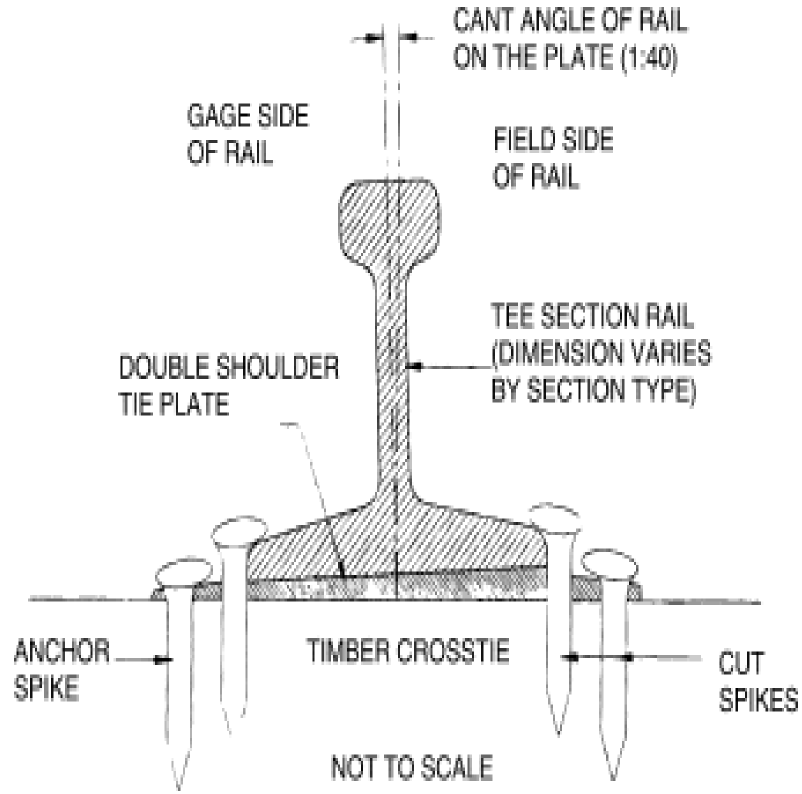
Typical Section - Railroad

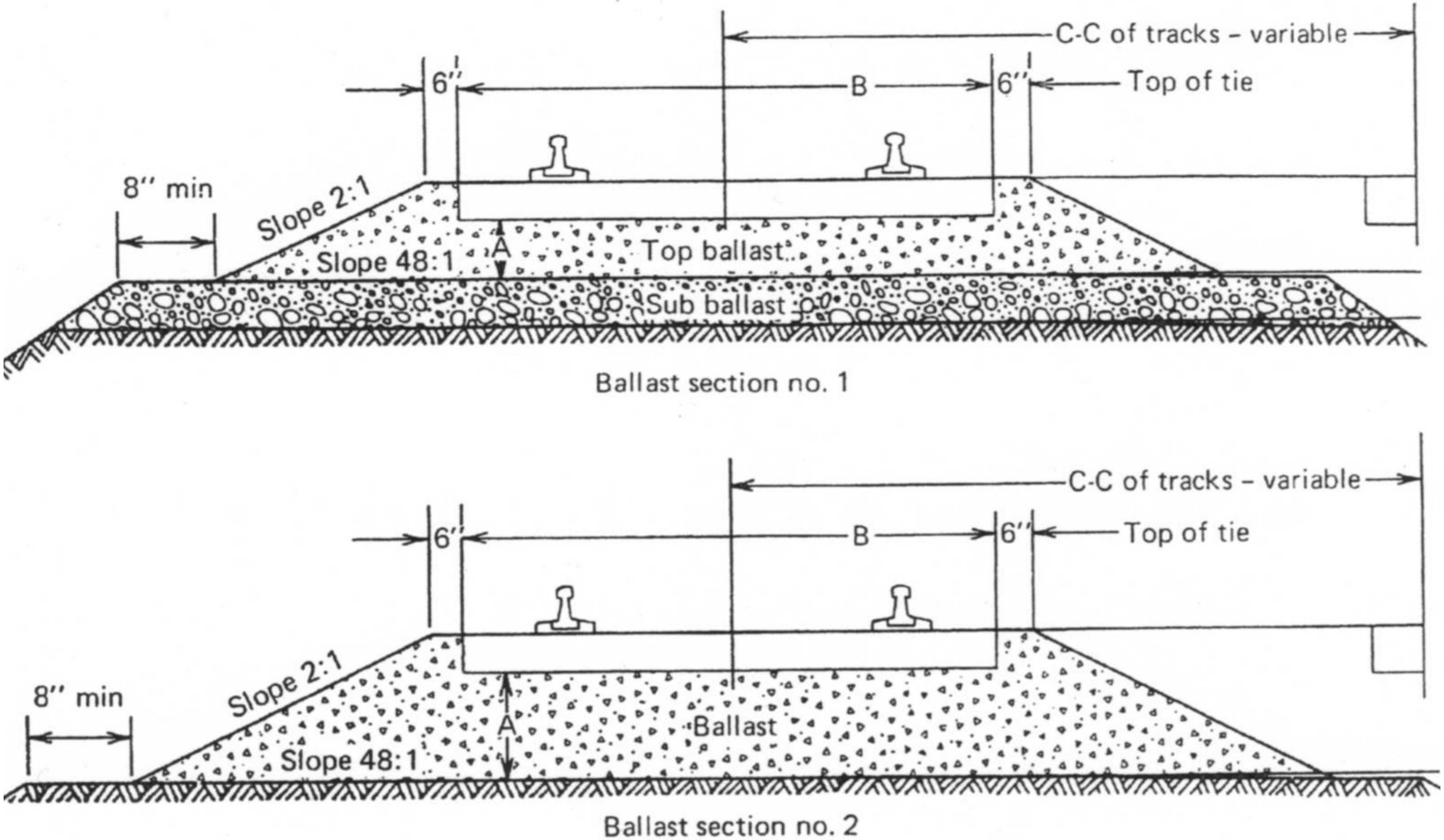
Subgrade top width of 24’ to 30’ for single track cess


Ballast shoulder
Cess
Permanent Way
Track [Structure]
Rails
Sleepers
Ballast & sub-ballast
Track Foundation
Formation
Blanket (optional)
Subgrade
Subsoil or Natural Ground

Cross-section Elements:

Ballast
Cross-ties (sleepers)
Rails
Tie plates
Fastenings
Rail anchors
Rail joints





Area ballast sections, single and multiple track, tangent

Notes:

Depth of ballast section to be used will depend on conditions peculiar to each railroad or location.
Sections apply to all types of ballast.
Sections for use with jointed or continuous rail.
Top of ballast determined by the use of various mechanized ballast distributing operations.

Figure 13-4 Typical roadbed section for single main track. (Courtesy Southern Railway System.)

1. Ballast

- Ballast is the material in which the track structure is imbedded for the purpose of holding the track to line and grade

- Material: crushed stone and washed river gravel

- Grain size: 1.5 – 1.75 inches

- <u>Sub-ballast:</u> used when ballast material is expensive, there is a short of supply, or very low sub grade quality exists

- <u>Ballast depth:</u> 6-30 inches depending on wheel loading, traffic density and speed, type and condition of foundation

- Sub-ballast depth: 12 in

Ballast is used for:

1. Distribute wheel loadings
2. Anchor the track
3. Provide immediate drainage
4. Minimize dust
5. Inhibits vegetation

2. Crossties (Sleepers)

Materials:

- Treated wood
- Concrete (pre-stressed & reinforced)

Section: 6 x 6 inch up to 7 x 9 inch

Length: 8, 8.5, & 9 ft

Average spacing: 21 inch

Functions of Crossties:

1. Spreading loads to ballast
2. providing correct gage between rails
3. anchoring the track
4. making the needed adjustments to vertical profile.

3. Rails

- Continuous inverted T-shape steel beam

- Function: transmits loads to crossties via tie plates and fastenings

- Length:

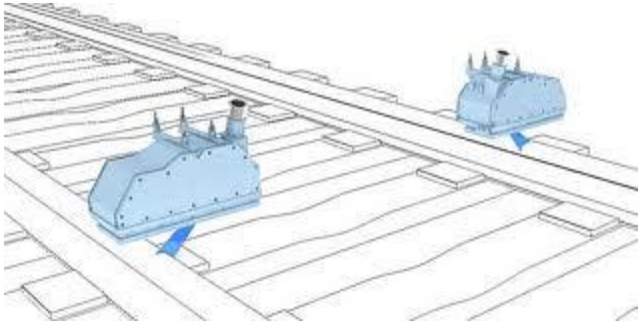
in the past 39 ft standard

recently 1440 ft is used

Advantages of long rails:

- less maintenance costs
- higher speeds are allowed
- less damage
- smoother ride

- Rail gage: is standard = 4’ 8.5’’



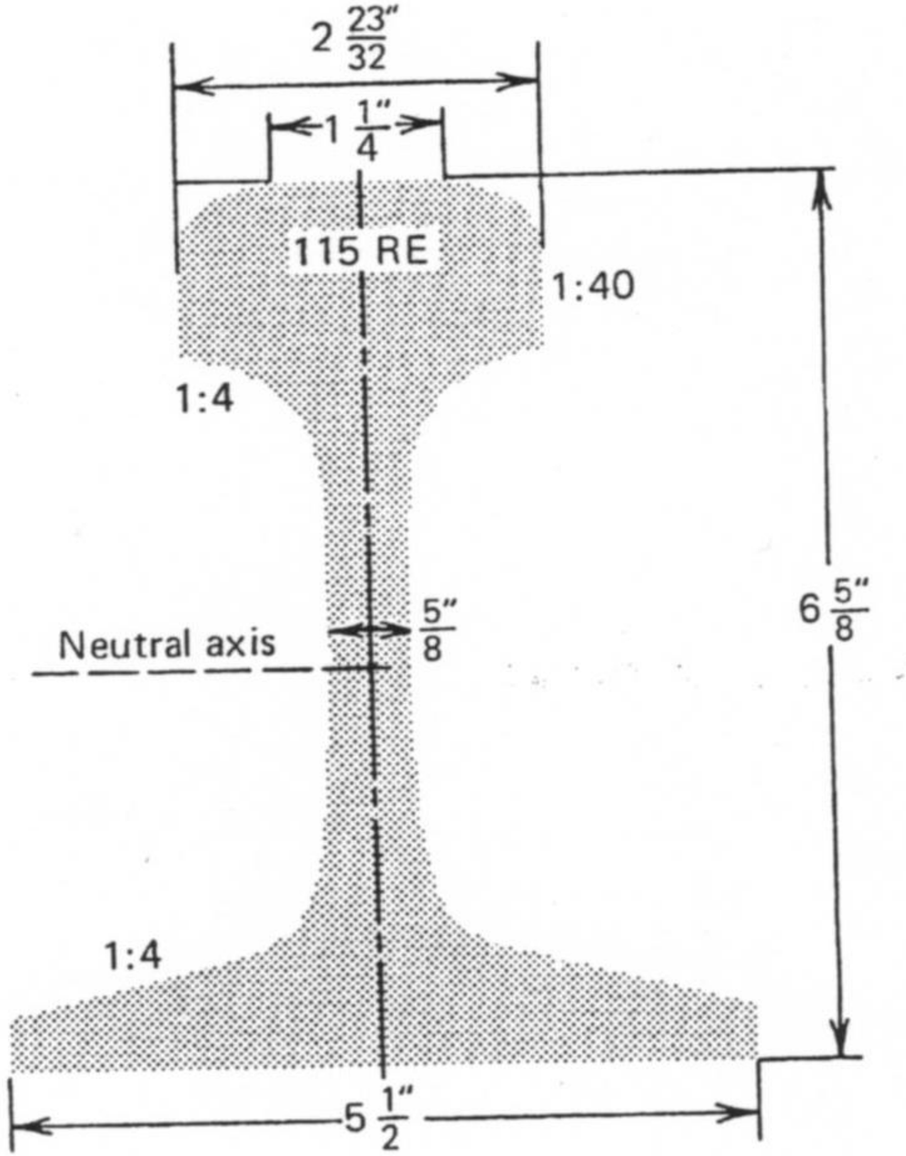
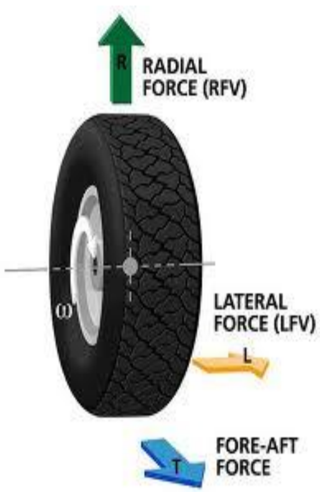


Figure 13-6 Typical rail section. (Courtesy Southern Railway System.)

4. Tie plates

- Laid on the crossties under rails
- Dimension: 7’’- 8’’ x 10’’-14’’ x 0.56’’-1’’
- Functions:
  1. Preventing damage to the wood crossties by distributing the wheel loads
  2. Holding the rails to proper gage
  3. Offsetting the outward lateral thrust of the wheel loads



5. Fastenings

Used to anchor the tie plates to the crossties

6. Anchors

Used to anchor the rails to the ballast in order to reduce the longitudinal movement & control the temperature expansion of rails

Fastenings

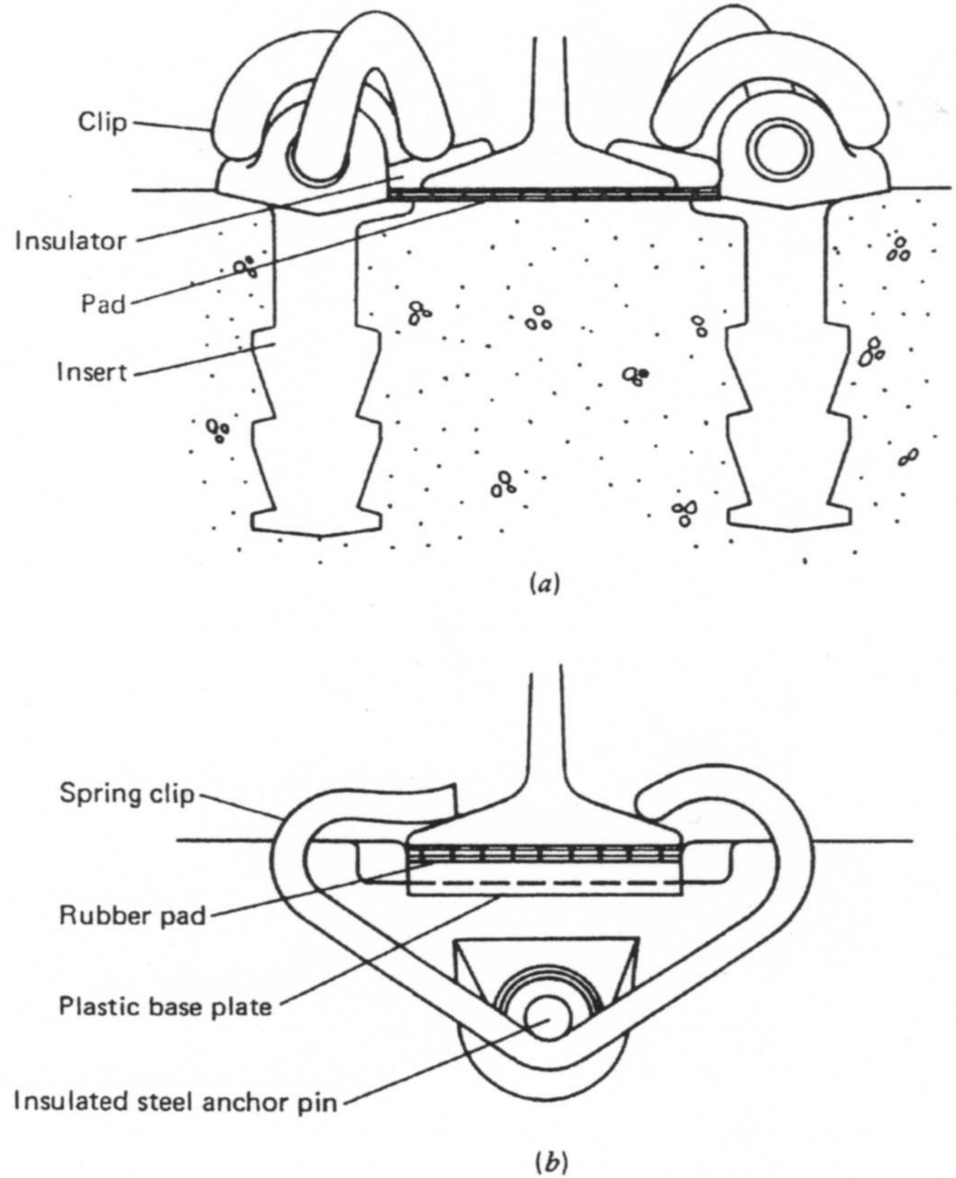


Figure 13-8 Examples of clip fastening systems. (*a*) Pandrol. (*b*) Fist. (Source: *Concrete Railway Sleepers, State of the Art Report,* Thomas Telford, London, 1987.)

7. Joints

- Functions:
    - Provide smooth continuity of rail ends
    - Transfer the wheel loads between rail ends

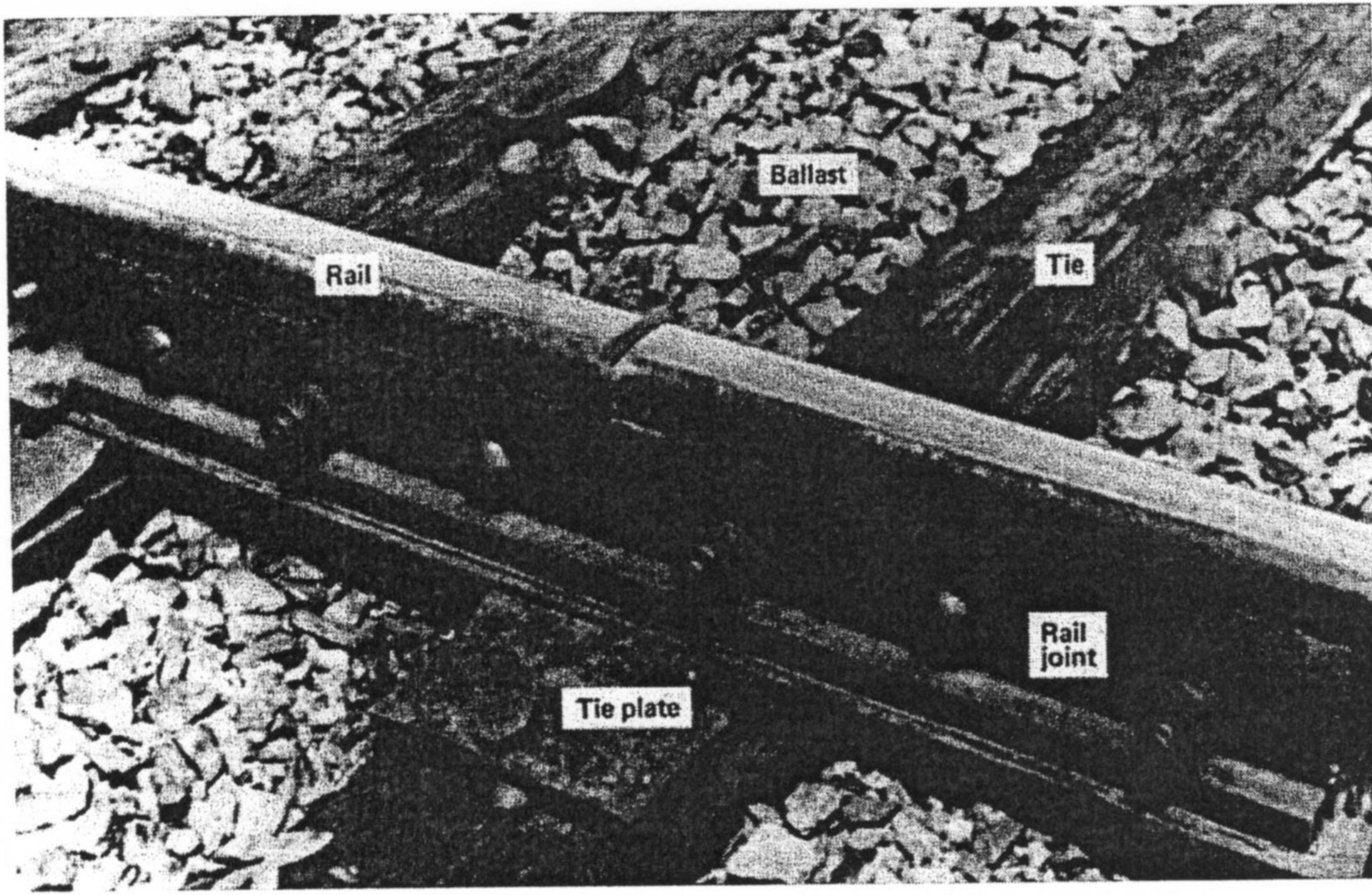


Figure 13-10 A rail joint. (Courtesy, Portec, Inc.)

Urban Mass Transit

Most Recent Urban Public Transport Systems

1 – Articulated Bus

2 – Bus Rapid Transit (BRT)

3 – Light Rail Transit (LRT)

4 – Metro

Advantages of mass Transit:

1. High capacity
2. Energy efficiency
3. Less pollution
4. Reduce congestion
5. Lower cost

System Classification:

A. By Route Type:

1. Cross town
2. Radial
3. Circumferential
4. Grid

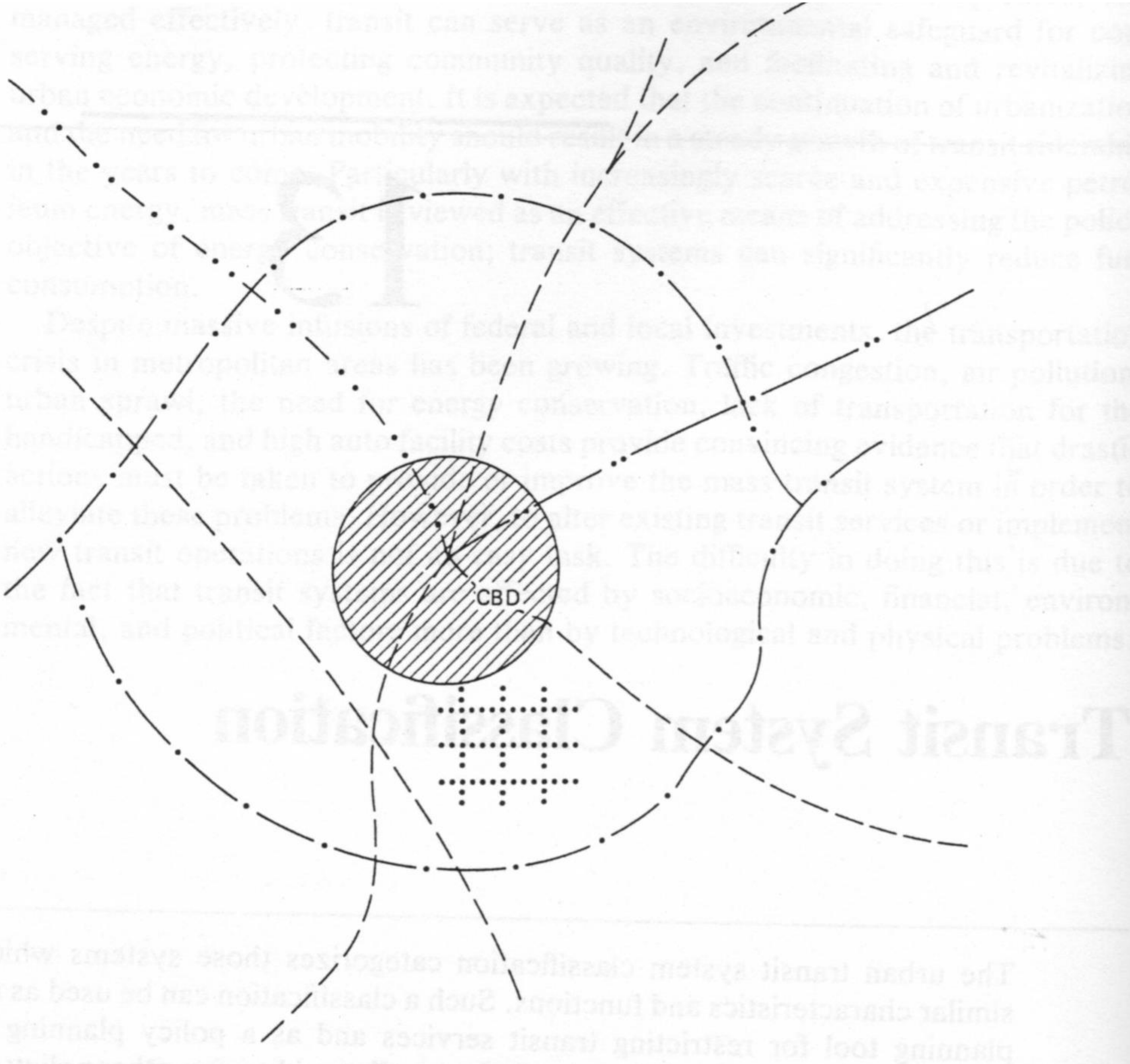


Figure 13.1 Transit system classification by route type. **Key:** — — —, crosstown route; —··—··—, radial or corridor route; —·—·—, circumferential route; ⋯, grid route.

B. By Service:

1. Residential collection system
2. Feeder system
3. Line-haul system
4. Downtown distribution system

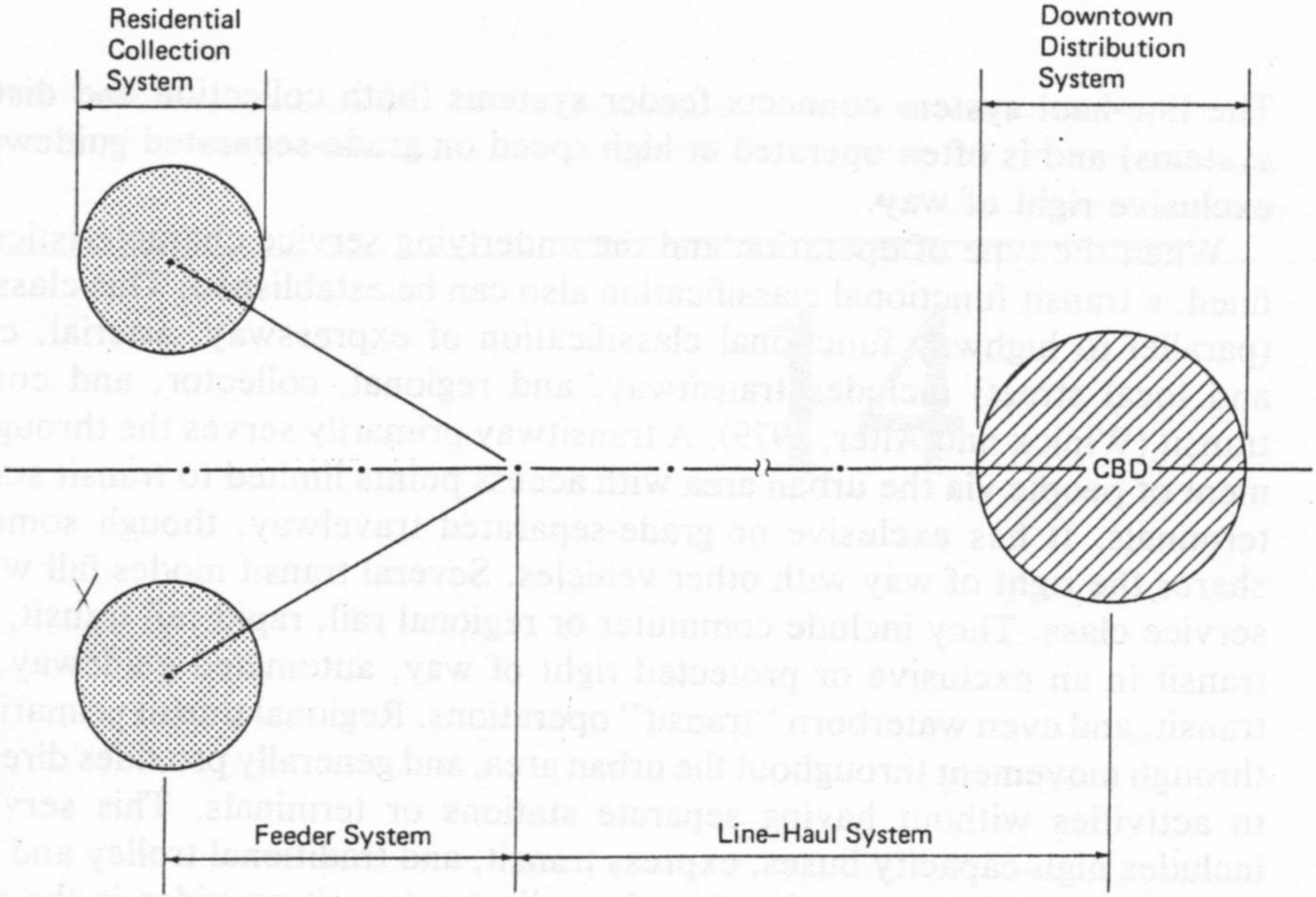


Figure 13.2 Transit system classification by service function.

Performance Measures:

1. Cost efficiency (cost per passenger mile)
2. Labor productivity (passenger miles per employee)
3. Energy efficiency (energy consumption per passenger mile)
4. Accessibility (within walking distance)
5. Quality of service (LOS: A – F based on travel time, % of trips on time, …)

System Economics

Five Categories:

1. Operating wages and benefits (straight time and overtime wages)
2. Transportation cost (fuel, maintenance, …)
3. Vehicle costs (insurance, license, damage, …)
4. Fixed overhead costs (management, office expenditures, …)
5. Capital costs (depreciation, …)

Transit Financing

1. General taxes (property, sales, & income taxes,
2. Auto disincentive taxes (gasoline, registration, parking taxes)
3. Direct benefit financing (local government subsidies)
4. Non-transit related taxes (cigarette taxes)

Transit Rate

$$F = F_b + K\,N$$

Where:

F = fare to be paid

F_b = base fare

K = increment in price per zone

N = number of zones crossed

Types of Bus Service

1. Local bus Transit: provides service on city streets & subject to interference from other traffic

2. Rapid Bus Transit: has exclusive right of way & can maintain higher speeds

3. Subscription Bus Service: Works on a daily or weekly basis

4. Dial-A-Bus System: user calls a central computer and request a bus. Used for elderly and handicapped

System Components

A. Bus Transit Vehicle:

The transit bus has a seat capacity of ten or more passengers. For Local buses, the area also provides space for standees in case of high demand.

Types of vehicles:

1. Minibus (length = 18-20 ft, # of seats = 16-24)
2. Conventional (length = 30-40 ft, of seats = 35 – 54)
3. Articulated (length = 55 – 60 ft, # of seats = 35-70)
4. Double deck (length = 25 – 35 ft, # of seats = 50 – 90 ft)


Victoria Station 73
ARRIVA
Buy tickets before boarding
BX04 NBK


London Bridge 141
Another red bus going green for London
ARRIVA

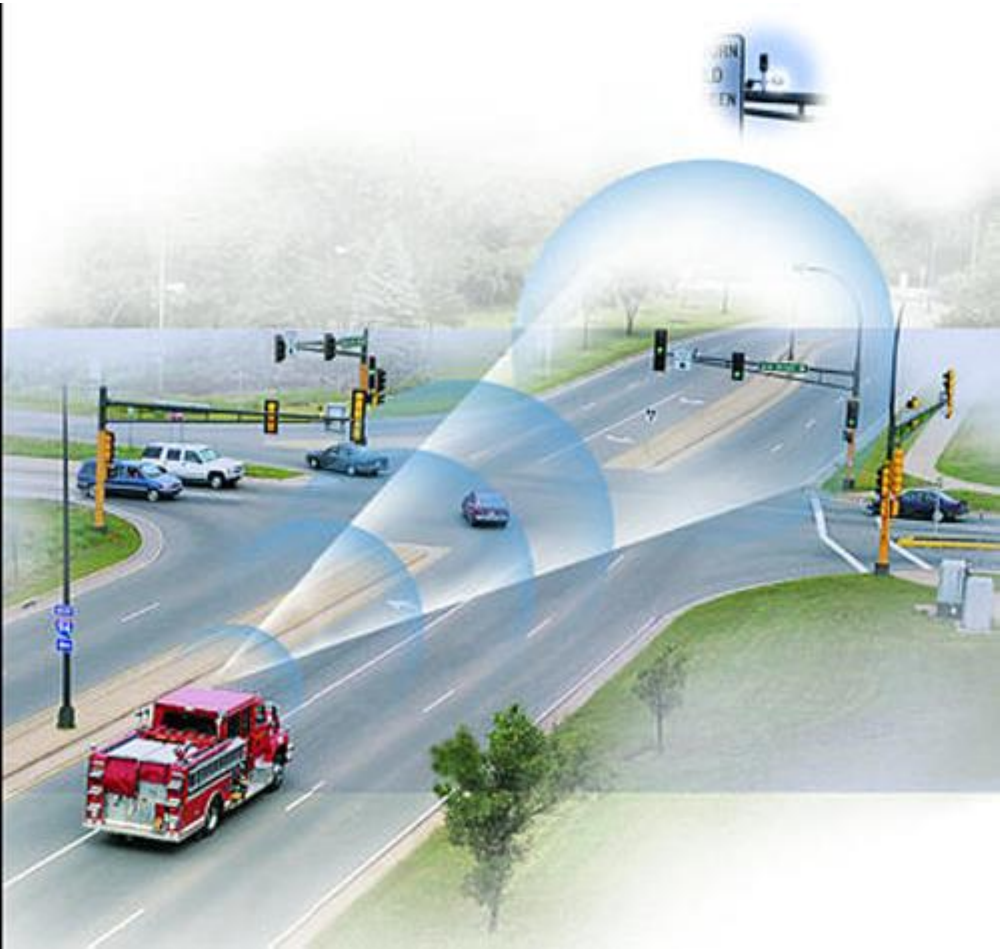
Conventional bus services being delayed by traffic congestion on Chang'an Avenue in Beijing, wiki

B. Bus Travel-way

1. Shared travel-way (affected by traffic delay and congestion)
2. Reserved lanes (separated from other types of vehicles)
3. Bus streets
4. Traffic signal preemption

<u>Warrants for reserved lanes:</u>

a. Freeways: at least 300 buses during peak period
b. City Streets: at least 30 – 40 buses during peak hour



signal preemption

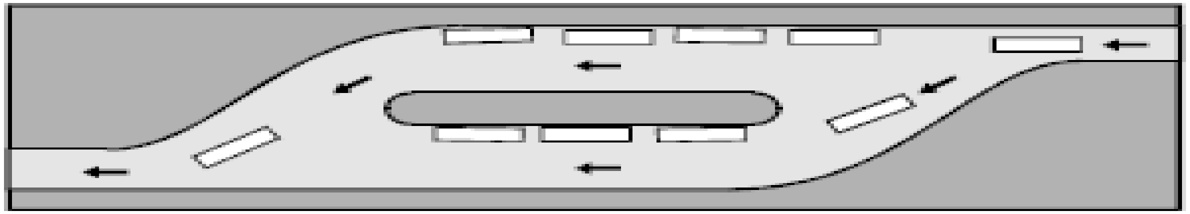
Reserved lanes

C. Bus Stop

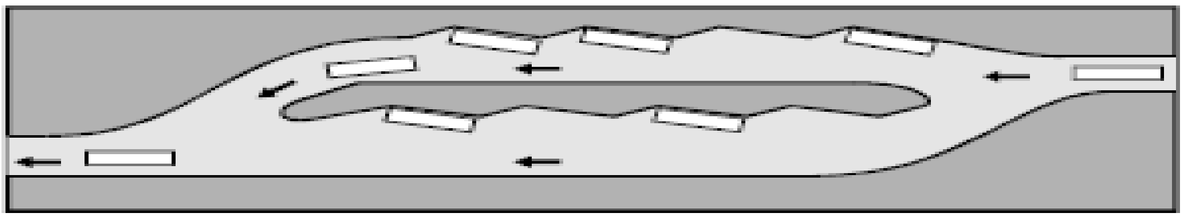
The main goals in planning and designing bus stops:

1. Provide direct bus access to and from express roads and busways
2. Minimize bus layover in order to maximize berth capacity
3. Separate loading from unloading operations
4. Utilize each berth by minimizing the number of different routes
5. Minimize walking distance to walking bus lines
6. Utilize automobile parking to reduce bus mileage in low density residential areas

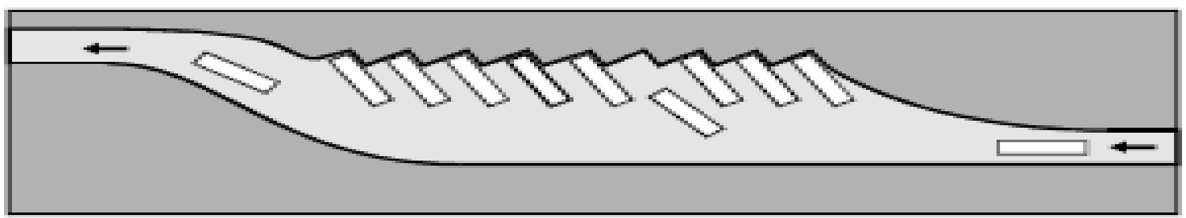
Linear Berths



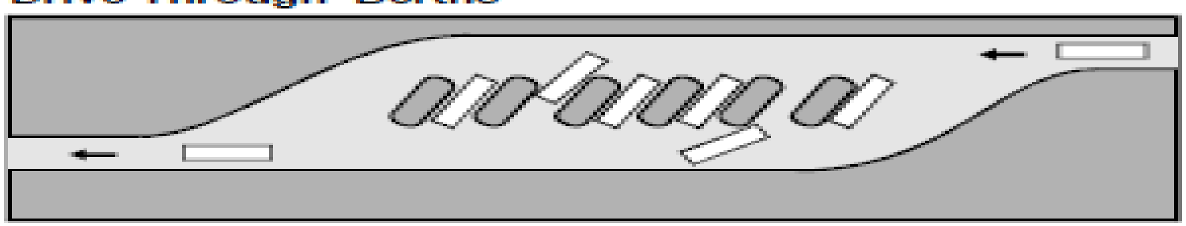
Sawtooth Berths



Angle Berths



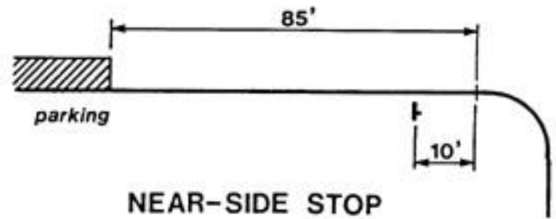
Drive Through Berths



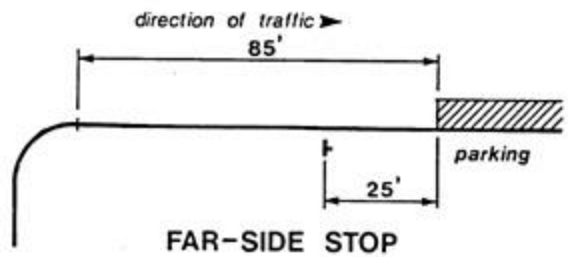
- Maximum spacing of stops for local bus system is usually about 0.5 miles

- Bus stops (according to their location from intersections) are:
    1. Near side (the bus is going to turn right on the same intersection)
    2. Far side (the bus is going to turn left on the next intersection)
    3. Midblock (the bus is going straight or intersection stops are not possible)

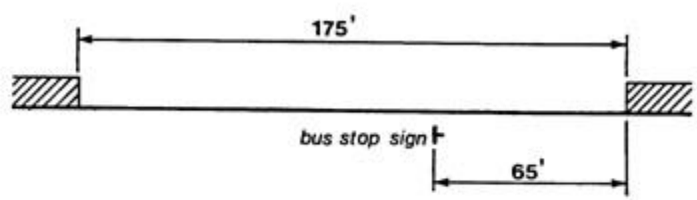
NEAR-SIDE, FAR-SIDE AND MID-BLOCK BUS STOPS



NEAR-SIDE STOP



FAR-SIDE STOP



MID-BLOCK STOP

- Special bus stop turnout are provided on freeways near park & ride services

- Bus stops may have:
    - ➢ Only a sign
    - ➢ A bench
    - ➢ A shelter

      Shelters may have advertising, telephones, scheduling information, …

Bus Stops

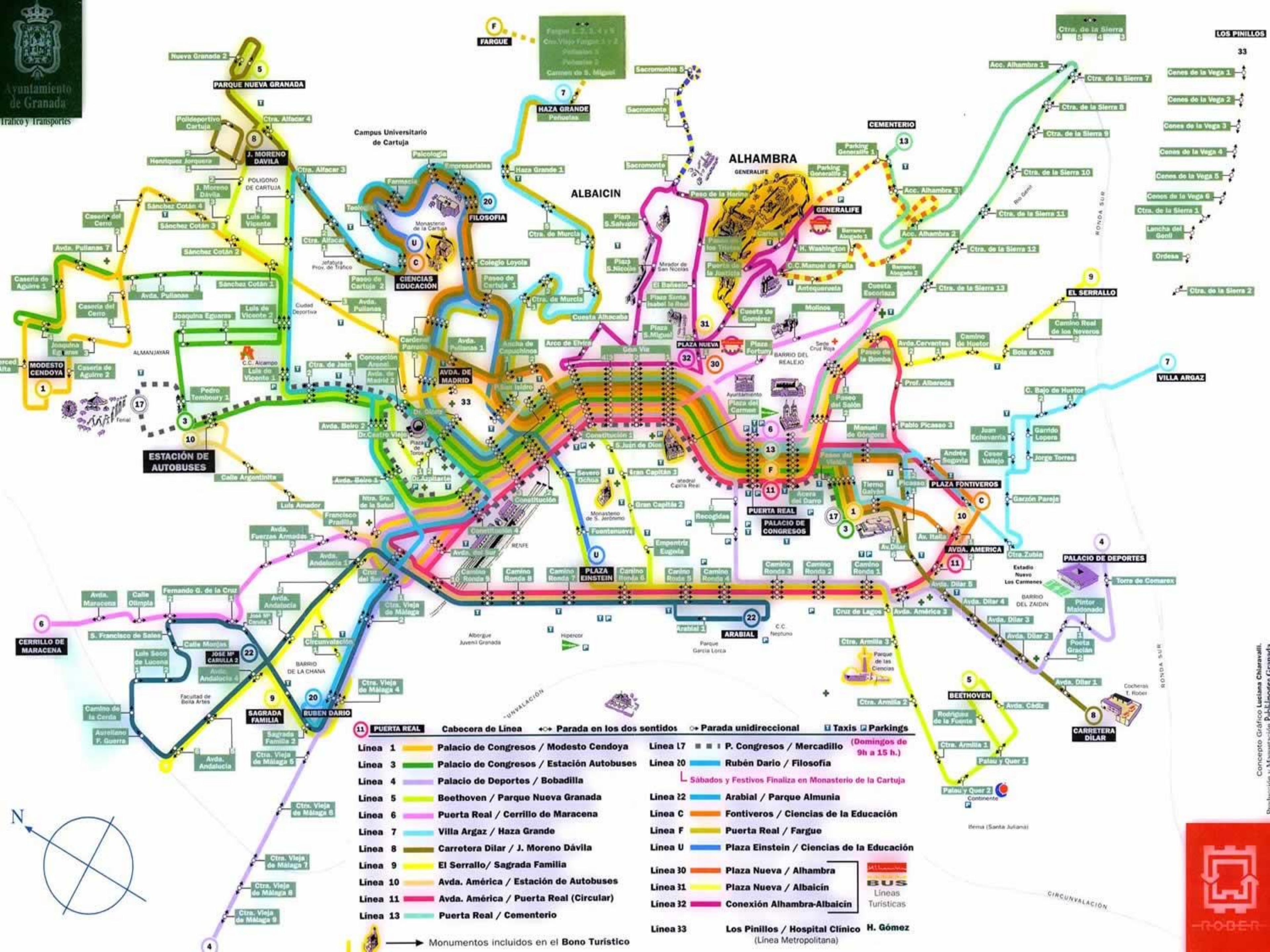
The elegant design fits easily into all street scenes and has won the approval of the Royal Fine Art Commission.

Most parts are reusable or recyclable thus minimising the impact on the environment.

The post is capable of accommodating cabling to support future developments such as electronic information systems and illumination.

Solar photovoltaic technology is being utilised to provide power for illuminating the timetable and bus stop sign.

1. Point letter
   Identifies the stop location at interchanges and town centres.
2. Bus stop flag
   The main recognisable road traffic sign for drivers and passengers.
3. Location name
4. Towards information
   General directional information
5. Route numbers
   Distinctive day and night services
6. Lightweight aluminium post
7. Timetable display cluster
   Available as single, double or triple sizes
8. Aggregate base
   Provide tactile indicator for the partially sighted and deflects pushchairs
9. O&D plate
   Origination and Destination survey plate
10. Stop number
    Unique bus stop asset number attached to underside of route display


Ayuntamiento de Granada
Tráfico y Transportes
FARGUE
HAZA GRANDE
Peñuelas
PARQUE NUEVA GRANADA
Nueva Granada 2
Campus Universitario de Cartuja
ALBAICIN
ALHAMBRA
GENERALIFE
CEMENTERIO
LOS PINILLOS
J. MORENO DAVILA
POLIGONO DE CARTUJA
CIENCIAS EDUCACIÓN
FILOSOFIA
Monasterio de la Cartuja
MODESTO CENDOYA
ALMANJAYAR
ESTACIÓN DE AUTOBUSES
AVDA. DE MADRID
PLAZA NUEVA
PUERTA REAL
PALACIO DE CONGRESOS
PLAZA FONTIVEROS
AVDA. AMERICA
PALACIO DE DEPORTES
EL SERRALLO
VILLA ARGAZ
PLAZA EINSTEIN
ARABIAL
CERRILLO DE MARACENA
SAGRADA FAMILIA
RUBEN DARIO
BARRIO DE LA CHANA
BEETHOVEN
CARRETERA DILAR
BARRIO DEL ZAIDIN
BARRIO DEL REALEJO
RENFE
RONDA SUR
CIRCUNVALACIÓN
PUERTA REAL Cabecera de Línea
Parada en los dos sentidos
Parada unidireccional
Taxis
Parkings
Línea 1 Palacio de Congresos / Modesto Cendoya
Línea 3 Palacio de Congresos / Estación Autobuses
Línea 4 Palacio de Deportes / Bobadilla
Línea 5 Beethoven / Parque Nueva Granada
Línea 6 Puerta Real / Cerrillo de Maracena
Línea 7 Villa Argaz / Haza Grande
Línea 8 Carretera Dilar / J. Moreno Dávila
Línea 9 El Serrallo/ Sagrada Familia
Línea 10 Avda. América / Estación de Autobuses
Línea 11 Avda. América / Puerta Real (Circular)
Línea 13 Puerta Real / Cementerio
Línea 17 P. Congresos / Mercadillo (Domingos de 9h a 15 h.)
Línea 20 Rubén Darío / Filosofía
Sábados y Festivos Finaliza en Monasterio de la Cartuja
Línea 22 Arabial / Parque Almunia
Línea C Fontiveros / Ciencias de la Educación
Línea F Puerta Real / Fargue
Línea U Plaza Einstein / Ciencias de la Educación
Línea 30 Plaza Nueva / Alhambra
Línea 31 Plaza Nueva / Albaicín
Línea 32 Conexión Alhambra-Albaicín
BUS Líneas Turísticas
Línea 33 Los Pinillos / Hospital Clínico H. Gómez
(Línea Metropolitana)
Monumentos incluidos en el Bono Turístico
Concepto Gráfico Luciana Chiaravalli
ROBER

Operating Characteristics
A. Service routes

<u>The factors that affect bus demand are:</u>

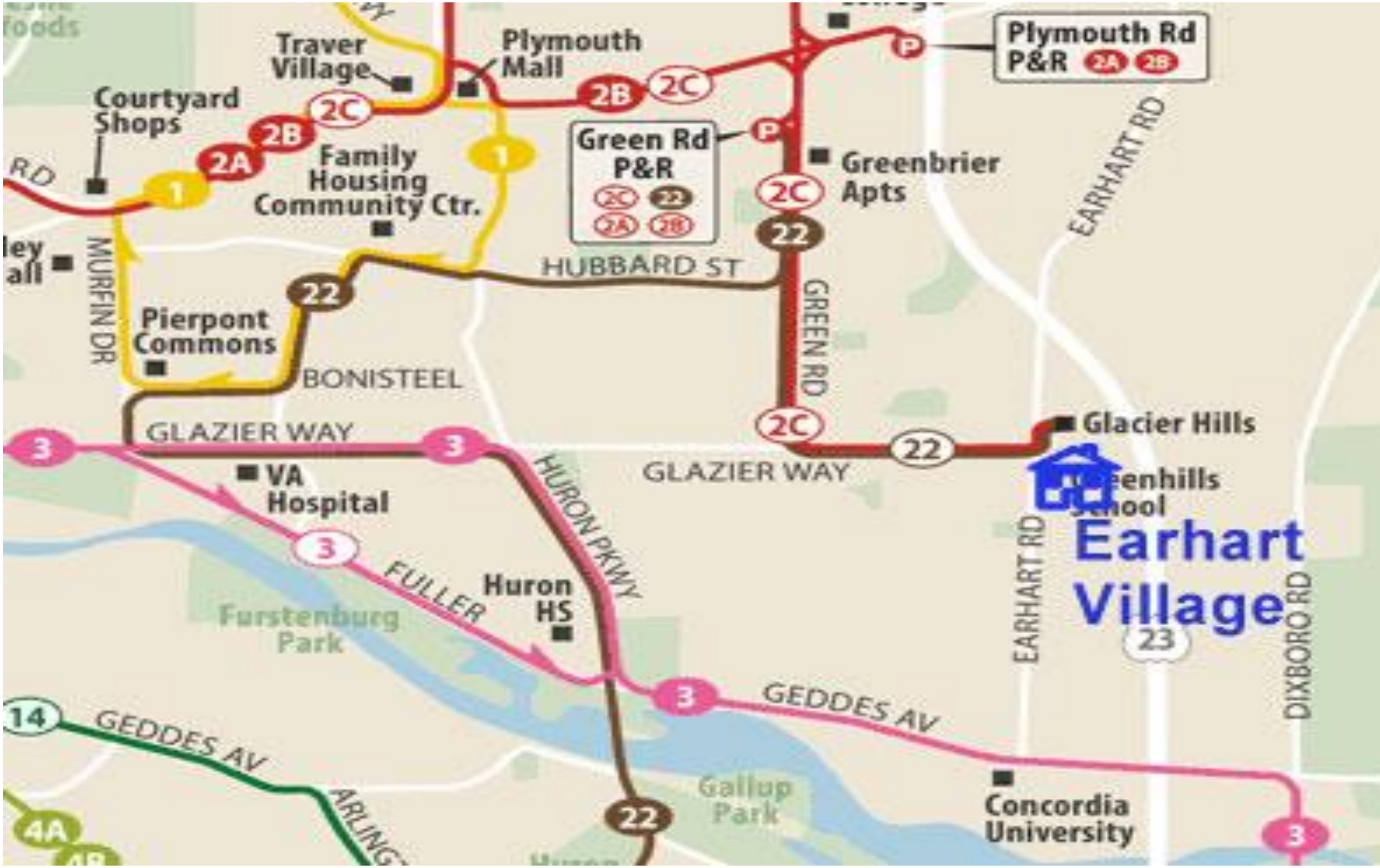
1. Density of residential areas
2. Non-residential areas size and density
3. Distance between residential and non-residential areas
4. Average auto ownership
5. Level of service of the bus system
6. Bus fares

The factors that affect the bus route configurations:

1. The overall system service
2. The geography of the area
3. Streets and highways available for bus use
4. Other competing transit services in the area

Route Layouts:

1. Radial
2. Circumferential
3. Grid


Traver Village
Plymouth Mall
Plymouth Rd P&R 2A 2B
Courtyard Shops
Family Housing Community Ctr.
Green Rd P&R
Greenbrier Apts
EARHART RD
HUBBARD ST
MURFIN DR
Pierpont Commons
BONISTEEL
GREEN RD
Glacier Hills
GLAZIER WAY
VA Hospital
HURON PKWY
Greenhills School
Earhart Village
FULLER
Huron HS
Furstenburg Park
DIXBORO RD
GEDDES AV
Gallup Park
Concordia University

B. Service Frequency

Frequency: $f = n / N$

f = frequency required (busses/hr)
n = demand for service (passenger/hr)
N = maximum number of passengers per bus (bus capacity)

Headway: $h = t_{da} + t_{db}$

h = minimum headway between buses in minutes

t_{da} = average dwell time for alighting in seconds

t_{db} = average dwell time for boarding in seconds

Dwell time = the total a mount of time a bus spends at a bus stop

$$t_{da} = aA + C \qquad \text{(for alighting only)}$$

$$t_{db} = bB + C \qquad \text{(for boarding only)}$$

a, b = average alighting, boarding service time per passenger in seconds

A, B = alighting, boarding passengers per bus in peak 10-15

C = Clearance time between successive buses in seconds

a = 1.5 – 2.5 seconds,

b = 2.5 – 3.5 seconds for fares collected by the driver

b = 1.5 – 2.5 seconds for fares collected before boarding

C = 15 seconds

C. Service Capacity

The factors that affect the capacity of a busway:

1. Roadway capacity
2. Bus station platform capacity
3. Headway
4. Vehicle capacity: determined by
   A. *Seating capacity (number of seats)*
   B. *Standing capacity (# of standees considering health/safety standards)*
   C. *Crash capacity (# of standees ignoring health/safety standards)*

$$C_t = C_a + z.C_b$$

$$R_c = 60\ C_t / h$$

C_t = total vehicle capacity
C_a = vehicle seating capacity
C_b= ultimate vehicle standing capacity
z = allowable fraction of ultimate vehicle standing capacity
R_c = maximum route capacity in passengers per hour
h = minimum headway in minutes

D. Scheduling

Where vehicle headways are greater than 10 minutes, the headway must be in 5 minute increments (15, 20, 25, 30, …)

Design of Land Transportation Terminals

- Terminals costs comprise a significant if not dominant portion of the total costs of transportation

- Inadequately designed terminal facility may cause inordinate delays to the movement of passengers or freight and ultimately may contribute to the failure of the system

- The physical features of land transportation terminals vary a great deal depending on:

  - **Transport mode**
  - **Type of commodity**
  - **Amount of traffic it serves**


wiseGEEK

MONCLOA
PictureWalking.com


Greyhound

Functions of Terminals

1. **Traffic concentration:** passengers arriving in continuous flows are grouped into batch movements; small shipment of freight are grouped in larger units for more efficient handling

2. **Processing:** includes ticketing, checking in, and baggage handling for passengers and preparation of waybills and other procedures for freight

3. **Classification and sorting:** passengers and freight units must be classified and sorted into groups according to destination and type of commodity

4. **Loading and unloading:** passengers and freight must be moved from waiting rooms, loading platforms, temporary storage areas, and the like to the transportation vehicle at the origin, and the process must be reversed at the destination

5. **Storage:** facilities for short-term such as waiting rooms for passengers and transit shed for freight commodities are required to permit loads to be assembled by concentration and classification

6. **Traffic interchange:** passengers and freight arriving at a terminal often are destined for another location and must transfer to a similar or different mode of travel to complete their journey

7. **Service availability:** terminals serve as an interface between the transport user and the carrier, making the transportation system and its services available to the shipper and travelling public

8. **Maintenance and servicing:** terminals often must include facilities for fueling, cleaning, inspection and repair of vehicles

Nature of the terminal planning process

The planner must design an optimum design:

Forecast the future level of activity at the terminal:

- – no. of passengers accommodated by terminal, their pattern and modes of arrival and departure and their needs while at terminal,
- – Volume of freight, classified by commodity type, patterns and modes of shipment to and from terminal

Forecasts can be based on historical data, empirical studies, and extrapolation of trends

- ➢ Forecasting for passengers' terminals, planners may need to perform surveys of parkers and travellers to determine current travel deficiencies and desires

- For freight terminals, assumed or known relationships between tonnage of freight and volume of wholesale or retail sales, gross regional product, or some GDP measurement

- It might be necessary for planners to perform special studies of vehicle arrival rates and times, loading and unloading rates, processing procedures, and work habits and rules

- **Usually terminals are deigned to provide for 5-10 years in the future**

Queuing theory

- We will discuss the most elementary applications of queuing theory to terminal planning

- Analysis of waiting lines or for studies of some component of more complex operations

Characteristics necessary of a queue:

1. Mean rate of arrivals and their probability distribution
2. Mean service rate and the probability distribution of the services
3. Number of channels or servers (e.g., truck loading spots, toll booths, etc.)
4. Queue discipline, the order in which arriving units will be served (FIFO, LIFO)

Waiting line:

Is referred to as being in a certain “state”, the queuing system is said to be in state (n) if there are (n) units (vehicles, people) in the system, including those being served.

State probabilities, indicating the fraction of time the system should operate with a specified number in the system, are useful in evaluating the effectiveness of various choices of terminal design features.

Other measures include: average no. of units in the system, average length of queue, and average time spent in the system.

why do queues form?

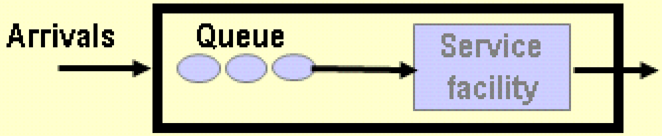
- Whenever demand arrival rate exceeds the service rate AND all the demand must be served.

- Note that what matters here is the timing of the arrivals. *E.g.*, if all people all arrive at the same time, there's going to be a long wait for some.

Queuing terminology and mechanisms:

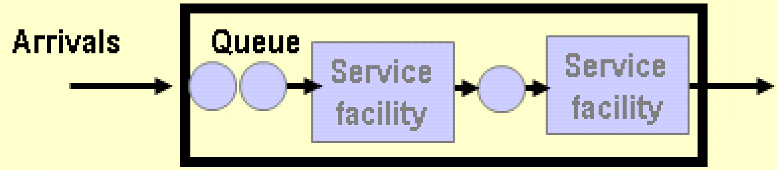
- **Queue:** waiting line.
- **Arrival:** the next person, machine, part, *etc*. that arrives and demands service.
- **Arrival rate:** number of arrivals per time interval (λ = mean arrival rate).
- **Inter-arrival time:** time between arrivals ($1 / \lambda$ = mean inter-arrival time)
- **Service rate:** number of customers or units served per time interval (μ = mean service rate (departure rate)).
- **Service time**: time it takes to execute the service ($1 / \mu$ = mean service time).
- **In the system**: arrivals in line or being worked on.
- **Phases:** number of steps in service for each arrival.
- **Channels:** number of servers.

Single-Channel, Single-Phase



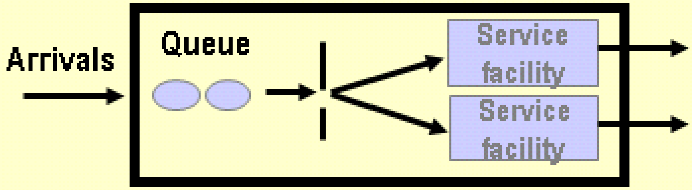
e.g., drive-through bank

Single-Channel, Multi-Phase



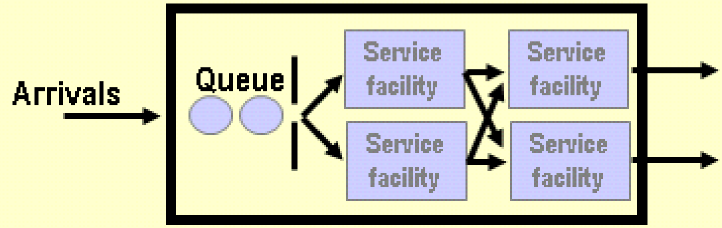
e.g., McDonald's drive-through

Multi-Channel, Single-Phase



e.g., U.S. Post Office

Multi-Channel, Multi-Phase



e.g., Suds & Suds Laundromat

- Arrival and service times are random variables. **Arrivals** **are discrete variables**, and **service times** **are continuous random variables**,

- It is often appropriate to describe units arriving at a terminal by a Poisson probability distribution:

$$P(n) = \frac{(\lambda t)^n e^{-\lambda t}}{n!}$$

- P(n): probability of n arrivals in a period t
- λ: mean arrival rate or volume
- E: Napierian logarithmic base

EXAMPLE 5.4

An observer counts 360 veh/h at a specific highway location. Assuming that the arrival of vehicles at this highway location is Poisson distributed, estimate the probabilities of having 0, 1, 2, 3, 4, and 5 or more vehicles arriving over a 20-second time interval.

SOLUTION

The average arrival rate, λ, is 360 veh/h, or 0.1 vehicles per second (veh/s). Using this in Eq. 5.23 with $t = 20$ seconds, the probabilities of having exactly 0, 1, 2, 3, and 4 vehicles arrive are

$$P(0) = \frac{(0.1 \times 20)^0 e^{-0.1(20)}}{0!} = \underline{\underline{0.135}}$$

$$P(1) = \frac{(0.1 \times 20)^1 e^{-0.1(20)}}{1!} = \underline{\underline{0.271}}$$

$$P(2) = \frac{(0.1 \times 20)^2 e^{-0.1(20)}}{2!} = \underline{\underline{0.271}}$$

$$P(3) = \frac{(0.1 \times 20)^3 e^{-0.1(20)}}{3!} = \underline{\underline{0.180}}$$

$$P(4) = \frac{(0.1 \times 20)^4 e^{-0.1(20)}}{4!} = \underline{\underline{0.090}}$$

For five or more vehicles,

$$\begin{aligned} P(n \geq 5) &= 1 - P(n < 5) \\ &= 1 - 0.135 - 0.271 - 0.271 - 0.180 - 0.090 \\ &= \underline{\underline{0.053}} \end{aligned}$$

A histogram of these probabilities is shown in Fig. 5.5.

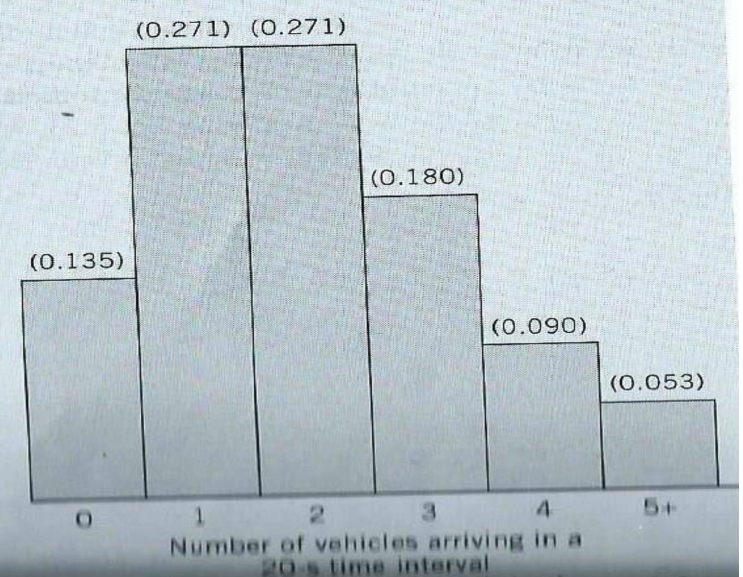


Figure 5.5 Histogram of the Poisson distribution for $\lambda = 0.1$ vehicles per

Traffic data are collected in 60-second intervals at a specific highway location as shown in Table 5.1. Assuming the traffic arrivals are Poisson distributed and continue at the same rate as that observed in the 15 time periods shown, what is the probability that six or more vehicles will arrive in each of the next three 60-second time intervals (12:15 P.M. to 12:16 P.M., 12:16 P.M. to 12:17 P.M., and 12:17 P.M. to 12:18 P.M.)?

Table 5.1 Observed Traffic Data for Example 5.5

Time period	Observed number of vehicles
12:00 P.M. to 12:01 P.M.	3
12:01 P.M. to 12:02 P.M.	5
12:02 P.M. to 12:03 P.M.	4
12:03 P.M. to 12:04 P.M.	10
12:04 P.M. to 12:05 P.M.	7
12:05 P.M. to 12:06 P.M.	4
12:06 P.M. to 12:07 P.M.	8
12:07 P.M. to 12:08 P.M.	11
12:08 P.M. to 12:09 P.M.	9
12:09 P.M. to 12:10 P.M.	5
12:10 P.M. to 12:11 P.M.	3
12:11 P.M. to 12:12 P.M.	10
12:12 P.M. to 12:13 P.M.	9
12:13 P.M. to 12:14 P.M.	7
12:14 P.M. to 12:15 P.M.	6

SOLUTION

Table 5.1 shows that a total of 101 vehicles arrive in the 15-minute period from 12:00 P.M. to 12:15 P.M. Thus the average arrival rate, λ, is 0.112 veh/s (101/900). As in Example 5.4, Eq. 5.23 is applied to find the probabilities of exactly 0, 1, 2, 3, 4, and 5 vehicles arriving.

Applying Eq. 5.23, with $\lambda = 0.112$ veh/s and $t = 60$ seconds, the probabilities of having 0, 1, 2, 3, 4, and 5 vehicles arriving in a 60-second time interval are (using $\lambda t = 6.733$)

$$P(0) = \frac{(6.733)^0 e^{-6.733}}{0!} = \underline{\underline{0.0012}}$$

$$P(1) = \frac{(6.733)^1 e^{-6.733}}{1!} = \underline{\underline{0.008}}$$

$$P(2) = \frac{(6.733)^2 e^{-6.733}}{2!} = \underline{\underline{0.027}}$$

$$P(3) = \frac{(6.733)^3 e^{-6.733}}{3!} = \underline{\underline{0.0606}}$$

$$P(4) = \frac{(6.733)^4 e^{-6.733}}{4!} = \underline{\underline{0.102}}$$

$$P(5) = \frac{(6.733)^5 e^{-6.733}}{5!} = \underline{\underline{0.137}}$$

The summation of these probabilities is the probability that 0 to 5 vehicles will arrive in any given 60-second time interval, which is

$$\begin{aligned} P(n \leq 5) &= \sum_{i=0}^{5} P(n) \\ &= 0.0012 + 0.008 + 0.027 + 0.0606 + 0.102 + 0.137 \\ &= 0.3358 \end{aligned}$$

So 1 minus $P(n \leq 5)$ is the probability that 6 or more vehicles will arrive in any 60-second time interval, which is

$$\begin{aligned} P(n \geq 6) &= 1 - P(n \leq 5) \\ &= 1 - 0.3358 \\ &= 0.6642 \end{aligned}$$

The probability that 6 or more vehicles will arrive in three successive time intervals (t_1, t_2, and t_3) is simply the product of probabilities, which is

$$\begin{aligned} P(n \geq 6) \text{ for three successive time periods} &= \prod_{t_i=1}^{3} P(n \geq 6) \\ &= (0.6642)^3 \\ &= \underline{\underline{0.293}} \end{aligned}$$

- The assumption of Poisson distributed vehicle arrivals also implies a distribution of the time intervals between the arrivals of successive vehicles (i.e., time headway)

Negative Exponential

- To demonstrate this, let the average arrival rate, λ, be in units of vehicles per second, so that

$$\lambda = \frac{q}{3600} \qquad \frac{\text{veh}/\cancel{\text{h}}}{\text{sec}/\cancel{\text{h}}} = \frac{\text{veh}}{\text{sec}}$$

- Substituting into Poisson equation yields

$$P(n) = \frac{\left(\frac{qt}{3600}\right)^n e^{\frac{-qt}{3600}}}{n!} \qquad \text{Eq. 1}$$

Negative Exponential

- Note that the probability of having no vehicles arrive in a time interval of length t [i.e., P (0)] is equivalent to the probability of a vehicle headway, h, being greater than or equal to the time interval t.

Negative Exponential

- So from Eq. 1,

$$P(0) = P(h \geq t) \qquad \text{(Eq. 2)}$$

$$= \frac{(1)e^{\frac{-qt}{3600}}}{1} = e^{\frac{-qt}{3600}}$$

Note:

$$x^0 = 1$$

$$0! = 1$$

This distribution of vehicle headways is known as the negative exponential distribution.

Negative Exponential Example

- Assume vehicle arrivals are Poisson distributed with an hourly traffic flow of 360 veh/h.

  1. Determine the probability that the headway between successive vehicles will be less than 8 seconds.

  2. Determine the probability that the headway between successive vehicles will be between 8 and 11 seconds.

- By definition,

$$P(h < t) = 1 - P(h \geq t)$$

$$P(h < 8) = 1 - P(h \geq 8)$$

$$P(h < 8) = 1 - e^{-qt/3600}$$

$$= 1 - e^{-360(8)/3600}$$

$$= 1 - 0.4493$$

$$= 0.551$$

$$
\begin{aligned}
P(8 \le h < 11) &= P(h < 11) - P(h < 8) \\
&= 1 - P(h \ge 11) - P(h < 8) \\
&= 1 - e^{-360(11)/3600} - 0.551 \\
&= 1 - 0.3329 - 0.551 \\
&= 0.1161
\end{aligned}
$$

Dimensions of Queuing Models

- **Dimensions of queuing models are:**

- arrival patterns
- Departure (service) patterns
- queuing discipline

- **Arrival patterns** (λ, in vehicles per unit time):
  - equal time intervals (derived from the assumption of uniform, deterministic arrivals) and
  - exponentially distributed time intervals (derived from the assumption of Poisson-distributed arrivals).
-
- **Departure patterns** (μ, in vehicles per unit time),
  - equal time intervals (derived from the assumption of uniform, deterministic arrivals) and
  - exponentially distributed time intervals (derived from the assumption of Poisson-distributed arrivals).

- **Queuing discipline**

    - first-in-first-out (FIFO), indicating that the first vehicle to arrive is the first vehicle to depart, and

    - last-in-first-out (LIFO), indicating that the last vehicle to arrive is the first to depart.

-
    – For virtually all traffic-oriented queues, the FIFO queuing discipline is the more appropriate of the two.

Queue Notation

Arrival rate nature

Number of service channels

$$X\,/\,Y\,/\,N$$

Departure rate nature

- Popular notations:
  - D/D/1, M/D/1, M/M/1, M/M/N
  - D = deterministic
  - M = some distribution

Procedure applicable when:

- Poisson arrivals
- Negative exponential service times
- First-come
- First served queue discipline
- No limitation on the length of the queue
- Steady-state conditions (do not apply for the conditions where the arrival rate exceeds the service rate)

M/*M*/1 Queuing

- exponentially distributed departure time patterns in addition to exponentially distributed arrival times (an *M*/*M*/1 queue).

- Toll booth where some arriving drivers have the correct toll and can be processed quickly, and others may not have the correct toll, thus producing a distribution of departures about some mean departure rate.

- Under standard *M*/*M*/1 assumptions, it can be shown that the following queuing performance equations apply (assuming ρ that is less than 1),


SUNPASS
EXACT COINS
SUNPASS
ONLY
SPEED LIMIT 25
DO NOT STOP
MPH

- Traffic intensity: the ratio of average arrival to departure rate,

$$\rho = \frac{\lambda}{\mu}$$

ρ: traffic intensity

λ: average arrival rate in units per unit time

μ: average departure rate in units per unit time

$$\overline{Q} = \frac{\rho^2}{1-\rho}$$

$$\overline{w} = \frac{\lambda}{\mu(\mu-\lambda)}$$

$$\bar{t} = \frac{1}{\mu-\lambda}$$

Where:

$\overline{Q}$ = average length of queue in vehicles,

$\overline{w}$ = average waiting time in the queue (for each vehicle),

$\bar{t}$ = average time spent in the system (the summation of average queue waiting time and average departure time),

λ = average arrival rate,

μ = average departure rate, and

ρ = traffic intensity (λ/μ).

Example

Assume:

Service time: 15 sec/veh,

Arrival rate =180 veh/h

Compute the average time spent in the system assuming M/M/1 queuing?

$$\lambda = \frac{180}{60} = 3veh/\min$$

$$\mu = \frac{60s/\min}{15s/veh} = 4\min/veh$$

$$\rho = \frac{\lambda}{\mu} = \frac{3}{4} = 0.75$$

- The average length of queue:

$$\overline{Q} = \frac{\rho^2}{1-\rho}$$

- Average waiting time in queue:

$$\overline{Q} = \frac{0.75^2}{1-0.75} = 2.25 veh$$

$$\overline{w} = \frac{\lambda}{\mu(\mu-\lambda)}$$

$$\overline{w} = \frac{3}{4(4-3)} = 0.75 \text{ min}/veh$$

- average time spent in the system:

$$\bar{t} = \frac{1}{\mu-\lambda}$$

$$\bar{t} = \frac{1}{4-3} = 1 \text{ min}$$

M/*M*/*N* Queuing

- *M*/*M*/*N* queuing is a reasonable assumption at toll booths on turnpikes or at toll bridges where there is often more than one departure channel available (more than one toll booth open).

- *M*/*M*/*N* queuing is also frequently encountered in non-transportation applications such as checkout lines at retail stores, security checks at airports, and so on.

- Unlike the equations for *M*/*M*/1, which require traffic intensity, ρ , be less than 1**,** the following equations allow ρ to be greater than 1 but apply only when ρ/N (which is called the utilization factor) is less than 1.


tag
reader
traffic
monitoring camera
E-ZPass
tag
5
MPH
traffic
gate
REDUCE
SPEED
PASS
traffic
information display
The E-ZPass Process
©2001 HowStuffWorks


PREPAID TOLLS
ONLY
E-PASS
PAY
TOLL
CASH LANES


CASH
ONLY
CASH
ONLY
CASH
ONLY

- probability of having no vehicles in the system (with
n_c = departure channel number, N = number of departure channels,),

$$P_0 = \frac{1}{\sum_{n_c=0}^{N-1} \frac{\rho^{n_c}}{n_c!} + \frac{\rho^N}{N!(1-\rho/N)}}$$

- probability of having *n* vehicles in the system,

$$P_n = \frac{\rho^n P_0}{n!} \qquad \text{for } n < N$$

$$P_n = \frac{\rho^n P_0}{N^{n-N} N!} \qquad \text{for } n \geq N$$

- probability of waiting in a queue (the probability that the number of vehicles in the system is greater than the number of departure channels),

$$P_{n>N} = \frac{P_0\,\rho^{N+1}}{N!\,N\left(1-\rho/N\right)}$$

As before ρ = traffic intensity (λ/μ).

- average length of queue (in vehicles),

$$\overline{Q} = \frac{P_0\, \rho^{N+1}}{N!\,N}\left[\frac{1}{\left(1-\rho/N\right)^2}\right]$$

- average waiting time in the queue,

$$\overline{w} = \frac{\rho + \overline{Q}}{\lambda} - \frac{1}{\mu}$$

- average time spent in the system,

$$\bar{t} = \frac{\rho + \overline{Q}}{\lambda}$$

Example

- At an enterance of a toll bridge, 4 toll booths are open.
- Arrivals rate=1200veh/h
- Departure rate= 10 sec/veh
- Arrivals and departures are exponentially distributed

- How would Average queue length, time in the system, and probability of waiting in a queue change if a fifth toll booth were opened?

- μ= 6veh/min, λ= 20 veh/min, ρ= 3.333, ρ/N= 0.833 (less than 1), M/M/N equations can be used:

- The probability of having no vehicles in the system with 4 booths open:

$$P_0 = \frac{1}{\sum_{n_c=0}^{N-1} \frac{\rho^{n_c}}{n_c!} + \frac{\rho^N}{N!(1-\rho/N)}}$$

$$P_0 = \frac{1}{1+\frac{3.333}{1!}+\frac{3.333^2}{2!}+\frac{3.333^3}{3!}+\frac{3.333^4}{4!(0.1667)}} == 0.0213$$

- The average queue length is:

$$\overline{Q} = \frac{P_0 \, \rho^{N+1}}{N!\,N}\left[\frac{1}{(1-\rho/N)^2}\right]$$

$$\overline{Q} = \frac{0.0213(3.333)^5}{4!4}\left[\frac{1}{(0.1667)^2}\right] = 3.287\,veh$$

- The average time spent in the system is:

$$\bar{t} = \frac{\rho + \overline{Q}}{\lambda}$$

$$\bar{t} = \frac{3.333 + 3.287}{20} = 0.331\,\mathbf{min}/\boldsymbol{veh}$$

- The probability of having to wait in a queue is:

$$P_{n>N} = \frac{P_0 \, \rho^{N+1}}{N! \, N\left(1 - \rho / N\right)}$$

$$\boldsymbol{P_{n>N}} = \frac{0.0213 \; (3.333)^5}{4!4\left(0.1667\right)} = 0.548$$

- With a fifth booth, the probability of having no vehicles in the system is:

$$P_0 = \frac{1}{1 + \frac{3.333}{1!} + \frac{3.333^2}{2!} + \frac{3.333^3}{3!} + \frac{3.333^4}{4!} + \frac{3.333^5}{5!}} = 0.0318$$

- The average queue length is:

$$\bar{Q} = \frac{0.0318(3.333)^6}{5!5}\left[\frac{1}{(0.333)^2}\right] = 0.654\,veh$$

- The average time spent in the system is:

$$\bar{t} = \frac{3.333 + 0.654}{20} = 0.199\ \mathrm{min}/veh$$

- The probabilty of having to wait in a queue is:

$$P_{n>N} = \frac{0.0318\ (3.333)^{6}}{5!5(0.333)} = 0.218$$

- A fifth booth will reduce the average queye length, average time in the system, and probability of waiting in a queue

A convenience store has four available parking spaces. The owner predicts that the duration of customer shopping (the time that a customer's vehicle will occupy a parking space) is exponentially distributed with a mean of 6 minutes. The owner knows that in the busiest hour customer arrivals are exponentially distributed with a mean arrival rate of 20 customers per hour. What is the probability that a customer will not find an open parking space when arriving at the store?

SOLUTION

Putting mean arrival and departure rates in common units gives μ = 10 veh/h and λ = 20 veh/h. So $\rho = 2.0$, and because $\rho/N = 0.5$ (which is less than 1), Eqs. 5.34 to 5.40 can be used. The probability of having no vehicles in the system with four parking spaces available (using Eq. 5.34) is

$$P_0 = \frac{1}{1 + \frac{2}{1!} + \frac{2^2}{2!} + \frac{2^3}{3!} + \frac{2^4}{4!(0.5)}}$$
$$= 0.1304$$

Thus the probability of not finding an open parking space upon arrival is (from Eq. 5.37)

$$P_{n>N} = \frac{0.1304(2)^5}{4!4(0.5)}$$
$$= \underline{0.087}$$

Terminal design control and criteria

Automobile Parking facilities

- Every person starts and ends his trip as a pedestrian. With the exception of drive-through facilities
- Major activity centers, from regional shopping malls to sports facilities to airports, rely on significant parking supply to provide site accessibility
- The economic survival of most activity centers, therefore, is directly related to parking and other forms of access
- However, parking supply must be balanced with other forms of:
  - **access (public transportation),**
  - **the traffic conditions created by such access, and**
  - **the general environment of the activity center**

Parking generation and supply

- **Parking generation:**

Parking generation relates to the maximum observed number of occupied parking spaces to one underlying variable that is used as a surrogate for the size or activity level of land use involved

Preferred and alternative variables for establishing parking generation rates are listed in Table 12.1

Also, a summary of parking generation rates and relationships, is shown in Table 12.2

Table 12.1 Typical Parking Generation Specification Units

Table 12.1: Typical Parking Generation Specification Units

Type of Land Use	Parking-Related Unit	
	Preferred	**Alternate**
Single-Family Residential	Per Dwelling Unit	Per Dwelling Unit with range by number of bedrooms
Apartment Residential	Per Dwelling Unit with range by number of bedrooms	Per Dwelling Unit
Shopping Center	Per 1,000 sq ft GLA*	N/A
Other Retail	Per 1,000 sq ft GFA**	N/A
Office	Per Employee	Per 1,000 sq ft GFA**
Industrial	Per Employee	Per 1,000 sq ft GFA**
Hospital	Per Employee	Per Bed
Medical/Dental	Per Doctor	Per Office
Nursing Home	Per Employee	Per Bed
Hotel/Motel	Per Unit	N/A
Restaurant	Per Seat	Per 1,000 sq ft GFA**
Bank	Per 1,000 sq ft GFA**	N/A
Public Assembly	Per Seat	N/A
Bowling Alley	Per Lane	Per 1,000 sq ft GFA**
Library	Per 1,000 sq ft GFA**	N/A

*GLA = gross leaseable area.

**GFA = gross floor area.

(*Source:* Used with permission of Transportation Research Board, "Parking Principles," *Special Report 125*, Washington DC, 1971, Table 3-1, p. 34.)

Table 12.2 Typical Parking Generation Rates

Table 12.2: Typical Parking Generation Rates

Land Use*	Avg Rate	Per	Equation†	R^2	No. of Studies
Residential—Low/Mid-Rise Apartment (Wkdy)	1.20	Dwelling Unit	$P = 1.43\,X - 46.0$	0.93	19
Residential—High-Rise Apartment (Wkdy)	1.37	Dwelling Unit	$P = 1.04\,X + 130.0$	0.85	7
Residential—Condominium/Townhouse (Wkdy)	1.46	Dwelling Unit	$P = 96.8\,\text{Ln}\,X - 272$	0.90	32
Hotel (Wkdy)	0.91	Room	$P = 1.13\,X - 60$	0.75	14
Motel (Wkdy)	0.90	Room	$P = 1.03\,X - 24$	0.76	5
Resort Hotel (Wkdy)	1.42	Room	N/A	N/A	3
Industrial—Light (Wkdy)	0.75	1,000 sq ft GFA	$P = 0.61\,X + 6$	0.81	7
Industry—Industrial Park (Wkdy)	1.27	1,000 sq ft GFA	$P = 0.76\,X + 26$	0.66	8
Industry—Warehousing (Wkdy)	0.41	1,000 sq ft GFA	$P = 0.41\,X - 5$	0.87	13
Medical—Urban Hospital (Wkdy)	1.47	Bed	N/A	N/A	23
Medical—Clinic (Wkdy)	4.33	1,000 sq ft GFA	$P = 4.24\,X + 1$	0.99	6

Table 12.2 (continued) Typical Parking Generation Rates

Office—Office Building (Wkdy)	2.84	1,000 sq ft GFA	$P = 2.51X + 27$	0.91	173
Shopping—Shopping Center (Sat-December)	4.74	1,000 sq ft GLA	$P = 4.59X + 140$	0.84	82
Restaurant—Quality Restaurant (Sat)	17.20	1,000 sq ft GFA	N/A	N/A	7
Restaurant—Urban Family Restaurant	10.1	1,000 sq ft GFA	N/A	N/A	21
Recreation—Movie Theater (Sat)	0.26	Seat	$P = 0.60X - 542$	0.65	6
Recreation—Health/Fitness Club (Wkdy)	5.19	1,000 sq ft GFA	$P = 3.62X + 27$	0.61	20
Religion—Church or Synagogue (Sat/Sun)	7.81	1,000 sq ft GFA	N/A	N/A	11

*Parking generation shown for peak day of the week.

†P = peak number of parking spaces occupied; X = appropriate underlying variable shown in the Per column.

(*Source:* Compiled from "Parking Generation," 3rd Edition, Institute of Transportation Engineers, Washington DC, 2004.)

- Consider the case of a small office building, consisting of 25000 square feet of office spaces. What is the peak parking load expected to be at this facility?

  - Using Table 12.2→ for office buildings:

  - the average peak parking occupancy is 2.84 per thousand square feet of building area, or in this case: 2.84*25=71 parking spaces.

  - A more precise estimate might be obtained using the equation related to facility size:

  - $P=2.51X+27=(2.51*25)+27=90$ spaces

  - This presents a significant range to the engineer (71-90 parking spaces needed). Thus, this guideline can provide some insight into parking needs, it is important to do localized studies of parking generation to augment national norms

- A more detailed model for predicting peak parking needs may be used.

- Peak parking demand supply may be estimated as:

$$D = \frac{NKRP * pr}{O}$$

D: Parking demand, spaces

N: size of activity measured in appropriate units (floor area, employment, dwelling units, or other appropriate land-use parameters)

K: portion of destinations that occur at any one time,

R: person-destinations per day (or other time period) per unit of activity

P: proportion of people arriving by car

O: average auto occupancy

pr: proportion of persons with primary destination at the designated study location

- Consider the case of a 400000 sq-ft retail shopping center in the heart of a central business district (CBD). The following estimates have been made:

- Approximately 40% of all shoppers are in the CBD for other reasons (pr= 0.60)

- Approximately 70% of shoppers travel to the retail center by automobile (P=0.70)

- Approximately total activity at the center is estimated to be 45 person-destinations per 1000 sq-ft of gross leasable area, of which 20% occur during the peak parking accumulation period (R=45; K= 0.20)

- The average auto occupancy of travelers to the shopping center is 1.5 persons per car (O=1.5)

Because the unit size is 1000 sq-ft of gross leasable area, N= 400.

$$D = \frac{400 * 45 * 0.20 * 0.70 * 0.60}{1.5} = 1008\, parking\ spaces$$

Which is equivalent to 1008/400=2.52 space per 1000 of GLA

Handicapped spaces

- in any parking facility, handicapped spaces must be provided by laws. Such standards affect both the number of spaces that must be required and their location.

- The Institute of Transportation Engineers recommends the following minimum standards for provision of handicapped spaces:

  - Office-0.02 spaces per 1000 sq-ft of GFA
  - Bank-1-2 spaces per bank
  - Retail (<500,000 sq-ft GFA) - 0.075 spaces per 1000 sq-ft
  - Retail (>= 500,000 sq-ft GFA) - 0.060 spaces per 1000 sq-ft

  - In all cases, there is an effective minimum of **ONE** handicapped space

Parking studies and characteristics

- A number of characteristics of parkers and parking have a significant influence on planning.

- Critical to parking supply needs are the:
  - duration,
  - accumulation, and
  - proximity requirements of parkers.

- If parking capacity is thought of in terms of “space-hours”, then vehicles parked for a longer duration consume more of that capacity than vehicles parked for only short period.

- The goal is to provide enough parking spaces to accommodate the maximum accumulation on a typical day.

1. Proximity: how far will parkers walk?

- The willingness of parkers to walk certain distances to (or from) their destination to their car must be well understood because it will have a significant influence over where parking capacity must be provided.

- Under any condition, drivers tend to seek parking spaces as close as possible to their destination.

- Even in cities of large population (1-2 million), 75% of drivers park within a 0.25 mile (400 m) of their final destination.

- Table 12.5 shows the distribution of walking distances between parking places and final destinations in urban areas.

Table 12.5 CBD Walking Distances to Parking Spaces

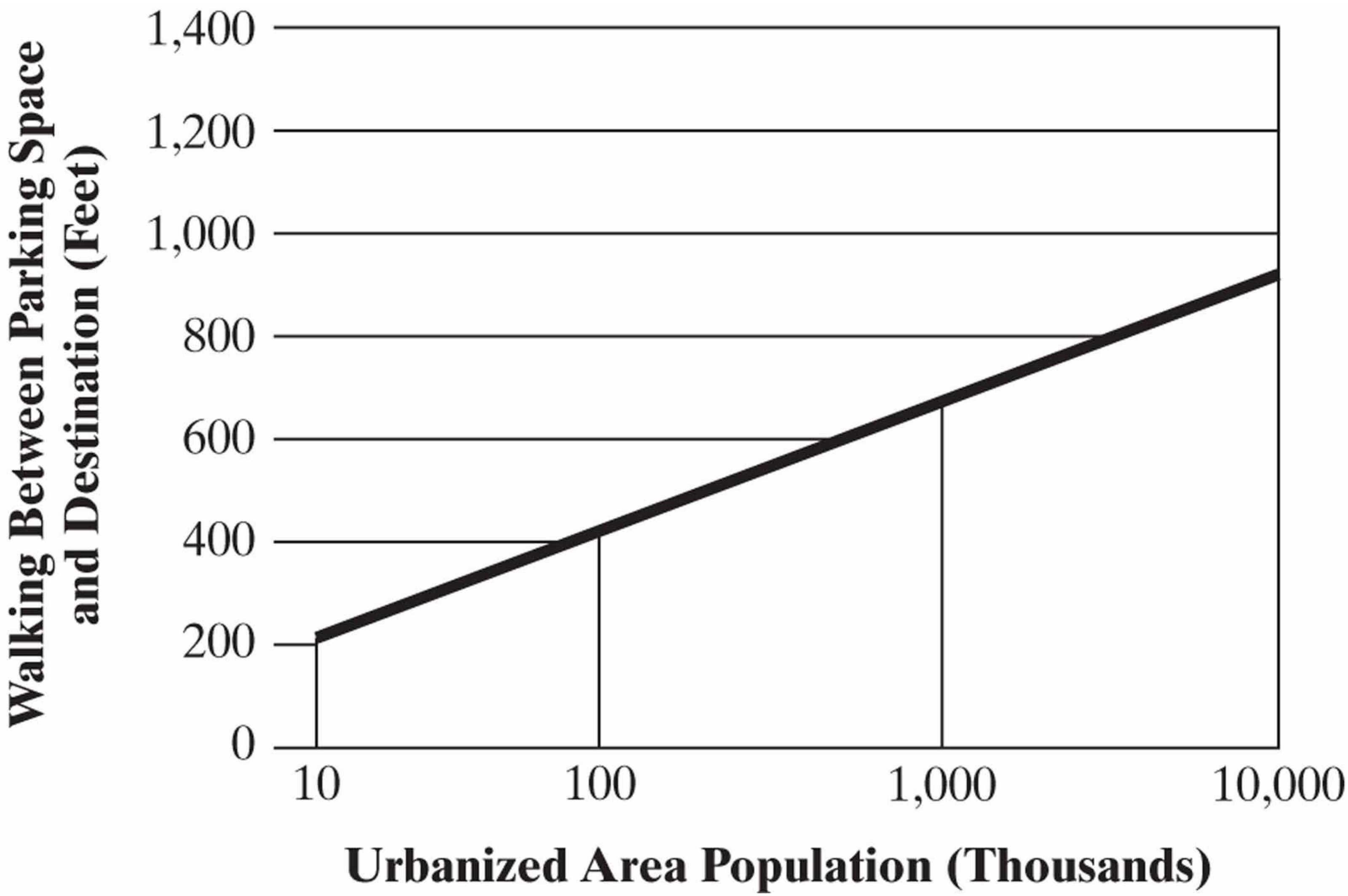
Table 12.5: CBD Walking Distances to Parking Spaced

Distance		% Walking This Distance or Further	
Feet	Miles	Mean	Range
0	0	100	
250	0.05	70	60–80
500	0.10	50	40–60
750	0.14	35	25–45
1,000	0.19	27	17–37
1,500	0.28	16	8–24
2,000	0.38	10	5–15
3,000	0.57	4	0–8
4,000	0.76	3	0–6
5,000+	0.95+	1	0–2

(*Source:* Used with permission of Eno Foundation for Transportation, Weant, R., and Levinson, H., *Parking*, Westport CT, 1990, Table 6-3, p. 98.)

50% of all drivers park within 500 ft (160m) of their destination

Figure 12.1 Average Walking Distance by Urbanized Area Population (*Source:* Used with permission of Eno Foundation for Transportation, Weant, R., and Levinson, H., *Parking,* Westport CT, 1990, Fig. 6.5, p. 98.)



- The data in the table emphasize the need to place parking capacity in close proximity to their destination(s) served.

- Even in an urban region of over 10 million population, the average walking distance to a parking place approximately is 900 feet (274 m).

- Trip purpose and trip duration affect the walking distance:

- **Short walking distance are sought when:**
  - shopping or trips where things must be carried
  - For short term parking, to get a food order
  - Drivers will not walk 10 minutes if they are going to be parked for 5 minutes

2. Parking inventories

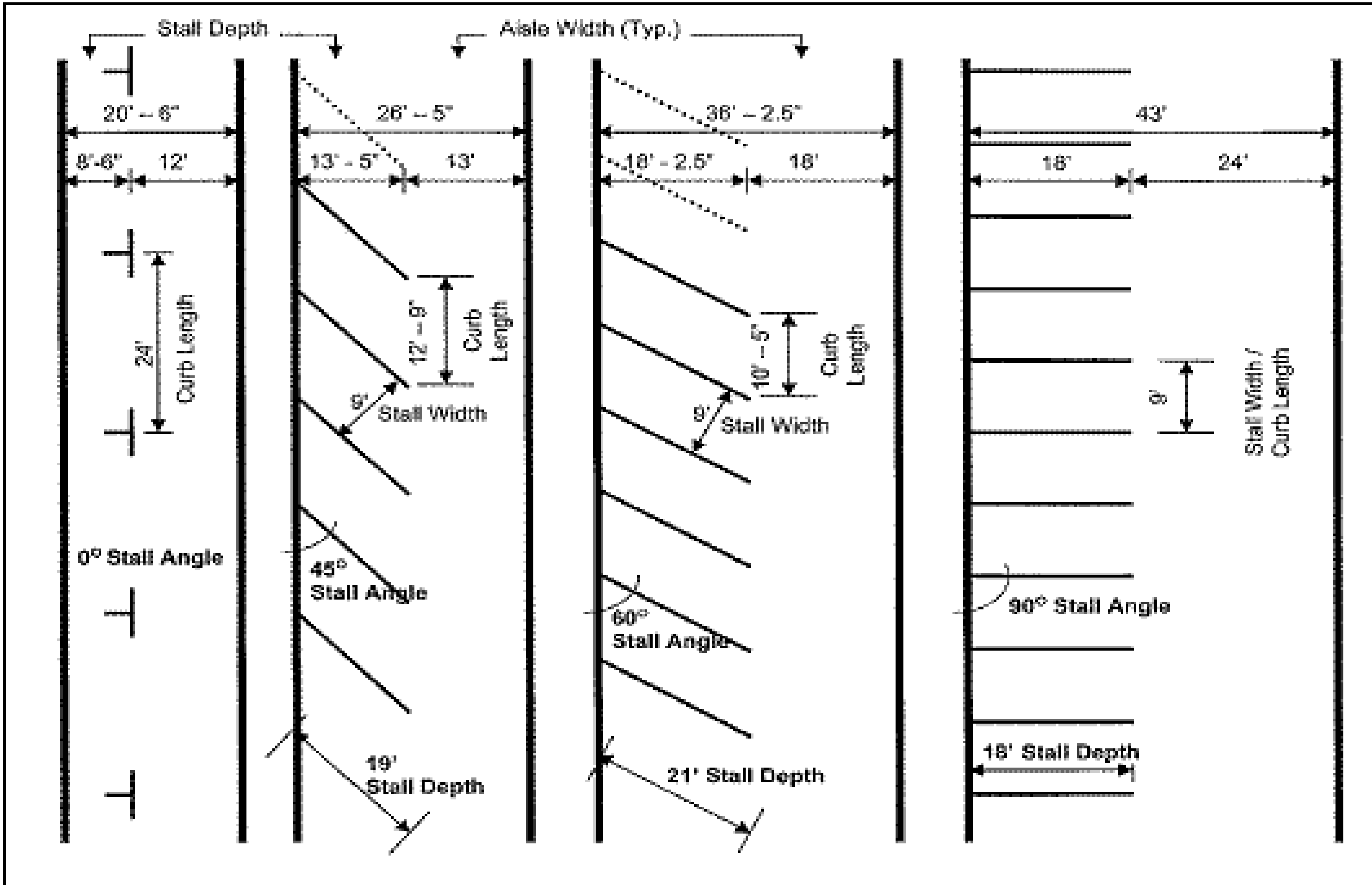
- Inventories include observations of the **number of parking spaces** and **their location**, **time restrictions** on use of parking spaces, and the **type of parking facility** (e.g., on-street, off-street lot, off-street garage)

- To facilitate the recording of parking locations, the study area is usually mapped and pre-coded in a systematic fashion. Figure 12.2 illustrate a simple coding system for blocks and block faces. Figure 12.3 illustrates the field sheets that would be used by observers.

- **Curb parking** places are subdivided by **parking restrictions** **and** **meter duration limits**

- Curb lengths are used to estimate the number of available parking spaces (when curb spaces are not clearly marked), using:

  - Parallel parking: **23 ft/stall**
  - Angle parking: **12 ft/stall**
  - 90-degree parking: **9.5 ft/stall**



Parking Space and Aisle Dimensions.

[South Pasadena Municipal Code]

Figure 12.2 Illustrative System for Parking Location Coding (*Source:* Used with permission of Institute of Transportation Engineers, Box, P., and Oppenlander, J., *Manual of Traffic Engineering Studies,* 4th Edition, Washington DC, 1976, Figs. 10-1 and 10-2, p. 131.)

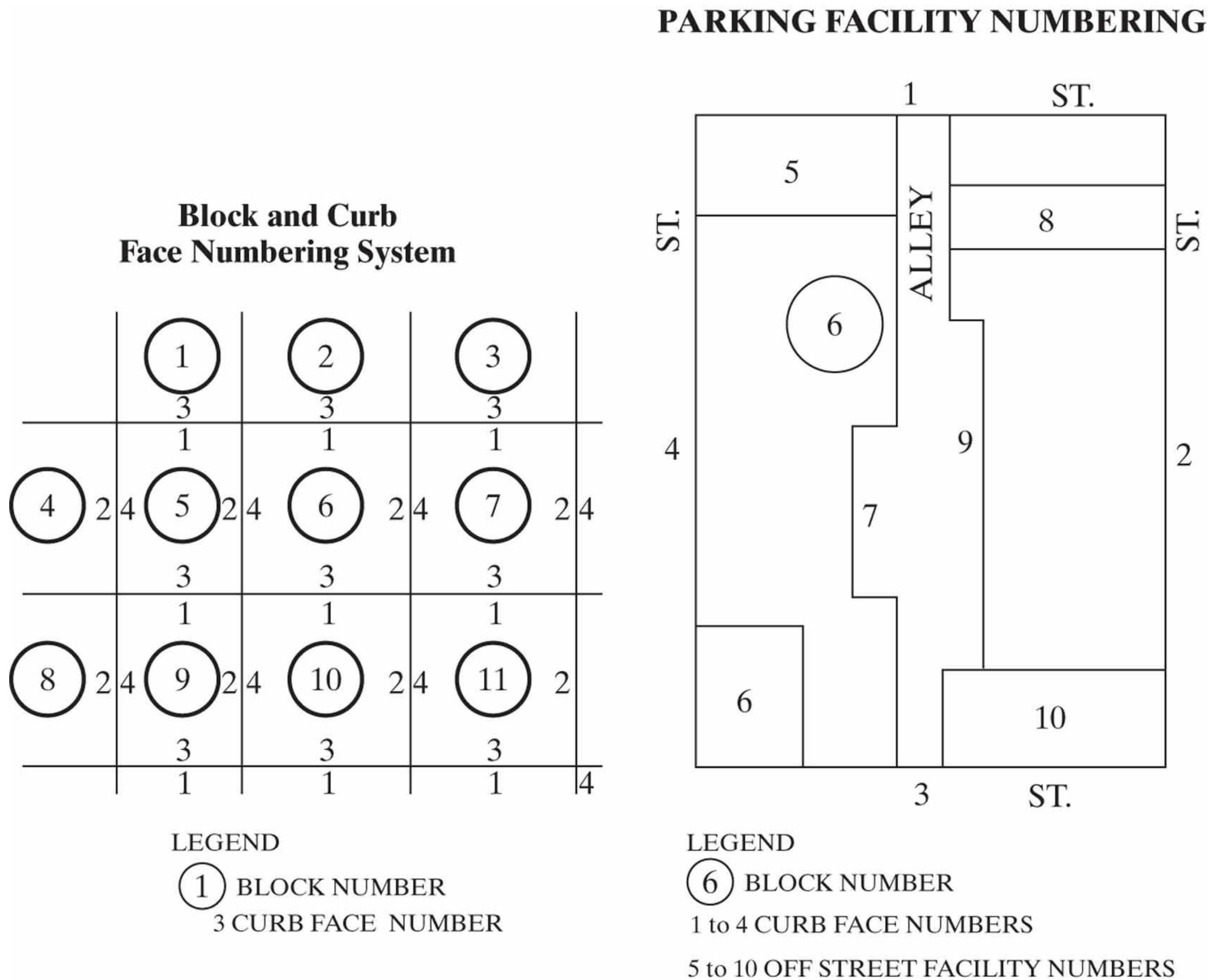


Figure 12.3 A Parking Inventory Field Sheet (*Source:* Used with permission of Institute of Transportation Engineers, Box, P., and Oppenlander, J., *Manual of Traffic Engineering Studies,* 4th Edition, Washington DC, 1976, Fig. 10-3, p. 133.)

AREA OF INVENTORY ______________________________

DATE OF INVENTORY ______________________________

BLOCK	FACILITY	STREET AND ALLEY STALLS						OFF-STREET PARKING		TOTAL STALLS
								PRIVATE	PUBLIC	

DATE ______________ COMPILED BY ______________________________

- Parking inventory basically counts the number of spaces available during some period of interest- often **8 to 11 hour business day**.

- However, parking supply evaluations must take into account **regulatory** and **time restrictions** on those spaces and the **average parking duration** for the area.

- Total **parking supply** can be measured in terms of **how many vehicles can be parked during the period of interest within the study area**:

$$P = \left(\frac{\sum_n NT}{D} \right) * F$$

P= parking supply, vehs

N= no. of spaces of a given type and time restriction

T= time that N spaces of a given type and time restriction are available during the study period, hrs

D= average parking duration during the study period, hrs/veh

F= insufficiency factor to account for turnover- values range from 0.85 to 0.95 and increases as average duration increases

Example:

A 12-hour study of an area revealed that there were 450 spaces available for the full 12 hours, 280 spaces available for 6 hours, 150 spaces available for 7 hours, and 100 spaces available for 5 hours.

The average parking duration in the area was 1.4 hours.

Insufficiency factor=0.90

Parking supply is computed as:

$$P = \left(\frac{[(450 * 12) + (280 * 6) + (150 * 7) + (100 * 5)]}{1.4}\right) * 0.9 = 5548 \text{ vehs}$$

This means that 5548 vehicles could be parked in the study area over 12-hour period of the study.

It does not mean that 5548 vehicles could be parked at the same time,

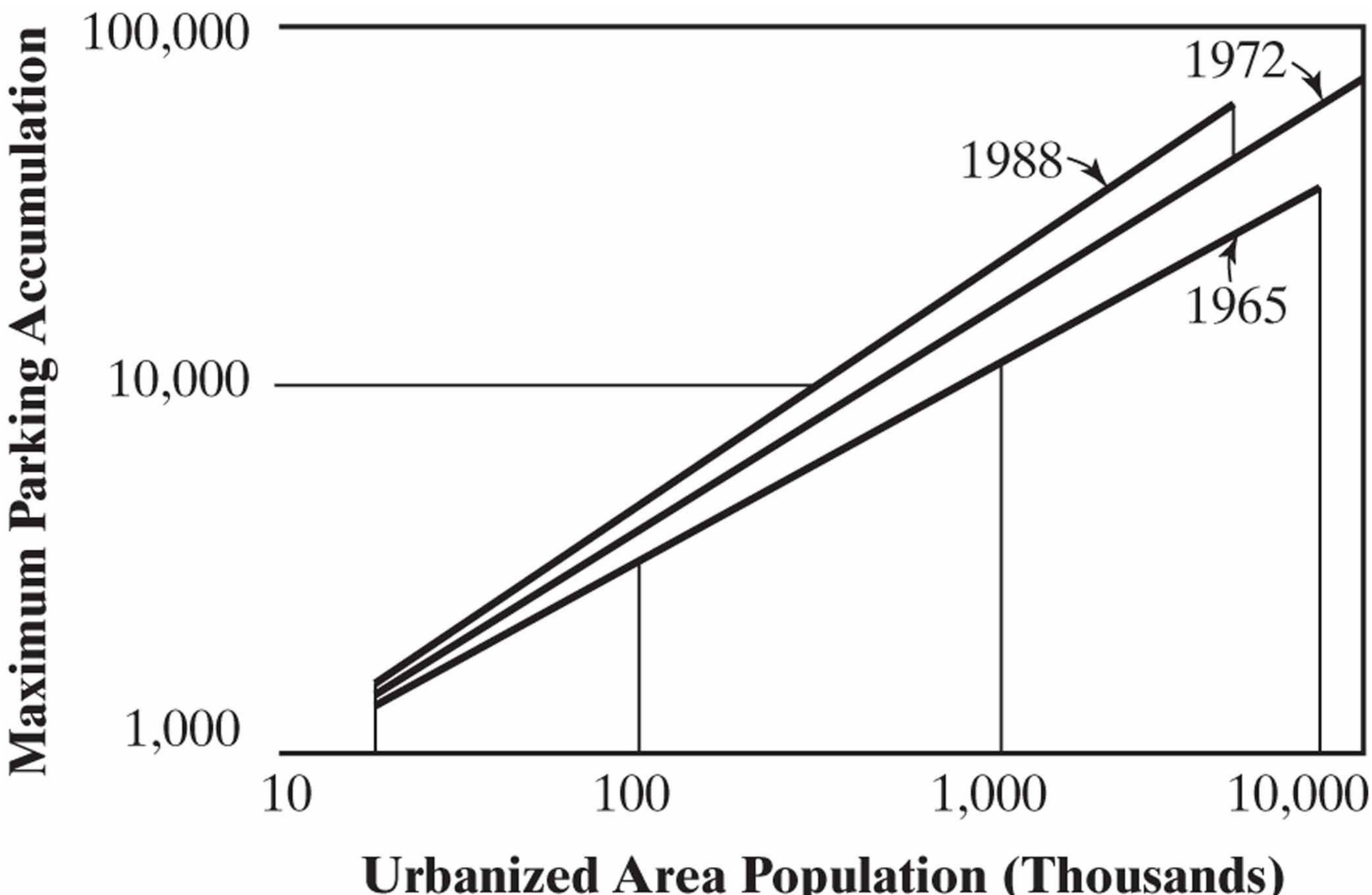
3. Accumulation and duration

- Parking accumulation is defined as the total number of vehicles parked at any given time.

- Many parking studies seek to establish the distribution of parking accumulation over time to determine the peak parking accumulation and when it occurs.

- Total accumulation in an urban area is strongly related to the urbanized area population, figure 12.4

Figure 12.4 Parking Accumulation in Urbanized Areas by Population (*Source:* Used with permission of Eno Foundation for Transportation, Weant, R., and Levinson, H., *Parking,* Westport CT, 1990, Fig. 6.8, p. 100.)



- Parking duration is the length of time that individual vehicles remain parked. It is a distribution of individual values, and both the distribution and the average value are of great interest.

- Parking duration is related to the size of the urban area, with the average duration increasing with the urban area population, figure 12.5

- Average duration also varies considerably with trip purpose, as indicated in Table 12.6.

- Table 12.6 shows that durations vary widely form location to location. Thus, local studies of both parking duration and parking accumulation are important elements of an overall approach to the planning and operation of parking facilities.

Figure 12.5 Parking Duration Versus Urbanized Area Population (*Source:* Used with permission of Eno Foundation for Transportation, Weant, R., and Levinson, H., *Parking,* Westport CT, 1990, Fig. 6.4, p. 97.)

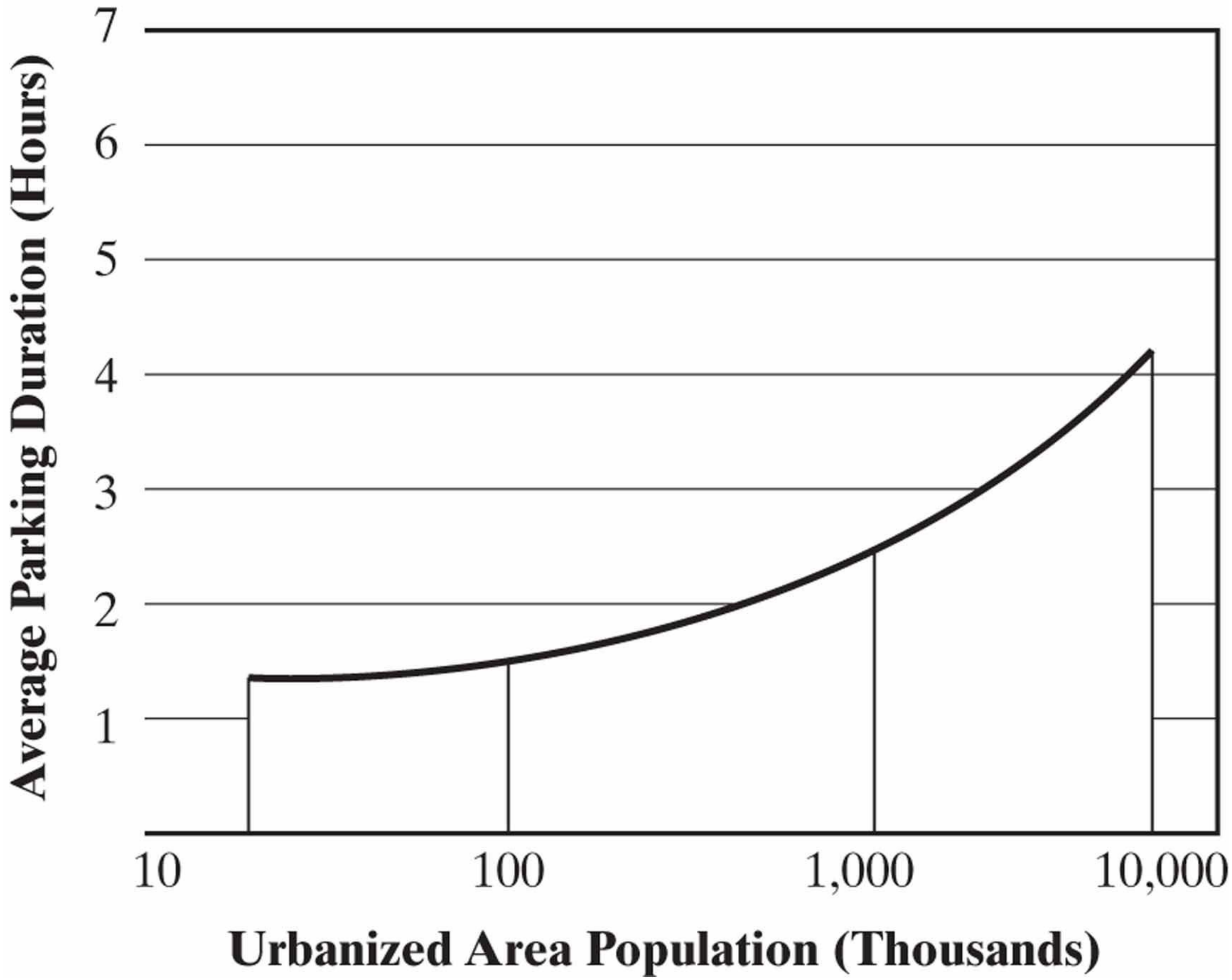


Table 12.6: Average Urban Parking Durations by Trip Purpose

Table 12.6: Average Urban Parking Durations by Trip Purpose

Trip Purpose	Average Duration (hours, minutes) Boston (1972)	Average Duration (hours, minutes) Charlotte (1987)
Work		
Manager	5h, 30m	8h, 8m
Employee	5h, 59m	
All		
Personal Business	2h, 6m	1h, 5m
Sales/Employment Business	2h, 14m	3h, 32m
Service	2h, 9m	
Recreational	2h, 18m	1h, 29m
Shopping	1h, 57m	4h, 17m
Other	3h, 12m	
All Purposes (Average)	4h, 20m	1h, 41m

(*Source:* Used with permission of Eno Foundation for Transportation, Weant, R., and Levinson, H., *Parking*, Westport CT, 1990, Table 6-2, p. 97.)

- The most commonly used technique for observing duration and accumulation characteristics of curb parking and surface parking lots is recording of **license plate numbers of parked vehicles**.

- At regular intervals from 10 to 30 minutes, an observer walks a particular route and records the license plate numbers of vehicles occupying each parking space. Figure 12.6

- Observers are expected to observe up to 60 spaces every 15 minutes.

- Analysis of data from field sheets:

  1. Accumulation totals: sum of columns=total accumulation within time period on each route
  2. Duration distribution: examining each line of field sheet, classifying vehicles as parked for one interval, or two, etc…
  3. Violations: no. of vehicles illegally parked.

Figure 12.6 A License-Plate Parking Survey Sheet (*Source:* Used with permission of Institute of Transportation Engineers, Box, P., and Oppenlander, J., *Manual of Traffic Engineering Studies,* 4th Edition, Washington DC, 1976, Fig. 10-6, p. 140.)

T: truck
TK: illegally parked and ticketed vehicles

LICENSE PLATE CHECK FIELD DATA SHEET

City ______ Date 10 MAY 1978 Recorded by JONES Side of Street W

Street WRIGHT between 5^{th} and 6^{th}

Codes: 000 last three digits of license number. √ for repeat number from prior circuit __ for empty space

Space and Regulation	Time circuit begins											
	07	07^{30}	08	08^{30}	09	09^{30}	10	10^{30}	11	11^{30}	12^{00}	
5^{th}												
X-WALK	–	–	–									
NPHC	–	–	–									
I HR M	–	713	✓	✓TK								
″ M	631	✓	✓	971								
″ M	512	34✓	✓	019								
DRIVEWAY	–	–	–	–								
″	–	–	–	613								
I HR M	–	–	418	✓								
″ M	117	220	✓	989								
″ M	–	148	096	✓								
FIRE HYD	–	–	–	–								
I HR M	042	–	216	✓								
N PHC	–	–	–	774								
X-WALK	–	–	–	–								
6^{th}												

- The average parking duration is computed as:

$$D = \frac{\sum_x (N_x * X * I)}{N_T}$$

D: average parking duration, h/veh

N_x: no. of vehicles parked for x intervals

X: no. of intervals parked

I: length of the observation interval, h

N_T: total number of parked vehicles observed

- The parkers turnover rate TR, indicates the no. of parkers that, on average, use a parking stall over a period of one hour. It is computed as:

$$TR = \frac{N_T}{P_S * T_S}$$

TR: parking turnover rate, veh/stall/h

N_T: total no. of parked vehicles observed

P_S: total no. of legal parking stalls

T_S: duration of the study period, h

Table 12.7 Summary and Computations from a Typical Parking Survey Field Sheet

Table 12.7: Summary and Computations from a Typical Parking Survey Field Sheet

Pkg* Space	Time														
	8:00	**8:30**	**9:00**	**9:30**	**10:00**	**10:30**	**11:00**	**11:30**	**12:00**	**12:30**	**1:00**	**1:30**	**2:00**	**2:30**	**3:00**
1	–	–	861	√	√	–	136	–	140	√	–	–	201	√	√
2	470	√	380	–	–	412	307	–	900	√	√	√	√	–	070
3	–	211	√	√	√	400	√	√	–	–	666	–	855	999	–
4	175	√	√	500	√	222	–	–	616	√	√	√	√	√	–
5	333	–	–	380	√	√	420	√	707	–	–	–	–	–	–
hydrant	–	–	–	–	–	–	–	242TK	–	–	–	–	–	–	–
1-hr	–	–	484	√	909	–	811	√	√	158	√	√	685	√	–
1-hr	301	–	–	525	√	√	696	√	422	–	299	√	√	–	892
1-hr	–	675	895	√	√	703	√	819	–	401	√	√	288	–	412
1-hr	406	–	442	781	882	√	√	√	444	–	903	√	–	–	–
1-hr	–	–	115	√	618	√	818	√	√	906	√	–	–	893	√
2-hr	–	509	√	√	–	705	√	√	√	688	√	696	–	–	807
2-hr	–	–	214	√	√	√	209	–	248	√	797	√	√	√	√
2-hr	101	√	√	√	–	531	√	–	940	√	√	√	628	√	√
2-hr	–	392	√	√	√	251	√	772	–	835	√	√	√	–	–
Accum.	**6**	**7**	**12**	**13**	**11**	**12**	**13**	**10**	**11**	**10**	**12**	**11**	**11**	**8**	**9**

*All data for Block Face 61; timed spaces indicate parking meter limits; √ = same vehicle parked in space.

Block 61

Table 12.8 Summary Data for an Entire Study Area Parking Survey

Max. accumulation=1410 at 11:00 AM
Which represents use of (1410/1500)*100=94% of available spaces

Table 12.8: Summary Data for an Entire Study Area Parking Survey

Block No.	Accumulation for Interval (1,500 Total Stalls)														
	8:00	8:30	9:00	9:30	10:00	10:30	11:00	11:30	12:00	12:30	1:00	1:30	2:00	2:30	3:00
61	6	7	12	13	11	12	13	10	11	10	12	11	11	8	9
62	5	10	15	14	16	18	17	15	15	10	9	9	7	7	8
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
180	7	8	13	13	18	14	15	15	11	14	16	10	9	9	6
181	7	5	18	16	12	14	13	11	11	10	10	10	6	6	5
Total	**806**	**900**	**1106**	**1285**	**1311**	**1300**	**1410**	**1309**	**1183**	**1002**	**920**	**935**	**970**	**726**	**694**

(a) Summarizing Field Sheets for Accumulation Totals

Table 12.8 (continued) Summary Data for an Entire Study Area Parking Survey

No. of vehicles in block 61 which were parked for one duration of time

Block Face No.	Number of Intervals Parked					
	1	**2**	**3**	**4**	**5**	**6**
61	28	17	14	9	2	1
62	32	19	20	7	1	3
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
180	24	15	12	10	3	0
181	35	17	11	9	4	2
Total	**875**	**490**	**308**	**275**	**143**	**28**

(b) Summarizing Field Sheets for Duration Distribution

Total vehicles parked= 875+490+308+275+143+28=2119

- The previous survey results illustrated in Table 12.8 includes only one study period. Thus vehicles parked at 3:00 PM will have a duration that ends at that time.

- Only the last three numbers of license plates are recorded.

- The average duration for the study area, based on the summary of Table 12.8 (b) is:

$$D = \frac{\sum \begin{matrix} (875 * 1 * 0.5) + (490 * 2 * 0.5) + (308 * 3 * 0.5) + \\ (275 * 4 * 0.5) + (143 * 5 * 0.5) + (28 * 6 * 0.5) \end{matrix}}{2119} = 1.12\ h/veh$$

The turnover rate is:

$$TR = \frac{2119}{1500 * 7} = 0.20 \frac{veh}{stall} /h$$

No. of stalls=1500

- For **off-street facilities**, the count is performed for the number of entering and departing vehicles recorded by 15 min. intervals

- Accumulation is computed as the difference between departing and entering vehicles

- Duration distribution is estimated by recording the license plates of entering and leaving vehicles

Design aspects of parking facilities

- Off- street parking facilities are provided as surface lots or parking garages

- The decision of how to provide off-street parking involves many considerations, including:

  1. availability of land,
  2. amount of parking needed, and
  3. the cost to provide it

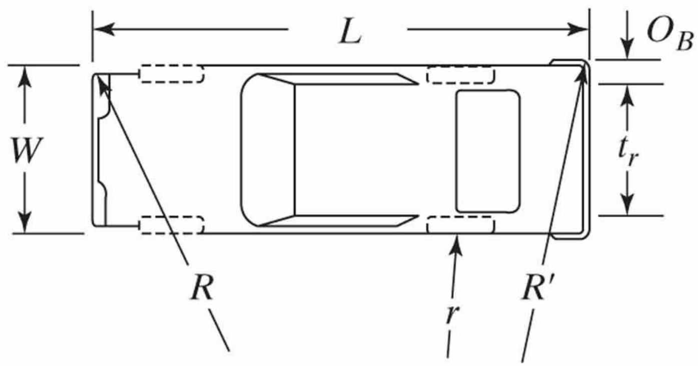
- Key objectives in the design of a parking facility:

  – A parking facility must be convenient and safe for the intended users
  – A parking facility should be space efficient and economical to operate
  – A parking facility should be compatible with its environs.

Basic parking dimensions

- Design vehicles used in the design of parking facilities:
  - Large cars
  - Small cars

Figure 12.7 Design Vehicles for Parking Design (*Source:* Used with permission of Eno Foundation for Transportation, Weant, R., and Levinson, H., *Parking,* Westport CT, 1990, reformatted from Table 8-1, p. 157.)



W = overall width, inches
L = overall length, inches
O_R = rear overhang, ft
O_B = body overhang from center of rear tire, ft
t_r = width from center of rear tires, ft

Minimum Turning Radius
r = inside rear wheel, ft
R = outside point, front bumper, ft
R' = outside point, rear bumper, ft

Dimension	Design Vehicle	
	Large Car	Small Car
Width, W (inches)	77	66
Length, L (inches)	215	175
Outside Front Bumper Radius, R (ft)	20.5	18.0
Inside Rear Wheel Radius, r (ft)	12.0	9.6
Rear Width, t_r (ft)	5.1	4.6
Body Overhang, Rear Tire, O_B (ft)	0.63	0.46
Rear Radius, R' (ft)	17.4	15.0

1. Parking stall width:

- Must be wide enough to encompass the vehicle and allow for door-opening and clearance
  - Min. door opening clearance= 22 inch (26 inch where turnover rates are high)
  - One door- opening clearance is provided per stall
  - For large cars, the parking stall width should range between 77+22= 99 inches and 77+26= 103 inches
  - For small cars, parking stall width= 66+22= 88 inches, and 66+26= 92 inches, typically 91inches standard width is used for small cars

2. Parking stall length and depth

- Parking length is measured parallel to the parking angle. It is generally taken as: the length of the design vehicle + 6 inches (for bumper clearance)

- For small cars: length= 175+6= 181’’
- For large cars: length= 215+6= 221’’

- Depth of the stall: is the projection of design vehicle length+ 6’’ bumper clearance

- For 90° parking stall, length=width
- For other angles, depth < length

3. Aisle width

- Must be sufficiently wide to allow drivers to enter and leave parking stalls safely and in a minimum number of maneuvers
- As stalls become narrower, the aisles need to be a bit wider
- Aisles also carry circulating traffic and accommodate pedestrians walking to or from their vehicles
- Aisle width depends on the angles of parking and on whether the aisle serves one-way or two-way traffic.

Parking modules

- A “parking module” refers to the basic layout of one aisle with a set of parking stalls on both sides of the aisle.

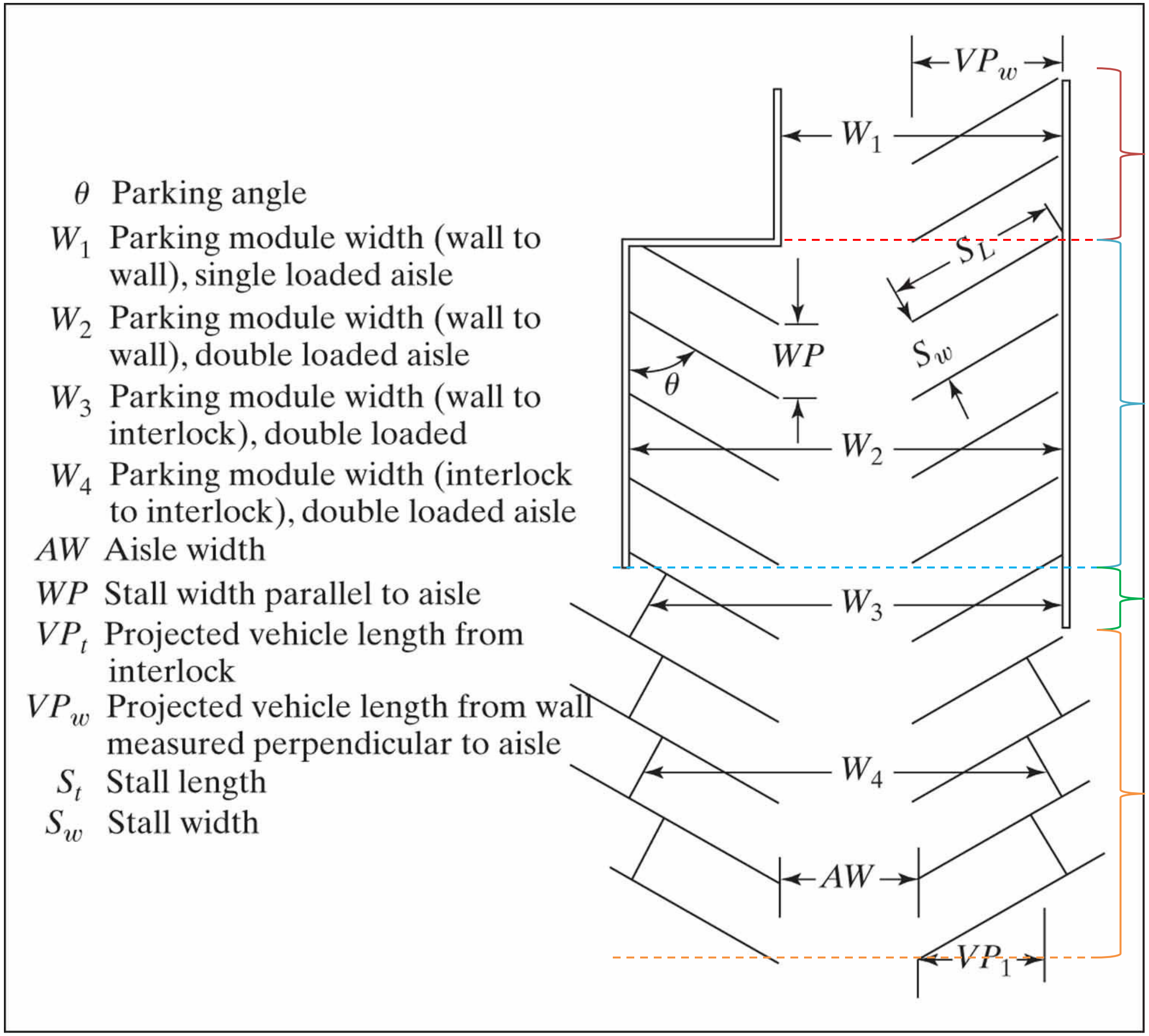
- Ways to layout a parking module:

- For 90° stalls, two-way aisles are virtually always used

- In angle parking, vehicle may enter a stall in only one direction of travel and must depart in the same direction, using either:

    – one-way aisles, stalls on both sides of the aisle, or
    – Two-way aisles, stalls on both sides of the aisle

Figure 12.8 Dimensional Elements of Parking Modules (*Source:* Used with permission of Institute of Transportation Engineers, *Guidelines for Parking Facility Location and Design: A Recommended Practice of the ITE,* Washington DC, 1994, Fig. 3, p. 6.)



Single set of stalls against a wall

Two sets of stalls against a wall

one set of stalls against a wall, another is interlocked

two sets of stalls are interlocked

Table 12.10 Parking Module Layout Dimension Guidelines

Table 12.10: Parking Module Layout Dimension Guidelines

Basic Layout	Parking Class	S_w Stall Width (ft)	WP Stall Width (ft)	VP_w Stall Depth to Wall (ft)	VP_i Stall Depth to Interlock (ft)	AW Aisle Width (ft)	Modules: W_2 Wall to Wall (ft)	Modules: W_4 Interlock to Interlock (ft)
Large Cars								
2-Way Aisle—90°	A	9.00	9.00	17.5	17.5	26.0	61.0	61.0
	B	8.75	8.75	17.5	17.5	26.0	61.0	61.0
	C	8.50	8.50	17.5	17.5	26.0	61.0	61.0
	D	8.25	8.25	17.5	17.5	26.0	61.0	61.0
2-Way Aisle—60°	A	9.00	10.4	18.0	16.5	26.0	62.0	59.0
	B	8.75	10.1	18.0	16.5	26.0	62.0	59.0
	C	8.50	9.8	18.0	16.5	26.0	62.0	59.0
	D	8.25	9.5	18.0	16.5	26.0	62.0	59.0
1-Way Aisle—75°	A	9.00	9.3	18.5	17.5	22.0	59.0	57.0
	B	8.75	9.0	18.5	17.5	22.0	59.0	57.0
	C	8.50	8.8	18.5	17.5	22.0	59.0	57.0
	D	8.25	8.5	18.5	17.5	22.0	59.0	57.0
1-Way Aisle—60°	A	9.00	10.4	18.0	16.5	18.0	54.0	51.0
	B	8.75	10.1	18.0	16.5	18.0	54.0	51.0
	C	8.50	9.8	18.0	16.5	18.0	54.0	51.0
	D	8.25	9.5	18.0	16.5	18.0	54.0	51.0
1-Way Aisle—45°	A	9.00	12.7	16.5	14.5	15.0	48.0	44.0
	B	8.75	12.4	16.5	14.5	15.0	48.0	44.0
	C	8.50	12.0	16.5	14.5	15.0	48.0	44.0
	D	8.25	11.7	16.5	14.5	15.0	48.0	44.0

Table 12.10 (continued)   Parking Module Layout Dimension Guidelines

Small Cars*

2-Way Aisle—90°	A/B C/D	8.0 7.5	8.0 7.5	15.0 15.0	15.0 15.0	21.0 21.0	51.0 51.0	51.0 51.0
2-Way Aisle—60°	A/B C/D	8.0 7.5	9.3 8.7	15.4 15.4	14.0 14.0	21.0 21.0	52.0 52.0	50.0 50.0
1-Way Aisle—75°	A/B C/D	8.0 7.5	8.3 7.8	16.0 16.0	15.1 15.1	17.0 17.0	49.0 49.0	47.0 47.0
1-Way Aisle—60°	A/B C/D	8.0 7.5	9.3 8.7	15.4 15.4	14.0 14.0	15.0 15.0	46.0 46.0	43.0 43.0
1-Way Aisle—45°	A/B B/C	8.0 7.5	11.3 10.6	14.2 14.2	12.3 12.3	13.0 13.0	42.0 42.0	38.0 38.0

*Although various angles are presented, the vast majority of small car layouts are for 90° parking.

(*Source:* Used with permission of Institute of Transportation Engineers, *Guidelines for Parking Facility Location and Design: A Recommended Practice of the ITE*, Washington DC, 1994, Tables 2 and 3, pp. 8 and 9.)

Parking garages

- Parking garages are subject to the same stall and module requirements as surface parking lots and have the same requirements for reservoir and circulation

- Parking garages have the additional burden of providing vertical as well as horizontal circulation for vehicles

- A general design and layout that includes a ramp system

Ramping system fall into two general categories:

- **Clearway systems:** ramps for inter-floor circulation are completely separated form ramps providing entry and exit to and from the parking garage.

- **Adjacent parking systems:** part or all of the ramp travel is performed on aisles that provide direct access to adjacent parking spaces

Figure 12.10 Parking Garage Circulation Systems (*Source*: Used with permission of Eno Foundation for Transportation, Weant, R., and Levinson, H., *Parking*, Westport CT, 1990, Figs. 9.5– 9.16, pp. 188–192.)

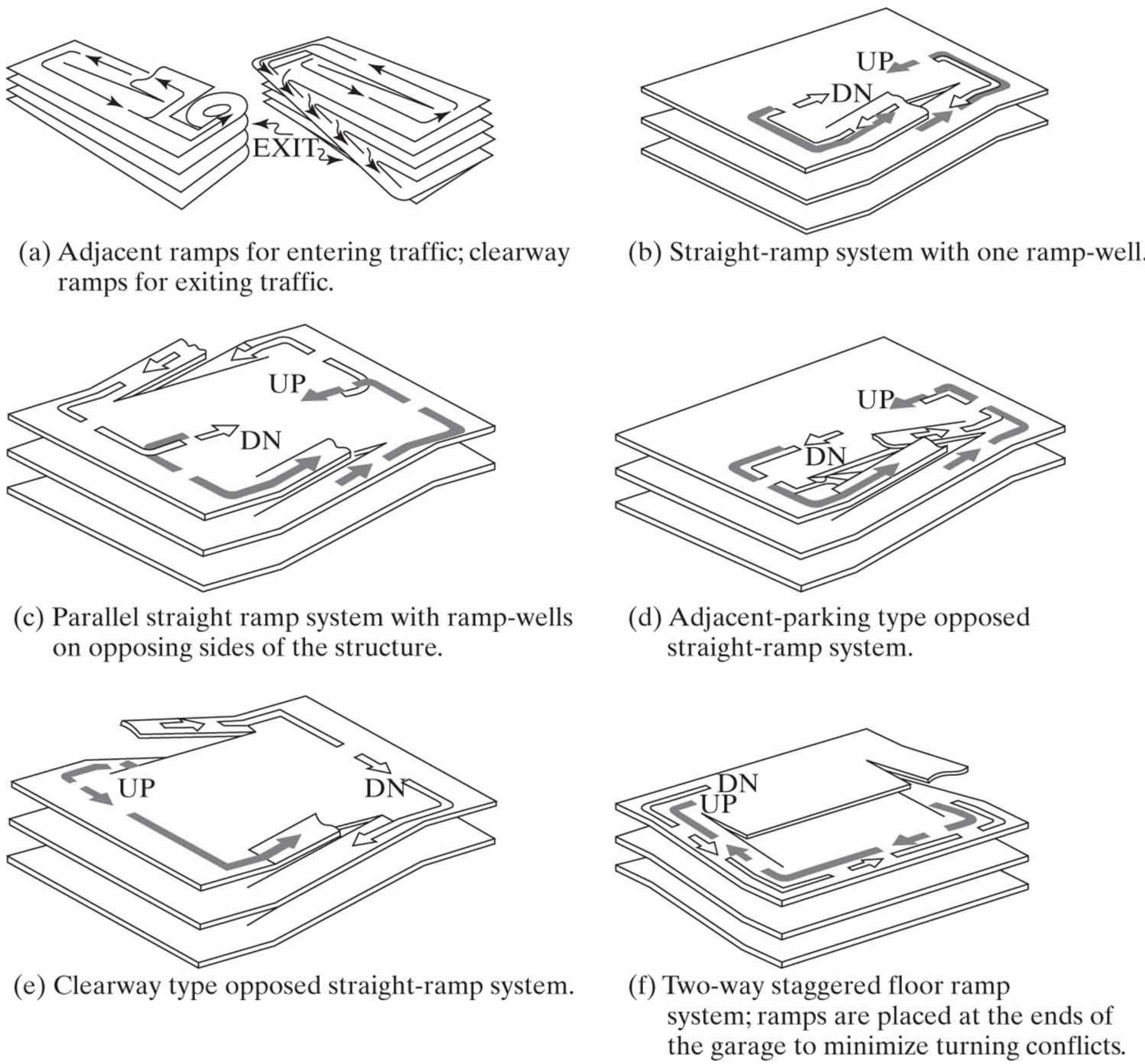
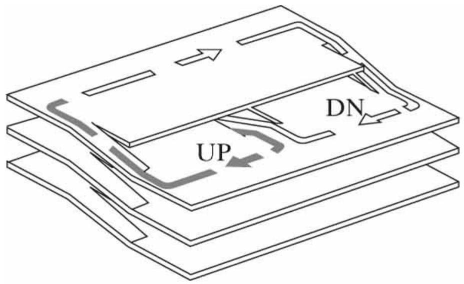
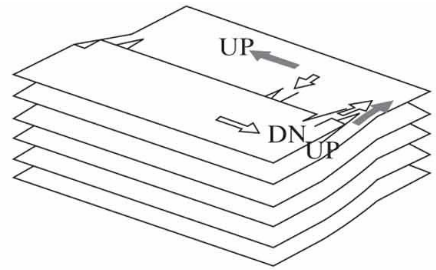


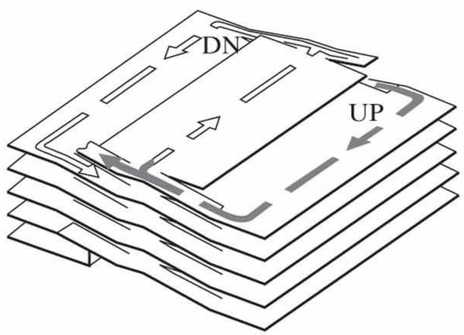
Figure 12.10 (continued) Parking Garage Circulation Systems (*Source:* Used with permission of Eno Foundation for Transportation, Weant, R., and Levinson, H., *Parking,* Westport CT, 1990, Figs. 9.5 – 9.16, pp. 188–192.)



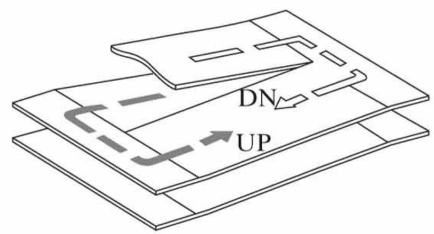
(g) Tandem staggered floor ramp system; ramps provide a clockwise circulation system.



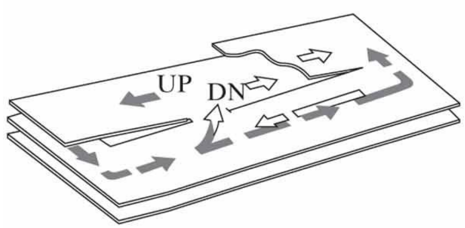
(h) This staggered floor ramp system provides parking on level floors and desirable one-way traffic flow.



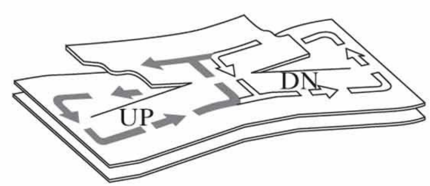
(i) Three-level staggered floor ramp system.



(j) Basic sloping floor concept.



(k) Sloping-floor system with crossover ramp at midpoint.



(l) Double sloping-floor system with midpoint crossover.

- In some attendant-park garages and surface lots, mechanical stacking systems are used to increase the parking capacity of the facility.

- They are generally slow,

- Most suited to longer-term parking durations, such as full day parking needs of working commuters

PLAY VIDEO

Air Transportation

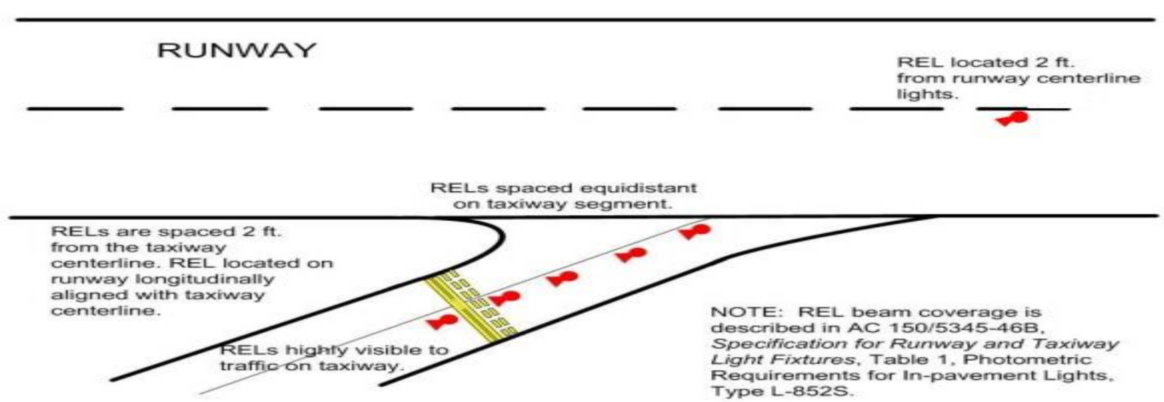
Aircraft Characteristics:

1. Weight: affects the design of pavement thickness for runways, taxi ways, and aprons.
2. Size: the aircraft length, width & height affect the size of airport facilities (widths of runway and taxiway, parking areas, hangers and maintenance sheds, turning radii, …).
3. Capacity: passenger & cargo capacity affect the design of ground services (terminal size, baggage handling facilities, departure lounges, gate positions, …).
4. Range: affect the frequency of operations.

Definitions

Runway: is a defined rectangular area on a land aerodrome prepared for the landing and takeoff of aircraft.

Taxiway: is a path on an airport connecting runways with ramps, hangars, terminals and other facilities.



- **Airport Apron:** is the area of
  an airport where aircraft are parked, unloaded or loaded, refueled, or boarded.

Airport Planning and Layout

Airport Demand Depends on:

1. Population and their density
2. Economic character
3. Proximity to other airports

Demand is referred to as annual passenger flow that is corrected to monthly, daily, peak day, and finally peak hour flow

<u>Example:</u>

Peak hour flow=

0.0917 x 1.26 x 0.03226 x 0.084117 x annual flow

- 0.0917 = Peak hour
- 1.26 = Peak day
- 0.03226 = daily
- 0.08417 = monthly

Selection of Airport Site

FAA Procedures:

I) Desk study of area (plans, wind direction, costs,…)

II) Physical inspections (alternative sites)

III) Evaluation and recommendations according to 10 criteria:

Evaluation and recommendations Criteria:

1. Convenience to users (center of most cities)
2. Availability of land and its cost
3. Design and layout of the airport (orientation)
4. Airspace obstruction (other airports, towers,…)
5. Engineering factors (level topography)
6. Social and environmental factors (noise)
7. Availability of utilities (water, electricity)
8. Atmospheric conditions (fog, snow)
9. Hazard of birds
10. Coordination with other airports

Runway Orientation

- Aircraft may not maneuver safely on a runway when the wind contains a large component at right angle to the direction of travel (crosswind)

- Crosswind speed component should be ≤ certain value according to the type of aircraft expected to use the airport

- FAA standards: 95% of the time crosswind should be less than the max allowable

The Wind Rose

- The appropriate orientation of the runway or runways at an airport can be determined through graphical vector analysis using a wind rose.

- A standard wind rose consists of a series of concentric circles cut by radial lines using polar coordinate graph paper.

- The radial lines are drawn to the scale of the wind magnitude such that the area between each pair of successive lines is centered on the wind direction.

The wind comes from the southeast (SE) with a magnitude between 20 and 25 mi/h.

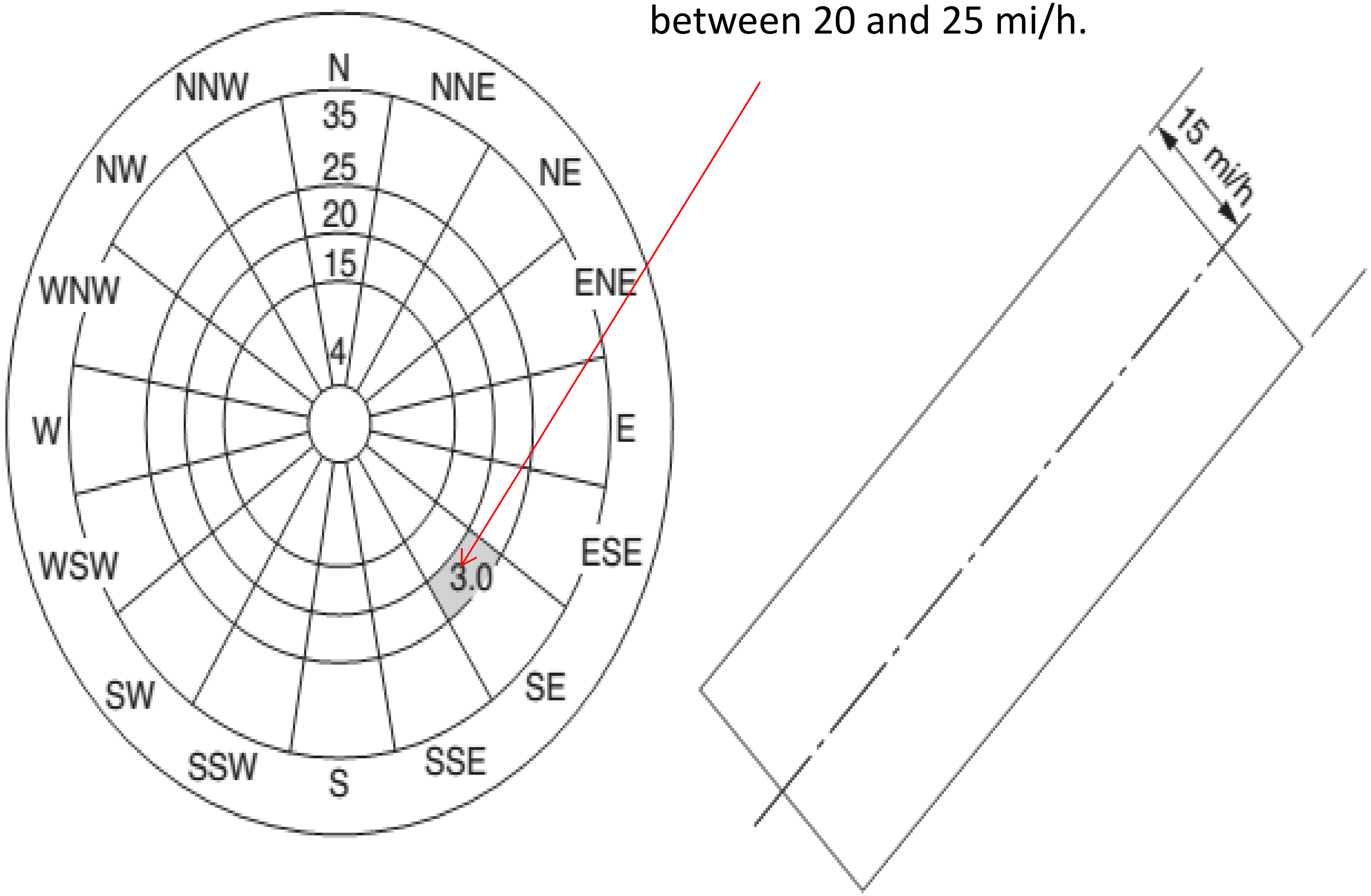


Figure 6-7 Wind rose coordinate system and template.

- As an example, assume that the wind data for all conditions of visibility are those shown in Table 6-4. This wind data is plotted to scale as indicated above to obtain a wind rose, as shown in Fig. 6-8.

Sector	True Azimuth	Wind Speed Range, mi/h				Total
		4–15	15–20	20–25	25–35	
		Percentage of Time				
N	0.0	2.4	0.4	0.1	0.0	2.9
NNE	22.5	3.0	1.2	1.0	0.5	5.7
NE	45.0	5.3	1.6	1.0	0.4	8.3
ENE	67.5	6.8	3.1	1.7	0.1	11.7
E	90.0	7.1	2.3	1.9	0.2	11.5
ESE	112.5	6.4	3.5	1.9	0.1	11.9
SE	135.0	5.8	1.9	1.1	0.0	8.8
SSE	157.5	3.8	1.0	0.1	0.0	4.9
S	180.0	1.8	0.4	0.1	0.0	2.3
SSW	202.5	1.7	0.8	0.4	0.3	3.2
SW	225.0	1.5	0.6	0.2	0.0	2.3
WSW	247.5	2.7	0.4	0.1	0.0	3.2
W	270.0	4.9	0.4	0.1	0.0	5.4
WNW	292.5	3.8	0.6	0.2	0.0	4.6
NW	315.0	1.7	0.6	0.2	0.0	2.5
NNW	337.5	1.7	0.9	0.1	0.0	2.7
Subtotal		60.4	19.7	10.2	1.6	91.9
Calms						8.1
Total						100.0

Table 6-4 Example Wind Data

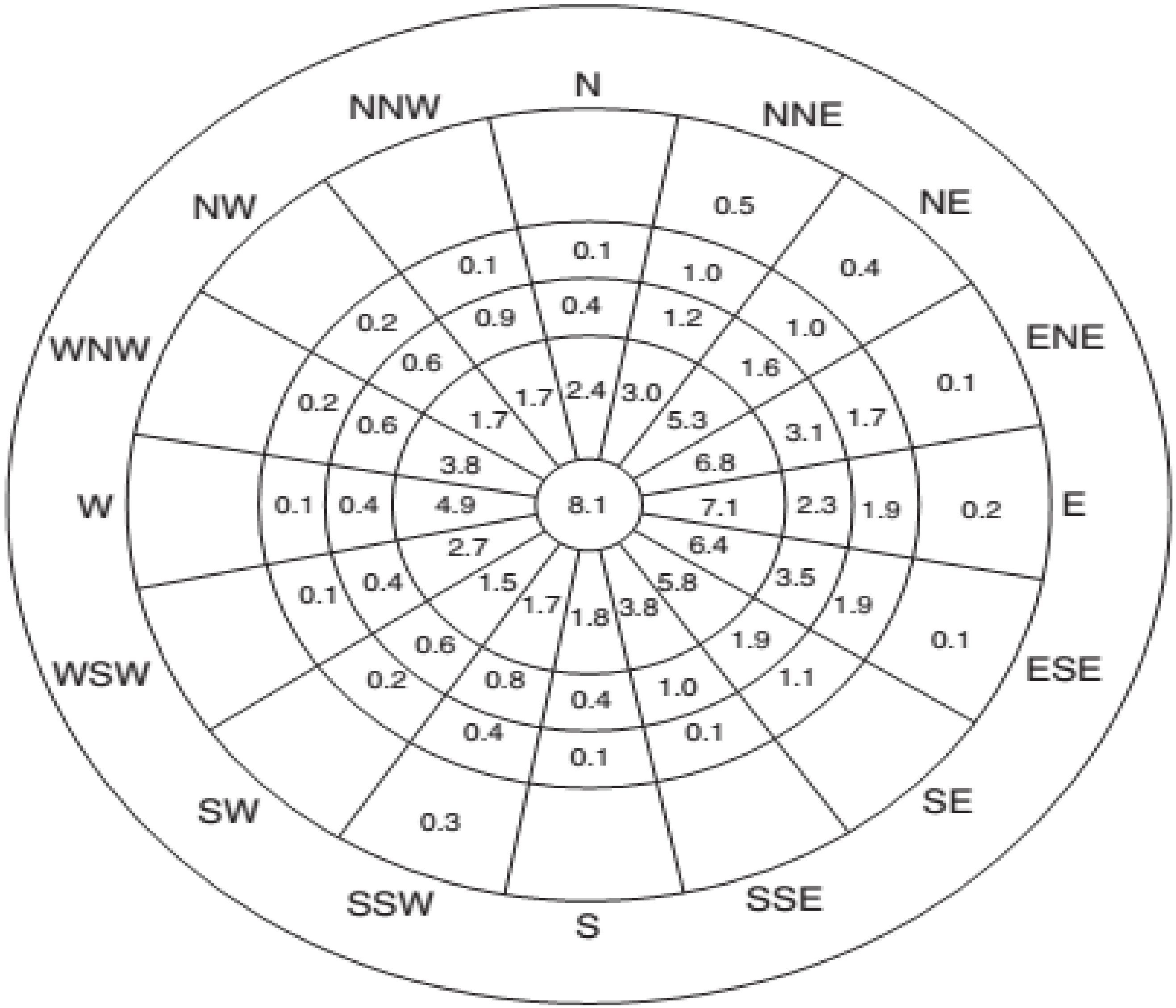


Figure 6-8 Wind data in wind rose format.

- The percentage of time the winds correspond to a given direction and velocity range is marked in the proper sector of the wind rose by means of a polar coordinate scale for both wind direction and wind magnitude.

- The template is rotated about the center of the wind rose, as explained earlier, until the direction of the centerline yields the maximum percentage of wind between the parallel lines.

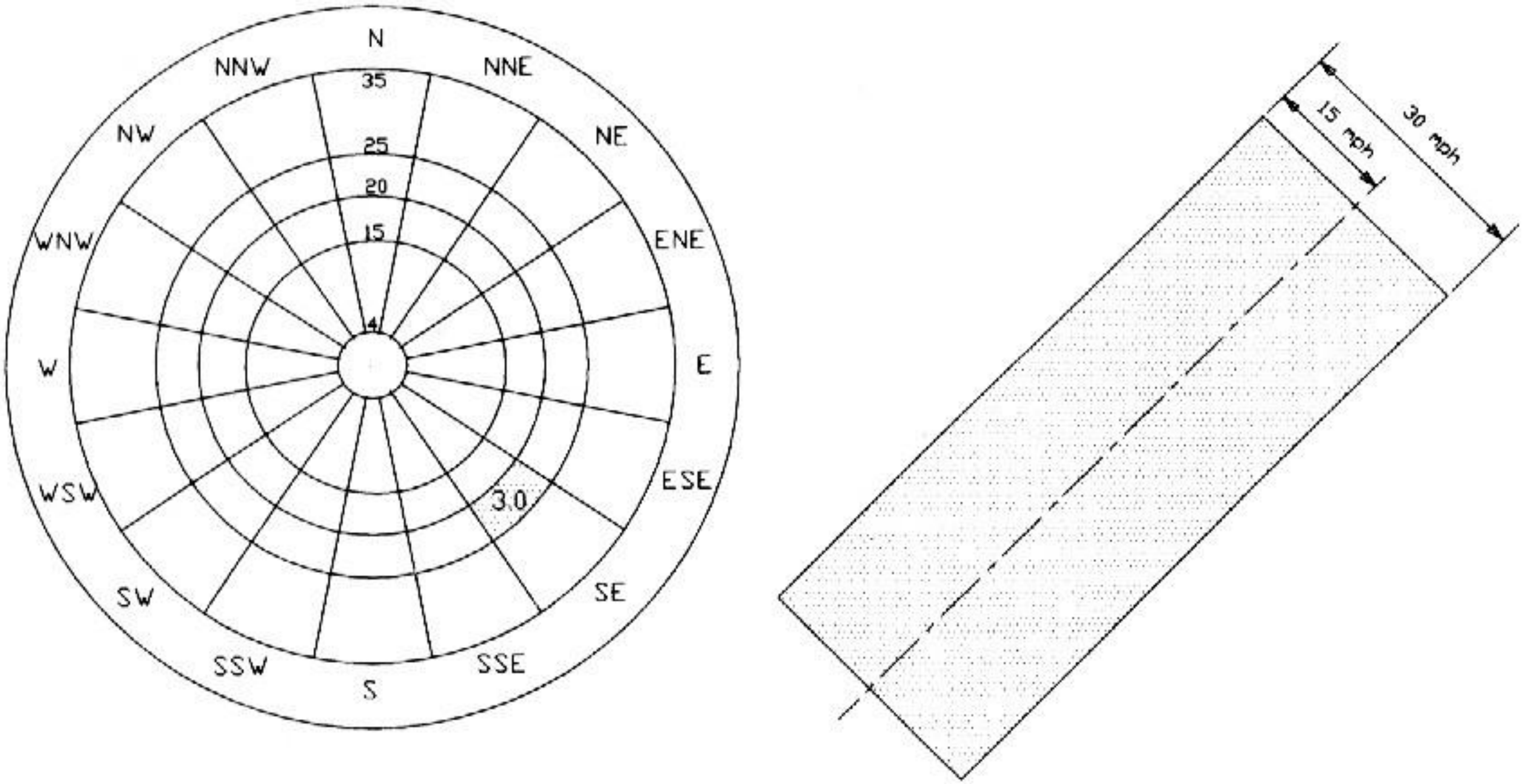


Figure 7-4 Wind rose coordinate system and template.

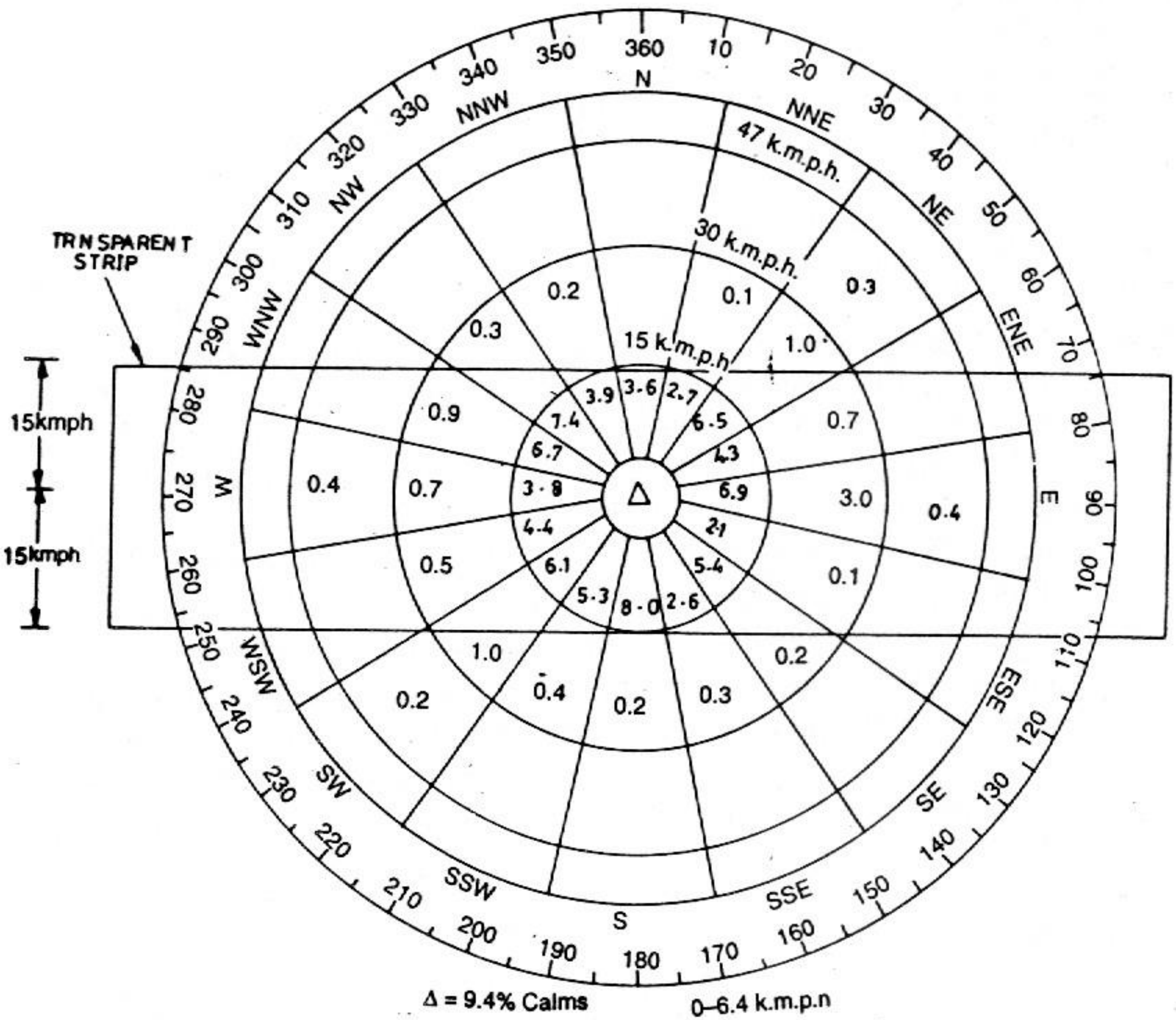


Fig. 6.2 Wind Rose Diagram (Method -II)

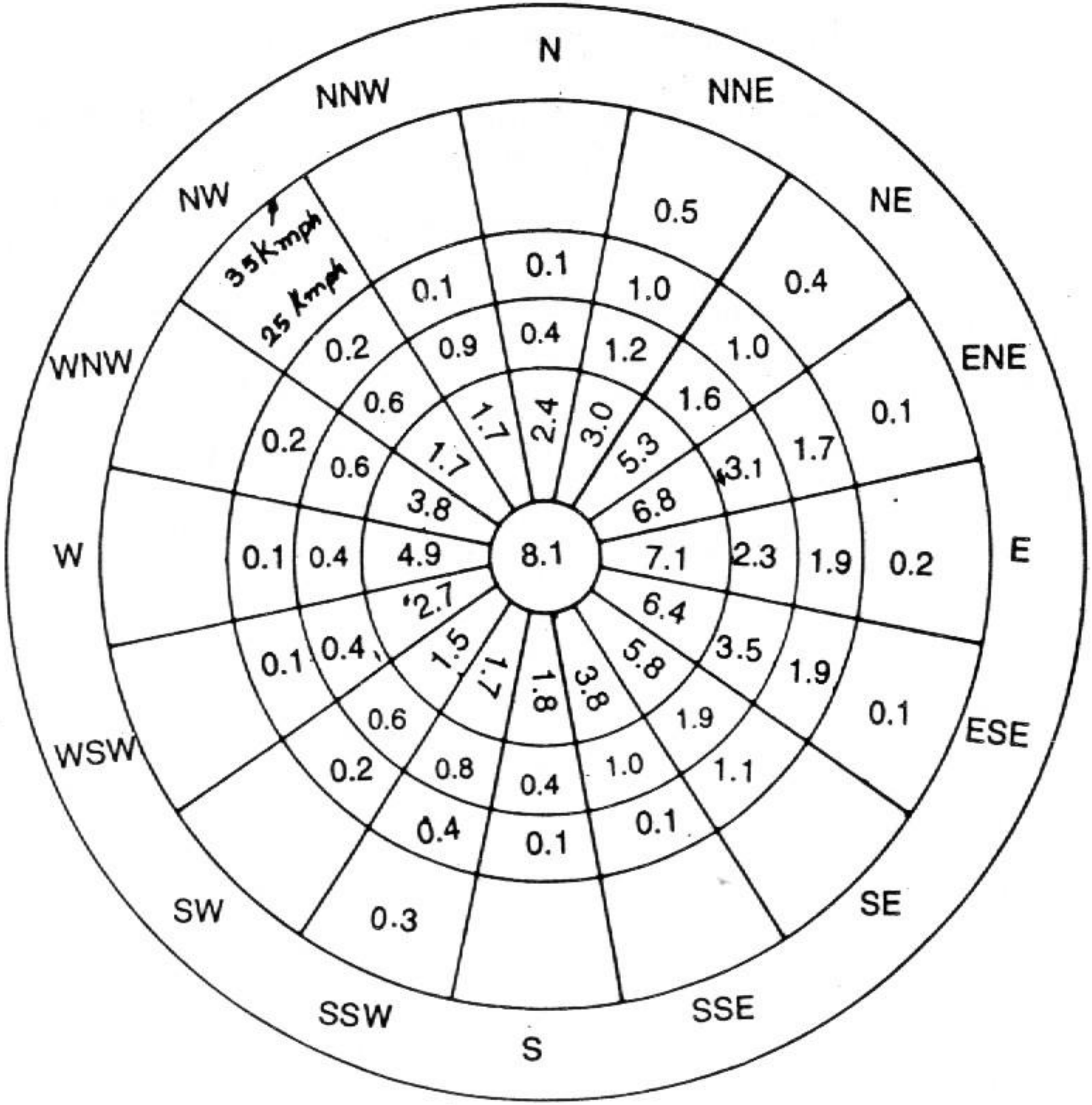


Fig. 6.10 Wind data plot

- The best runway orientation = 90° to 270°
- Runway designation = 9-27
- Wind coverage = 90.8 % < 95%

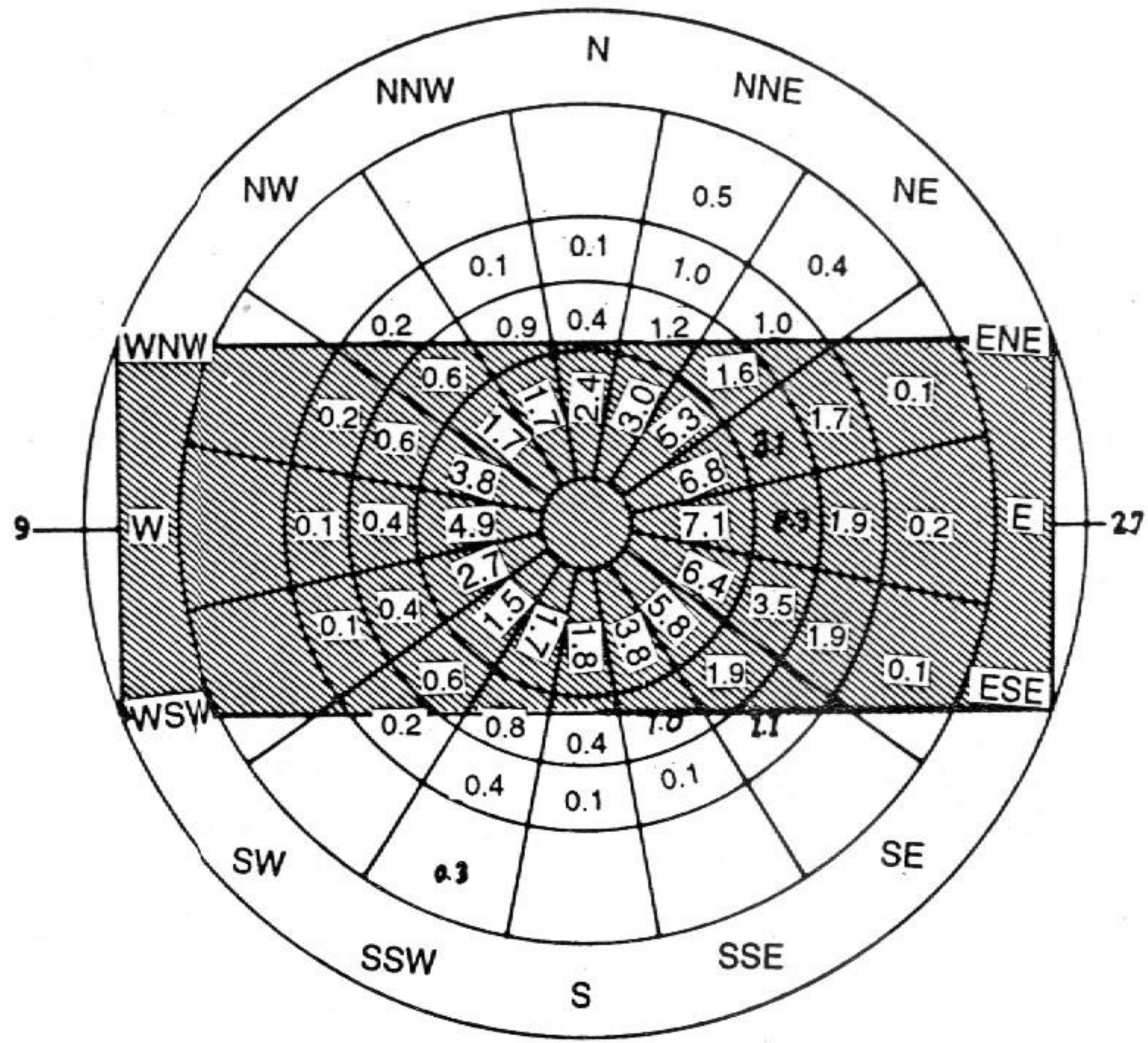


Fig. 6.11 Wind coverage for runway 9-27

(ii)

- Crosswind runway orientation = 30° to 210°
- Runway designation = 3-21
- Wind coverage = 84.8 %
- Additional wind coverage = 5.8%
- Primary Runway orientation =90° to 270°
- Wind coverage for primary =90.8%
- Total wind coverage for both = 90.8+5.8 = 96.6%>95% (Fig. 6.13)

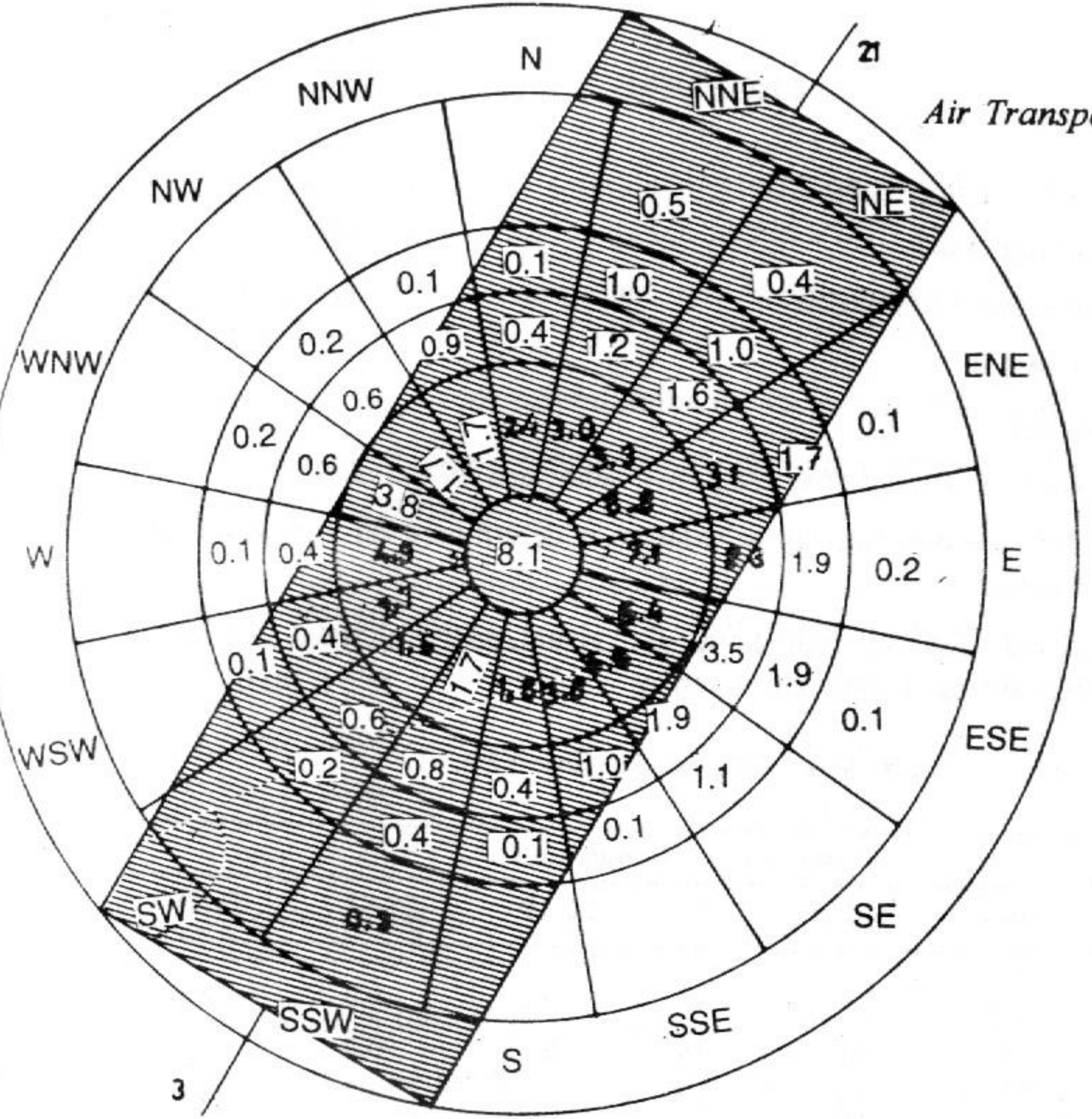


Fig. 6.12 Wind coverage for runway 3-21

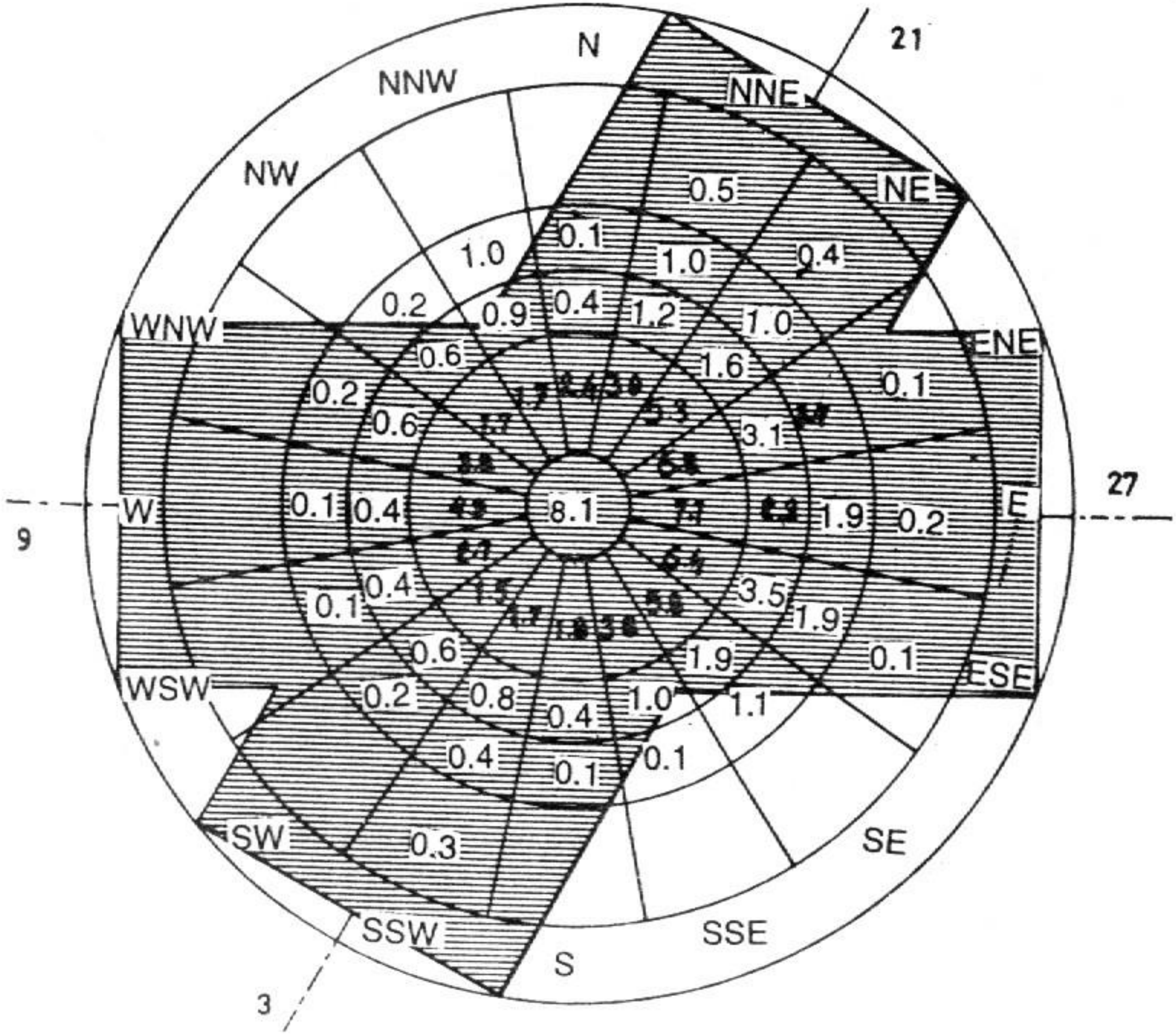


Fig. 6.13 Wind coverage for runways 9-27 and 3-21

Objects Affecting Navigable Airspace

- Obstacles should be removed or clearly marked

- FAA regulation define imaginary surfaces free of objects hazardous to air navigation (Fig 16.5)

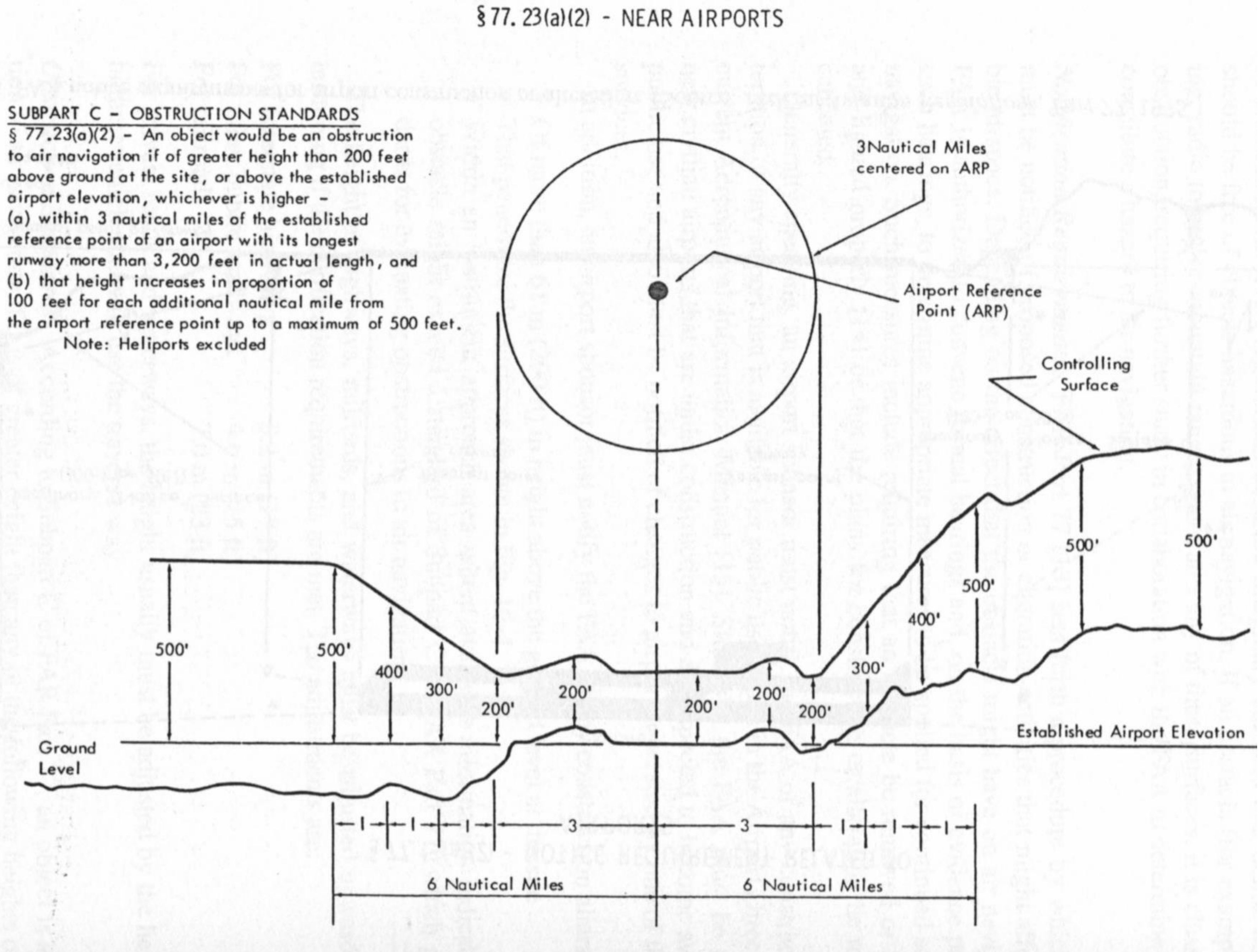


Figure 16-5 Obstruction standards in the vicinity of airports. (Source: *Federal Aviation Regulations, Part 77*, 1975.)

3

Obstacle Height:

1. Within 3 nautical miles a height of 200 ft above the established airport level (longest runway > 3200 ft) and the height increases 100 ft for every 1 nautical mile up to max 500 ft

2. In addition to any obstacles in the terminal area, or any other airport area …

Runway Capacity

- **Saturation Capacity:**

  maximum number of aircraft operations that can be handled during a given period under conditions of continuous demand

- Depends on:
  1. Aircraft mix
  2. Weather
  3. Visual flight rules (VFR) or instrument flight rules (IFR)
  4. Layout and design of the system
  5. Arrival/departure ratio

Aircraft Mix:

Class A: small engine aircraft (wt ≤12,500 lb)

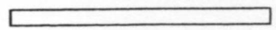
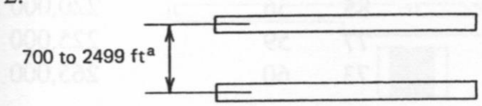
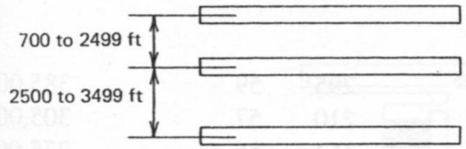
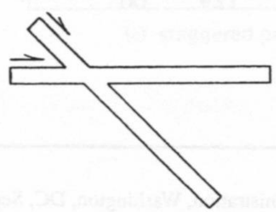
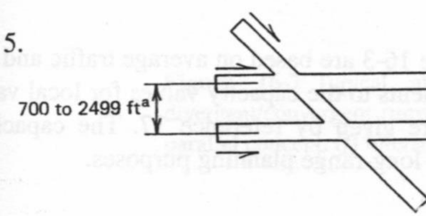
Class B: small multi engine aircraft (wt ≤12,500 lb)

Class C: large aircraft (12,500 < wt ≤300,000 lb)

Class D: heavy aircraft (wt > 300,000 lb)

Mix index = (% in C) + 3 (%in D)

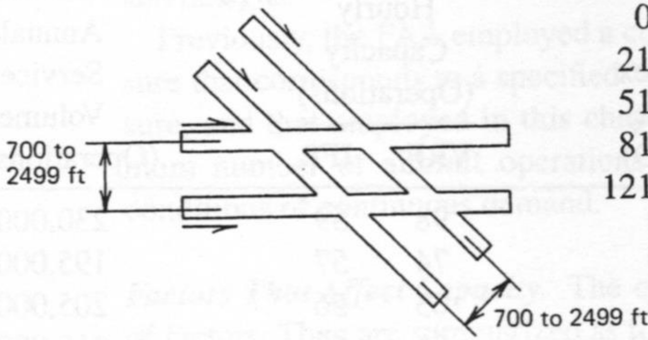
Table 16-3 Airport Capacities for Long-Range Planning Purpose

Runway Use Configuration	Mix Index (Percent) (C + 3D)	Hourly Capacity (Operations) VRF	Hourly Capacity (Operations) IFR	Annual Service Volume (Operations/yr)
1. 	0–20	98	59	230,000
	21–50	74	57	195,000
	51–80	63	56	205,000
	81–120	55	53	210,000
	121–180	51	50	240,000
2. 	0–20	197	59	355,000
	21–50	145	57	275,000
	51–80	121	56	260,000
	81–120	105	59	285,000
	121–180	94	60	340,000
3. 	0–20	295	62	385,000
	21–50	219	63	310,000
	51–80	184	65	290,000
	81–120	161	70	315,000
	121–180	146	75	385,000
4. 	0–20	98	59	230,000
	21–50	77	57	200,000
	51–80	77	56	215,000
	81–120	76	59	225,000
	121–180	72	60	265,000
5. 	0–20	197	59	355,000
	21–50	145	57	275,000
	51–80	121	56	260,000
	81–120	105	59	285,000
	121–180	94	60	340,000

Continued on following page

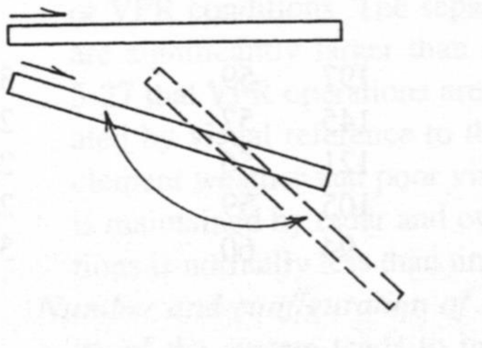
Table 16-3 *Continued*

6.



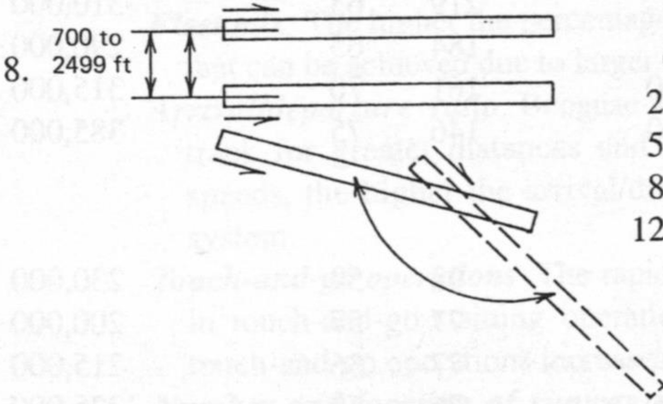
0–20	197	59	355,000
21–50	147	57	275,000
51–80	145	56	270,000
81–120	138	59	295,000
121–180	125	60	350,000

7.



0–20	150	59	270,000
21–50	108	57	225,000
51–80	85	56	220,000
81–120	77	59	225,000
121–180	73	60	265,000

8.



0–20	295	59	385,000
21–50	210	57	305,000
51–80	164	56	275,000
81–120	146	59	300,000
121–180	129	60	355,000

[a]Staggered threshold adjustments may apply.

Source: Airport Capacity and Delay, AC 150/5060.5, Federal Aviation Administration, Washington, DC, Sept. 23, 1983.

Runway Configuration

Best runway configuration depends on:

1. Safety requirements
2. Wind direction
3. Topography
4. Available space shape and amount
5. Airport design

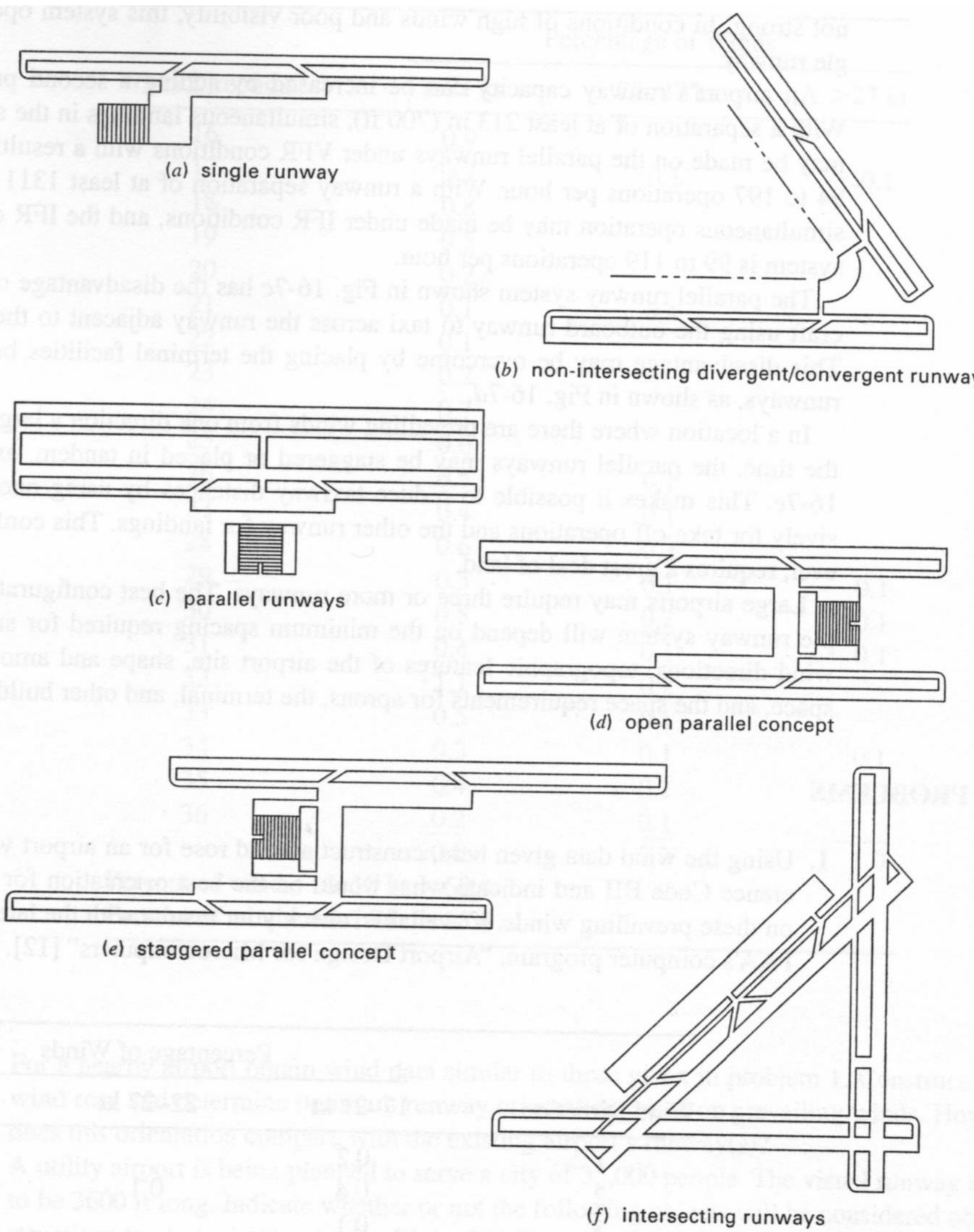
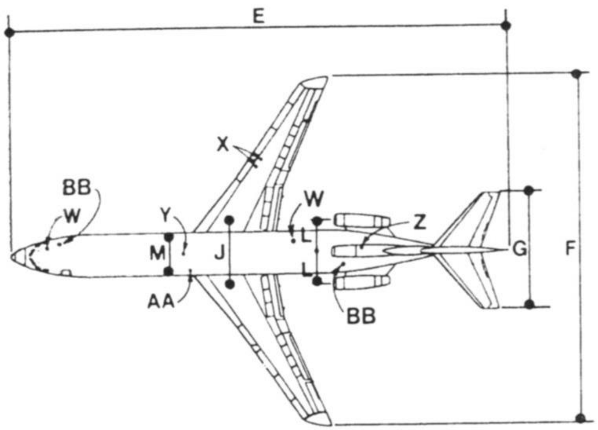


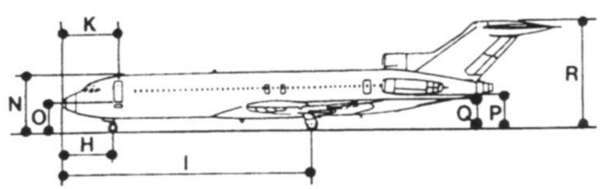
Figure 16-7 Typical airport configurations. (*a*) Single runway. (*b*) Nonintersecting divergent/convergent runways. (*c*) Parallel runways. (*d*) Open parallel runways (*e*) Staggered parallel concept. (*f*) Intersecting runways.

B7727-200

Notes:

*	Dimensions Not Shown On Drawing
**	Steering Angle 78° (3° Slip) (Outside to outside of tire...no differential braking)
***	All seating capacities shown for mixed class (2)



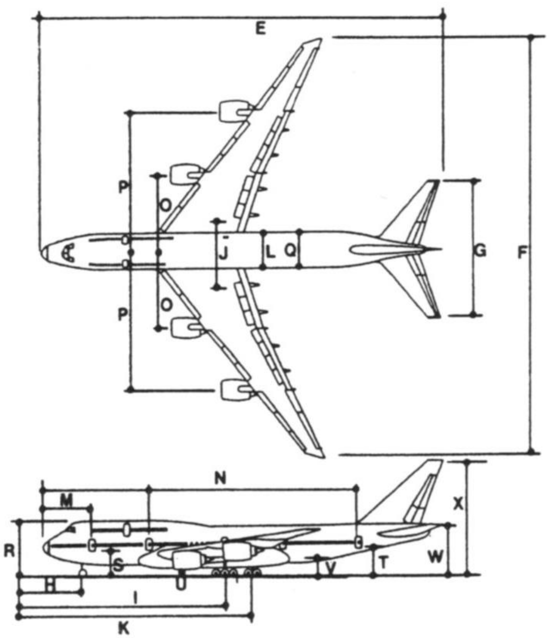


	Airport Reference Code	C-III	
	Aircraft Range	1,900-2,500 nm	
	Fuel Capacity	54,200 lbs	24,600 kg
	Main Gear	Dual	
***	Passenger Capacity	134 seats	
A.	Maximum Aircraft Ramp Weight	210,000 lbs	95,300 kg
B.	Maximum Aircraft Landing Weight	161,000 lbs	73,100 kg
C.	Maximum Aircraft Takeoff Weight	209,500 lbs	95,100 kg
**D.	Minimum Pavement Width for 180° Turn	82'-6"	25.2m
E.	Length (Overall)	153'-2"	46.69m
F.	Wing Span	108'-0"	32.92m
G.	Tail Span	35'-9"	10.90m
H.	Nose to Nose Gear	15'-1"	4.60m
I.	Nose to Main Gear	78'-4"	23.88m
J.	Main Gear Width	18'-9"	5.72m
K.	Nose to Forward Passenger Door	16'-6"	5.03m
L.	Engine from Aircraft Centerline	9'-4"	2.84m
M.	Fuselage Width	12'-4"	3.76m
N.	Fuselage Height Above Ground	17'-11"/16'-7"	5.41m/5.05m
O.	Forward Passenger Door Sill Height Above Ground	10'-1"/8'-0"	3.07m/2.44m
P.	Engine Clearance Above Ground	10'-4"/10'-2"	3.15m/3.10m
Q.	Wing Tip Vertical Clearance	11'-5"/4'-9"	3.48m/1.45m
R.	Tail Height	34'-11"/31'-7"	10.64m/9.63m
*S.	Nose to Lower Cargo Doors	38'-4" 89'-3"	11.68m 27.20m
*T.	Nose to Main Deck Cargo Door	Not Available	
*U.	Lower Cargo Doors Sill Height Above Ground	5'-6"/4'-2" 5'-5"/3'-10"	1.68m/1.27m 1.65m/1.17m
*V.	Main Deck Cargo Door Sill Height Above Ground	Not Available	

B747-600 X
Preliminary

Preliminary Notes:

*	Dimensions Not Shown On Drawing
**	Steering Angle 58° (Outside to outside of tire...no differential braking)
***	All seating capacities shown for mixed class (3)



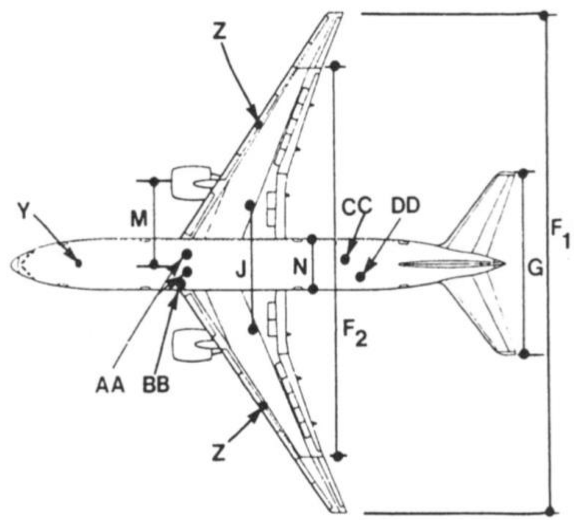
Airport Reference Code	F-VI
Aircraft Range	7,750 nm
Fuel Capacity	Not Available
Main Gear	Double Dual Tandem & Double Triple Tandem
*** Passenger Capacity	450-550 seats

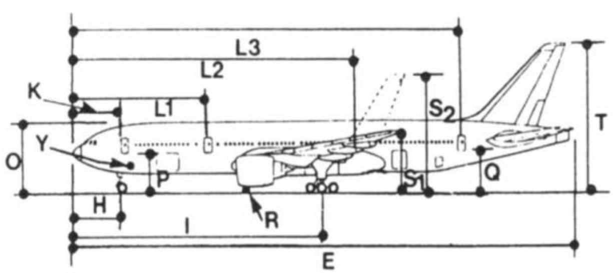
A.	Maximum Aircraft Ramp Weight		1,203,000 lbs	545,680 kg
B.	Maximum Aircraft Landing Weight		845,000 lbs	383,292 kg
C.	Maximum Aircraft Takeoff Weight		1,200,000 lbs	544,320 kg
**D.	Minimum Pavement Width for 180° Turn		Not Available	
E.	Length (Overall)		278'-11"	85.01m
F.	Wing Span		255'-0"	77.72m
G.	Tail Span		78'-1"	78.08m
H.	Nose to Nose Gear		25'-5"	7.75m
I.	Nose to Forward Main Gear		131'-9"	40.16m
J.	Forward Main Gear Width		34'-2"	10.41m
K.	Nose to Rear Main Gear		149'-9"	45.64m
L.	Rear Main Gear Width		12'-10"	3.91m
M.	Nose to Forward Passenger Door		40'-6"	12.34m
N.	Nose to Mid & Aft Passenger Doors		82'-11" 130'-4" 178'-8" 225'-9"	25.27m 39.23m 54.46m 68.81m
O.	Inboard Engine from Aircraft Centerline		46'-0"	14.02m
P.	Outboard Engine from Aircraft Centerline		88'-6"	26.97m
Q.	Fuselage Width		21'-4"	6.50m
R.	Fuselage Height Above Ground		16'-0"/16'-11"	4.88m/5.16m
S.	Forward Passenger Door Sill Height Above Ground		16'-11"/18'-4"	5.16m/5.59m
T.	Aft Passenger Door Sill Height Above Ground		16'-11"/18'-4"	5.16m/5.59m
U.	Inboard Engine Clearance Above Ground		4'-9"	1.45m
V.	Outboard Engine Clearance Above Ground		9'-8"	2.95m
W.	Wing Tip Vertical Clearance		Not Available	
X.	Tail Height		71'-0"	21.64m
*Y.	Nose to Lower Cargo Doors (Right Side Only)	FWD MID AFT	56'-9" 192'-9" 204'-7"	17.30m 58.75m 62.36m
*Z.	Lower Cargo Doors Sill Height Above Ground	FWD MID AFT	9'-4" 10'-0" 12'-4"	2.84m 3.05m 3.76m

B777-200

Notes:

*	Dimensions Not Shown On Drawing
**	Steering Angle 70° (5° Slip) (Outside to outside of tire...no differential braking)
***	All seating capacities shown for all economy, two and three classes

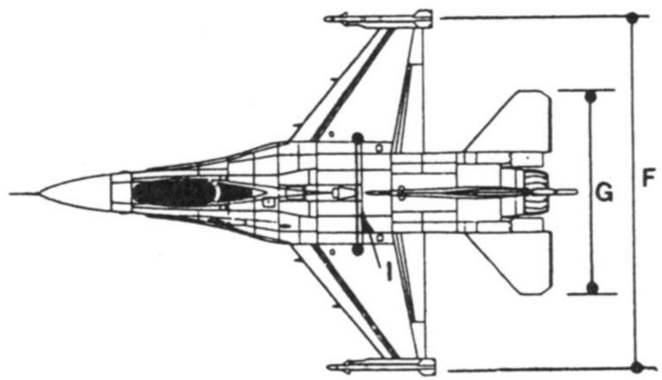


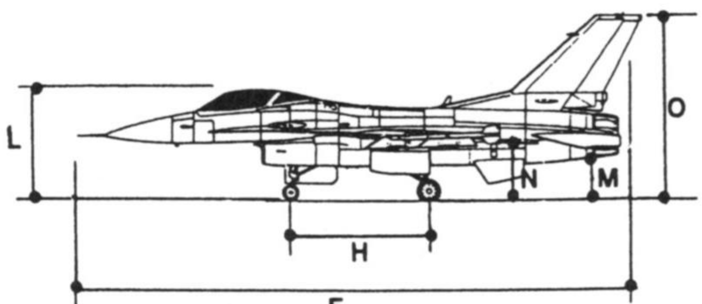


	Airport Reference Code	D-IV	
	Aircraft Range	3,930-4,785 nm	
	Fuel Capacity	207,700 lbs	94,240 kg
	Main Gear	Dual Tridem	
***	Passenger Capacity	440/375/305 seats	
A.	Maximum Aircraft Ramp Weight	634,500 lbs	287,800 kg
B.	Maximum Aircraft Landing Weight	455,000 lbs	206,305 kg
C.	Maximum Aircraft Takeoff Weight	506,000 lbs	229,520 kg
**D.	Minimum Pavement Width for 180°Turn	152'-0"	46.4m
E.	Length (Overall)	209'-1"	63.73m
F^1.	Wing Span	199'-11"	60.93m
F^2.	Wing Span With Folding Wing Tips	155'-3"	47.32m
G.	Tail Span	70'-7.5"	21.52m
H.	Nose to Nose Gear	19'-4"	5.98m
I.	Nose to Main Wing Gear	104'-3.8"	31.87m
J.	Main Gear Width	36'-0"	10.98m
K.	Nose to Forward Passenger Door	22'-1.5"	6.75m
L^1.	Nose to 2nd Passenger Door	56'-0"	17.07m
L^2.	Nose to 3rd Passenger Door	119'-2"	36.33m
L^3.	Nose to 4th Passenger Door	162'-6"	49.54m
M.	Engine from Aircraft Centerline	31'-7"	9.61m
N.	Fuselage Width	20'-4"	6.20m
O.	Fuselage Height Above Ground	27'-6"/28'-6"	8.39m/8.68m
P.	Forward Passenger Door Sill Height Above Ground	15'-5"/16'-5"	4.71m/5.00m
Q.	Aft Passenger Door Sill Height Above Ground	17'-4"/18'-2"	5.28m/7.1m
R.	Engine Clearance Above Ground	3'-2"/3'-5"	0.96m/1.04m
S^1.	Wing Tip Vertical Clearance	23'-6"/24'-6"	7.16m/7.49m
S^2.	Wing Tip (Folding) to Ground	46'-8"	14.23m
T.	Tail Height	60'-5"/61'-6"'	18.42m/18.76m
*U.	Nose to Forward Cargo Doors	38'-8.5"	11.90m
*V.	Nose to Aft Large Cargo Door	135'-4"	41.30m
*W.	Forward Cargo Doors Sill Height Above Ground	9'-3"/10'-0"	2.81m/3.05m
*X.	Aft Large Cargo Door Sill Height Above Ground	10'-7"/11'-2"	3.23m/3.41m

F-16C

Notes:
* Dimensions Not Shown On Drawing
** (Outside to outside of tire...no differential braking)





	Airport Reference Code	E-I	
	Aircraft Range	1,420-2,100 nm	
	Fuel Capacity	5,650 lbs	2,568 kg
	Main Gear	Single	
	Crew Size	1	
A.	Maximum Aircraft Ramp Weight	Not Available	
B.	Maximum Aircraft Landing Weight	Not Available	
C.	Maximum Aircraft Takeoff Weight	42,300 lbs	19,187 kg
**D.	Minimum Turning Radius	39'-0"	11.89m
E.	Length (Overall)	49'-5.2"	15.07m
F.	Wing Span (over missile)	32'-9.75"	10.00m
G.	Tail Span	18'-3.75"	5.58m
H.	Wheel Base	13'-1.5"	4.00m
I.	Wheel Track	7'-9"	2.36m
*J.	Engine from Aircraft Centerline	0'	0m
*K.	Fuselage Width	Varies	
L.	Fuselage Height Above Ground	11'-4"	3.46m
M.	Engine Clearance Above Ground	3'-6"	1.07m
N.	Wing Tip Vertical Clearance	5'-0"	1.52m
O.	Tail Height	16'-7.8"	5.07m

Airport Passenger Terminal Area

Terminal Area Includes:

1. Automobile parking lots
2. Aircraft parking aprons
3. Passenger terminal building
4. Facilities for intra- and inter terminal transportation

Terminal Area should accommodate peak hour traffic to avoid delay

Types of Airports:

1. Utility airports:

   Includes small building for commercial activities and maintenance and administration building for pilots, passengers and visitors

2. Hub airports:

   large airports

Typical Air Trip

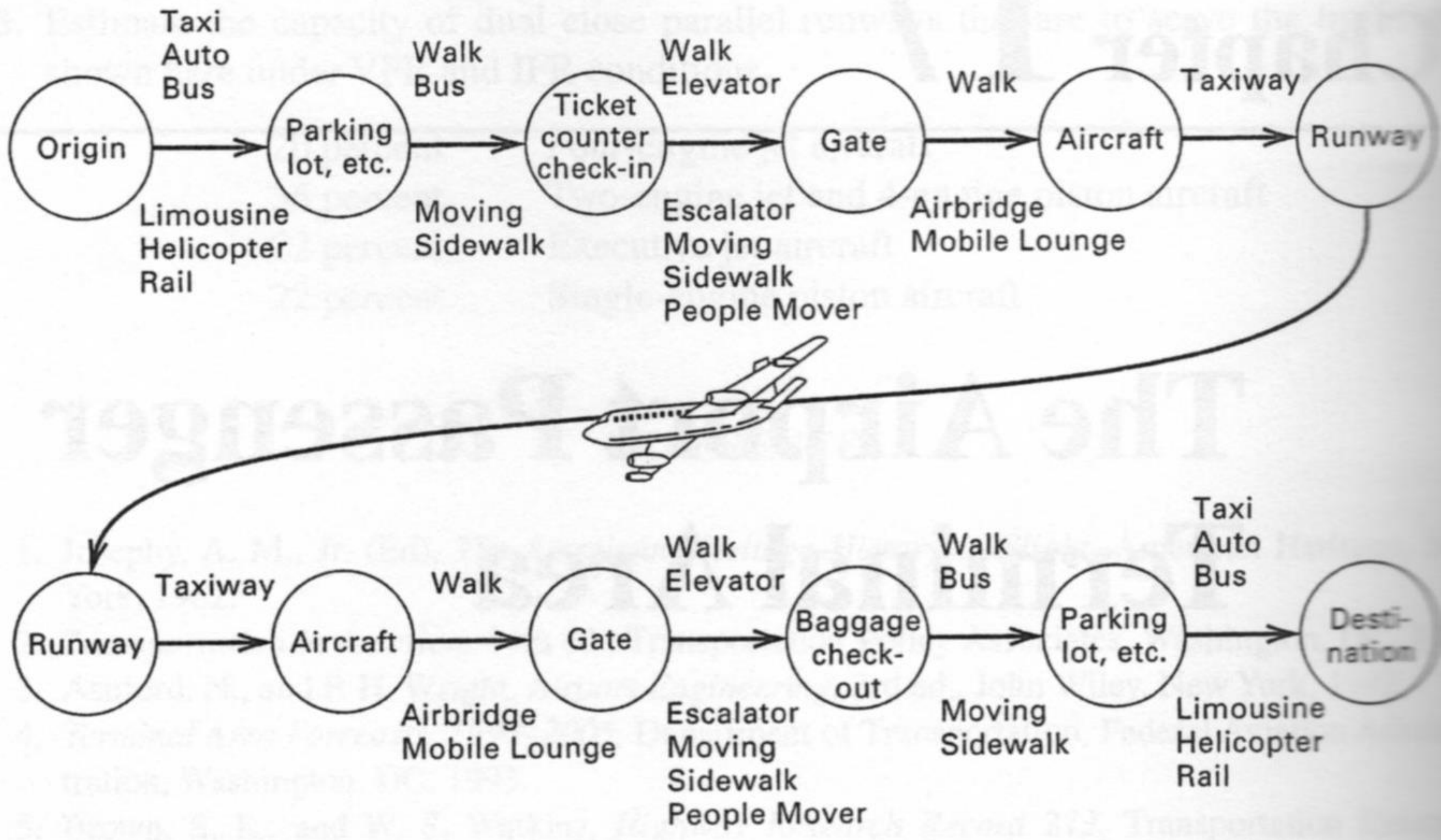


Figure 17-1 A typical air trip.

Terminal Planning and Design

Involves four organizations:

1. Airport owner: financing
2. Federal government: immigration, customs, and health inspection
3. Airlines: each has its own needs
4. Concessionaires: restaurants, shops, car rentals

Terminal Layout Concepts

Design objectives:

1. Adequate space
2. Flexibility to cope with technology
3. Reduce walking distances for pedestrians and taxiing requirements for aircrafts
4. Obtain revenues
5. Acceptable working environment for airport and working staff

Terminal Layout Schemes

1. Frontal
2. Pier finger
3. Satellite
4. Remote apron
5. Remote pier (linear)
6. Remote pier (cruciform)
7. Gate arrival

Airport Terminal Designs

Early airport terminals opened directly onto the tarmac: passengers would walk or take a bus to their aircraft. This design is still common among smaller airports, and even many larger airports have "bus gates" to accommodate aircraft beyond the main terminal. A Pier Design uses a long, narrow building with aircraft parked on both sides. One end connects to a ticketing and baggage claim area. Piers offer high aircraft capacity and simplicity of design, but often result in a long distance from the check-in counter to the gate (up to half a mile in the case of Kansai International Airport). Most large international airports have piers, including Chicago's O'Hare International Airport, Frankfurt International Airport, London Heathrow Airport and Miami International Airport.

A Satellite Terminal is a building detached from other airport buildings, so that aircraft can park around its entire circumference. Satellite terminals offer high aircraft capacity for their square footage, but require comparatively sophisticated transit systems to move passengers in and out (often underground or by people mover). Paris's Charles de Gaulle International Airport (Terminal-1) and London Gatwick Airport (South Terminal) both have circular satellite terminals; Orlando International Airport and Pittsburgh International Airport have multiplier satellite terminals, and Denver International Airport has linear satellite terminals.

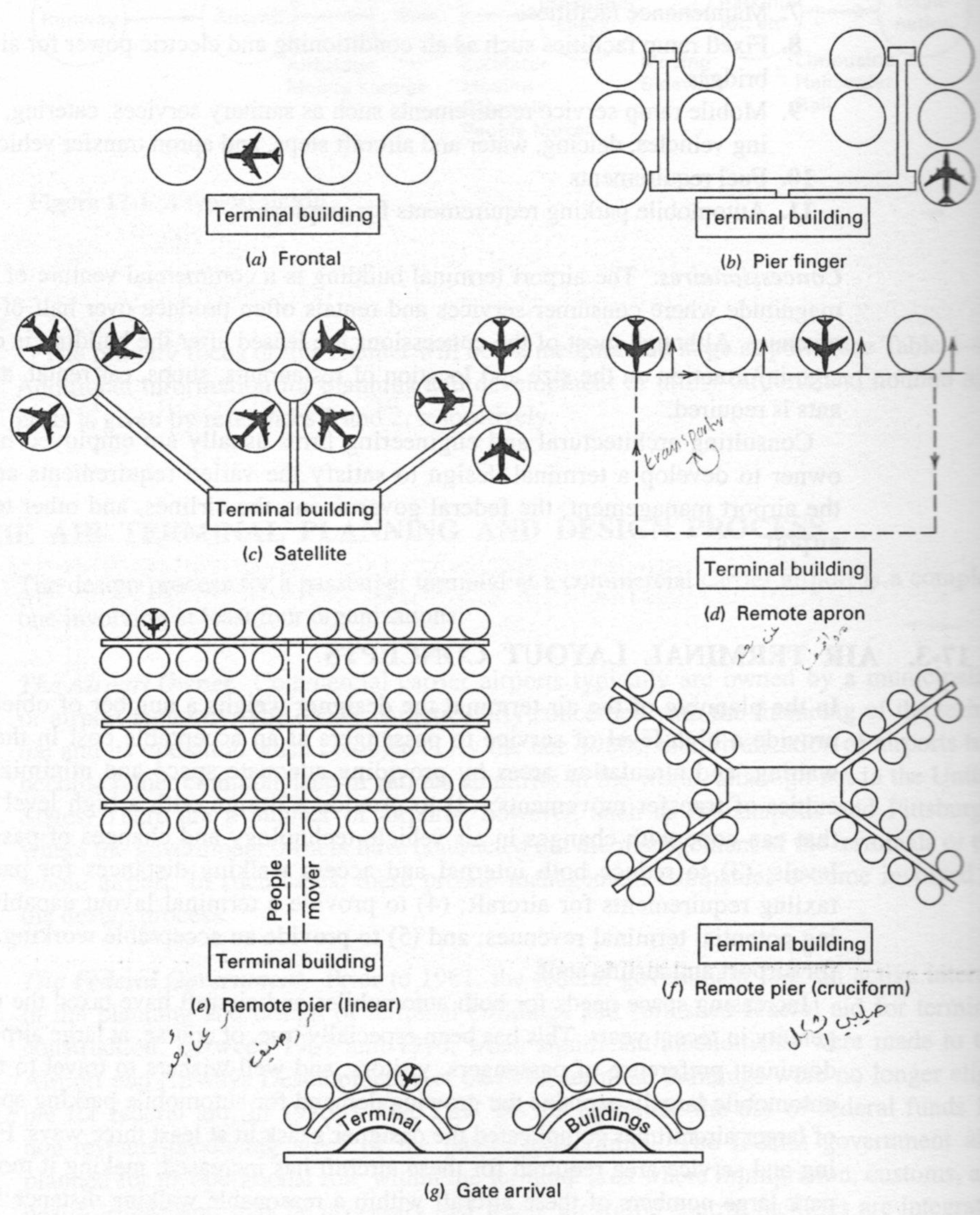


Figure 17-2 Terminal layout schemes.

Intra - & Inter Terminal Transportation

Results of a Study:

- Average walking distance to nearest gate = 565 ft
- Average walking distance to farthest gate = 1342 ft
- Average walking distance between airlines = 4091 ft

Large airports use: moving sidewalks, vehicle system, and mobile lounges

Automotive Parking and Circulation Needs

- More than 50% of passengers use cars to/from airports

- Parking spaces should be within 300-400 ft from terminal building (max 1000 ft)

- Multi-level parking structures are used

- Parking users:

  1. Passengers
  2. Visitors brining passengers
  3. Employees
  4. Business callers
  5. Rental cars & taxis

- Spaces for employees can be far by providing shuttle busses

- Vehicular Circulation:
    - ➢ Counter clockwise
    - ➢ One way
    - ➢ No at-grade intersection

- Curb parking should be provided for pickup & drop-off

Terminal Apron Space Requirements

- **Apron:**

  An area for parking of aircraft

- Size of gate positions depends on size and maneuverability of aircrafts

- Number of gate (stand) positions depends on :

   1. The peak volume of aircraft to be served

   2. How long each aircraft occupies a gate position

- Gate Occupancy time depends on:

1. Type of aircraft
2. No. of passengers
3. Amount of baggage
4. Magnitude and nature of other services required
5. Efficiency of apron personnel

- Required number of stands, $n = vt/u$

where:

v = design hour volume for departures or arrivals, aircraft/hour

t = weighted mean stand occupancy, hr

u = utilization factor, 0.6 to 0.8 where stands are shared

European Standards:

- Required number of stands, n = mqt

where:

m = design hour volume for departures or arrivals, aircraft/hour

q = proportions of arrivals to total movements

t = mean stand occupancy, hr

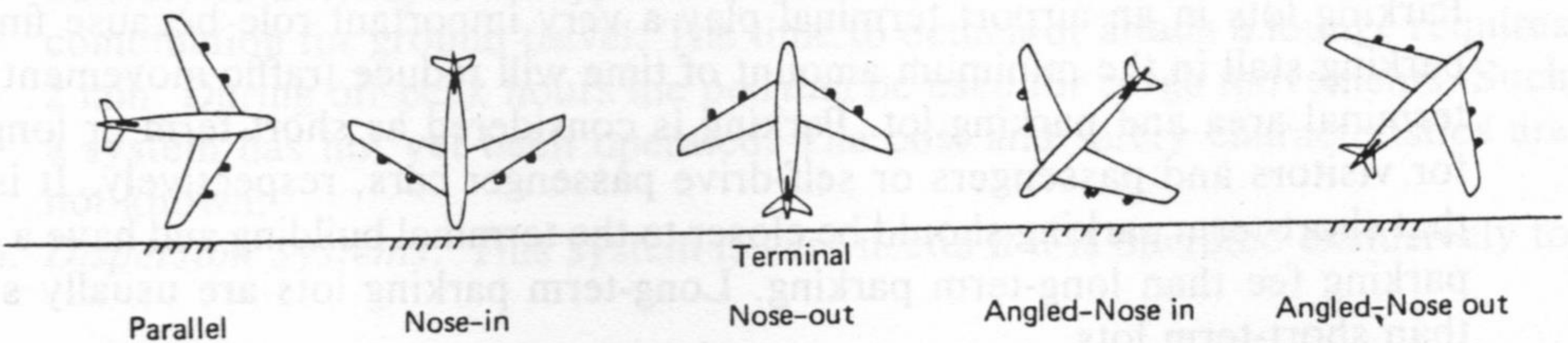
Future Stands

$$Future\ \ S\tan ds = \left[(present\ \ s\tan ds - 2) \times \frac{future\ \ passengers}{present\ \ passengers} \right] + 2$$

Aircraft Parking Configurations:

1. Nose in
2. Nose out
3. Parallel
4. Angled

Figure 21.6 Aircraft parking types. *Source:* From Ashford, N., and Wright, P.H., 1979. *Airport Engineering*. New York: John Wiley and Sons.



Terminal Building

- Space should be provided for:

  1. Facilities for passengers: tickets sales, waiting areas, baggage checking & claming, security, flight information, telephones, gift shops, car rentals, medical services, hotels, motels, restaurants, barbers, shops, …

2. Aircraft Operations: communication center, operation rooms for crews

3. Airport operations & Maintenance: air traffic control, ground traffic control, airport administration, FAA offices, airport maintenance, fire protection, utilities

Design Considerations

- Terminal building should be flexible for future expansion (staged design, using partitions, …)

- Use multi-level building for passenger circulation

Apron Terminal Area

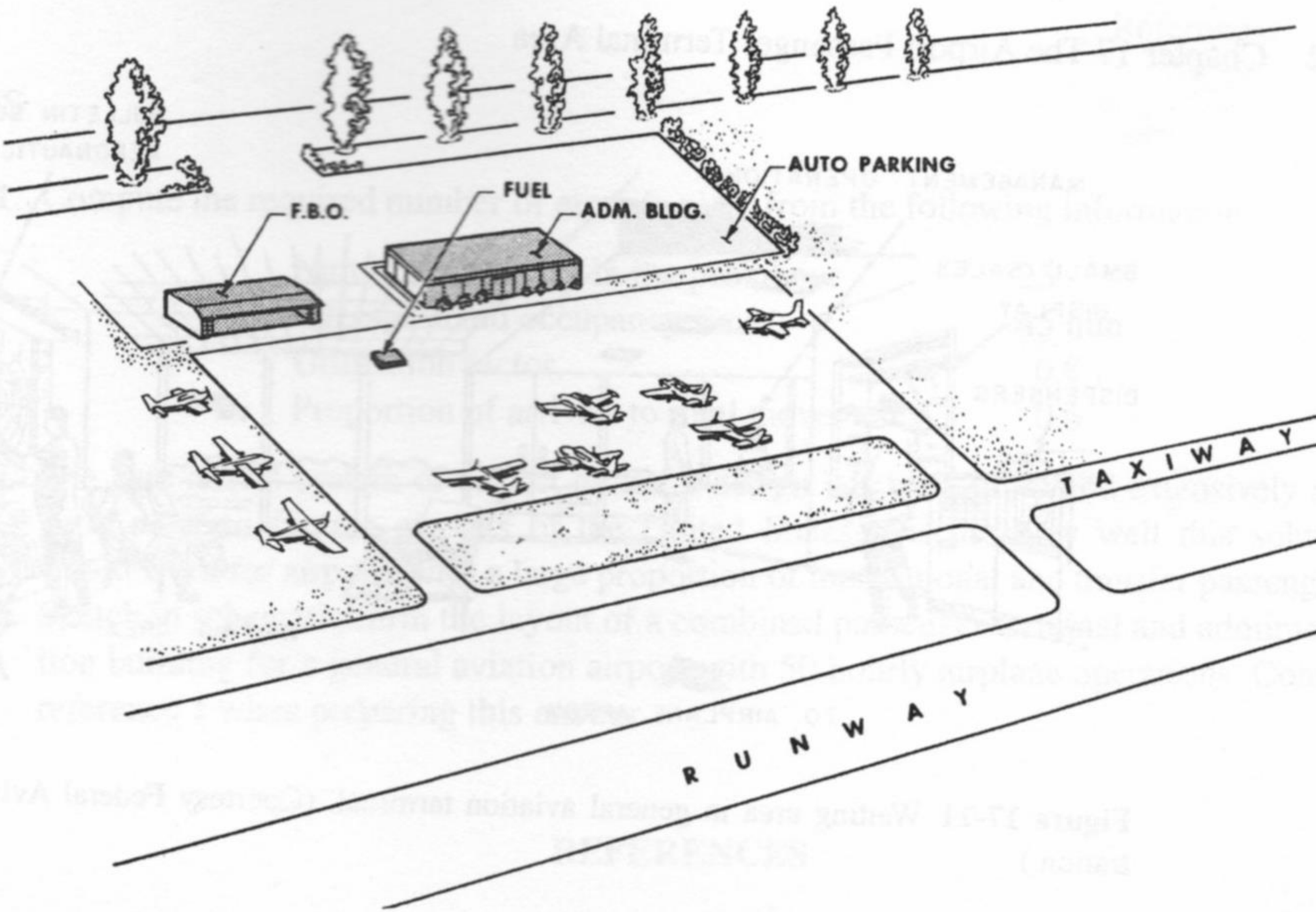
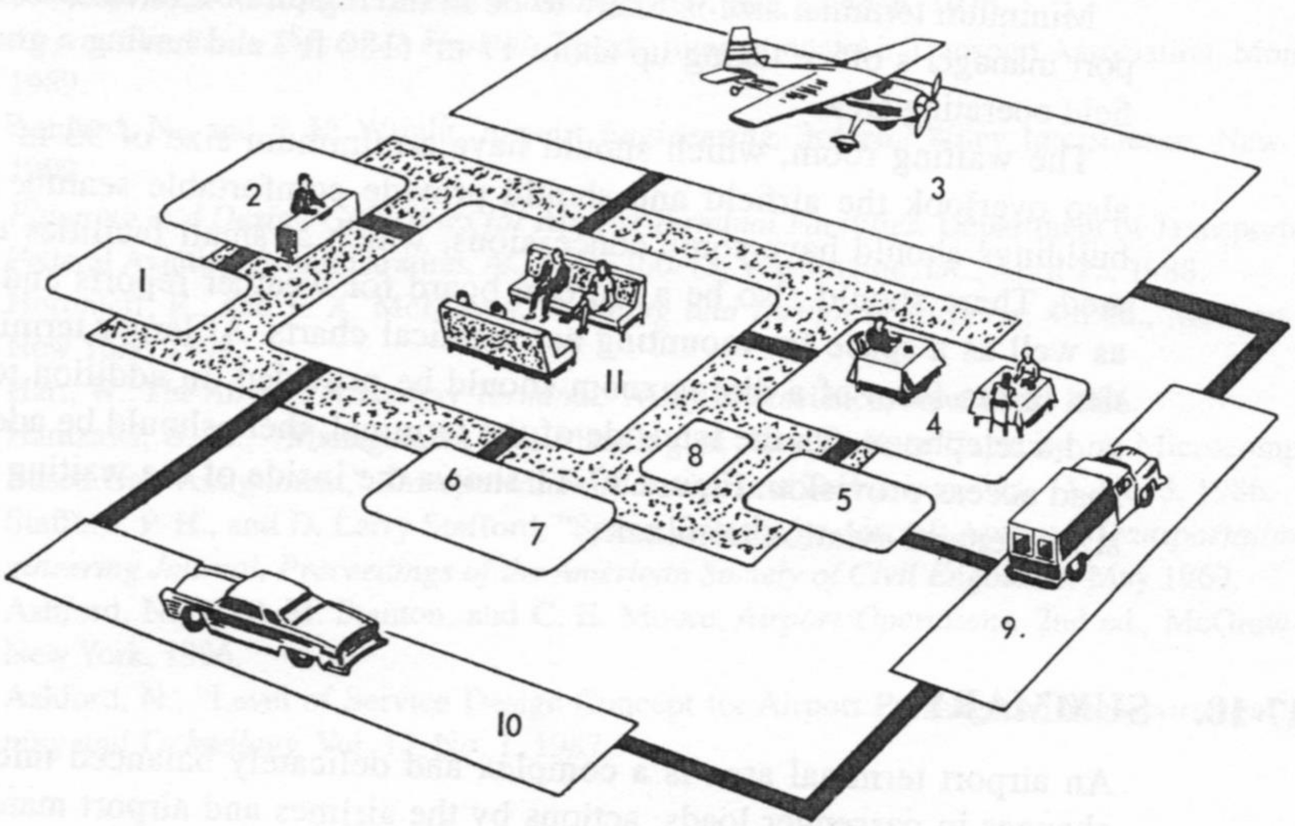


Figure 17-9 Apron terminal area at a general aviation airport. (Courtesy Federal Aviation Administration.)

General Aviation Terminal Area



1. STORAGE
2. OPERATION MANAGEMENT
3. AIRPLANE LOADING APRON
4. DINING AREA
5. KITCHEN
6. REST ROOMS
7. JANITOR CLOSET
8. UTILITIES
9. SERVICE AND APRON ACCESS DRIVE
10. ADMINISTRATION BUILDING DRIVE
11. WAITING AREA

Figure 17-10 A general aviation terminal/administration building. (Courtesy Federal Aviation Administration.)

Waiting Area in general Aviation Terminal

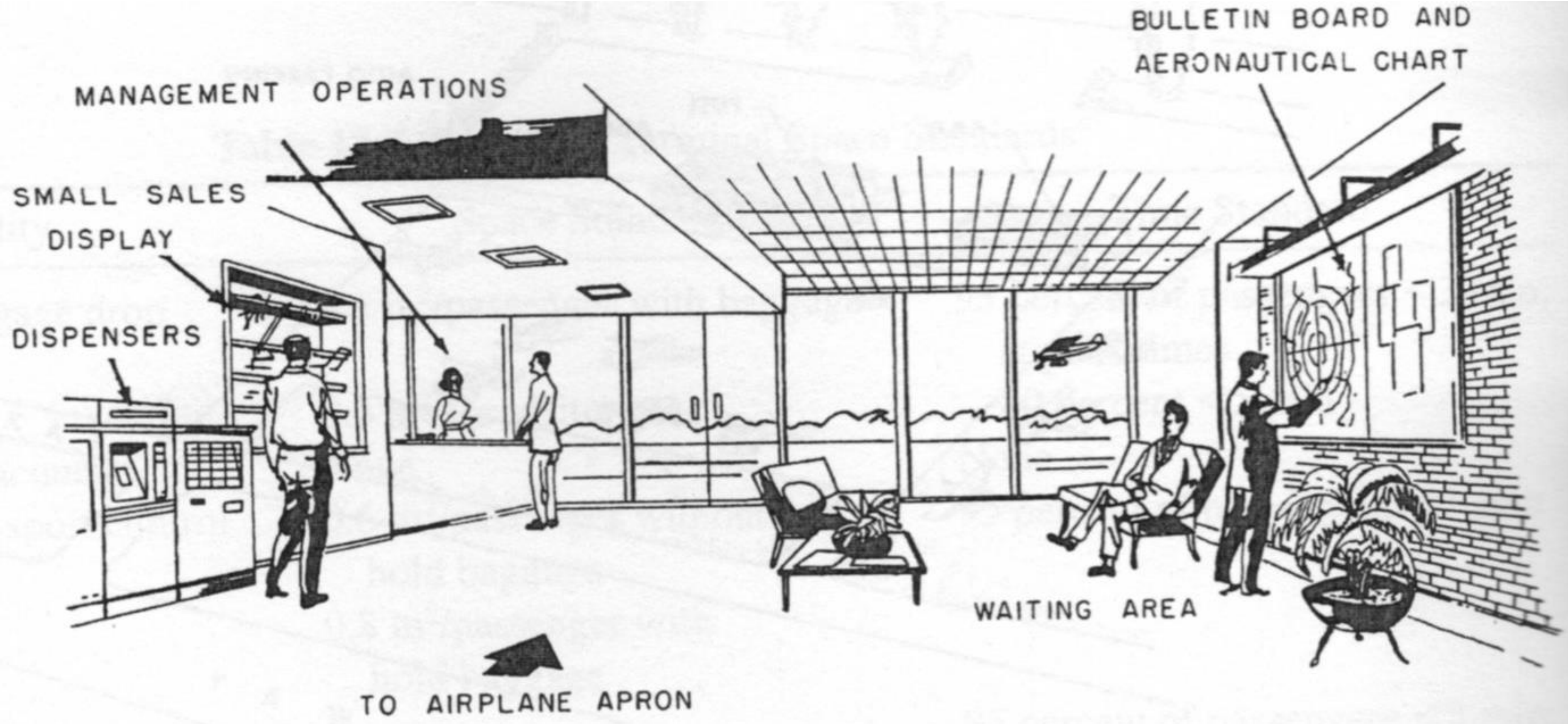


Figure 17-11 Waiting area in general aviation terminal. (Courtesy Federal Aviation Administration.)

Introduction to Water Transportation

- Egyptians had ships 6000 B.C.
- Recently, increase in use is attributed to growing population, new products and new sources of raw materials,…etc
- A need for most modern and efficient port facilities
- 99% of overseas freight tonnage is transported by ships.

Nature of water transportation

- Suitable for heavy commodities
- For long distances
- Where time of transport is not a critical factor

Principal classes of service for shipping industry

1. Liner service: Predetermined schedules between specific ports.

2. Non-Liner service: No schedules, chartering and special voyages.

3. Tanker service: for the carriage of liquid cargo.

Passenger Ships

Few passenger ships remain in service due its low speeds compared with other modes of transportation.

Types:

1. Passenger ferries. (for short distances)
2. Cruising ships. (for recreation)

General Cargo ships:
Trend is increasing the size and the speed.

Bulk Carriers:
Used for carrying the ore and coal.

Tankers:
- Liquid cargo (oil, asphalt, gasoline, chemicals, ...)

Special Ships:

- Container ships: carries containers with standard sizes (ex: 8 x 8 x 20 ft)
- Barge carrying ships: carries its loading and unloading equipment.
- Roll on - Roll off ships: carries loaded pickups and trucks.


Barge carrying ships
MERSINA


Roll on - Roll off ships


Container ships

Ships Characteristics

1- Dimensions:

- Length: governs the length and layout of the sea port terminal
- Beam: governs the width of channels and basins, & cargo handling equipment
- Draft: governs the depths of channels, basins, and ports

2. Cargo carrying capacity
3. Cargo handling (crane, pumps)
4. Types of cargo
5. Shape
6. Mooring equipment
7. Maneuverability

Design of Harbors

Port:

used for commercial activities

Harbor:

partially enclosed water area to protect ships from waves and winds and to control the erosion of the beach

Environmental Considerations:

protection should be provided against biological (termites attack wood) and chemical (rust of steel) factors

Winds:

cause horizontal forces on all structures above water level

Waves:

cause horizontal forces on all structures at the boundaries of the port

Current:

similar to waves but has lower speed

Tide:

rising & falling of water surface (caused by the gravitational attractions of the moon & the sun)

Classes of Harbors

<u>According to Structures:</u>

1. Natural: formed in bays and inlets
2. Artificial: using artificial structures

<u>According to Uses:</u>

1. Commercial: for trade
2. Military: navy

Desirable Features of A Harbor Site

1. Sufficient depth (21 – 37 ft up to 94 ft for tankers)
2. Secure anchorage
3. Adequate anchorage area
4. Narrow channel entrance: width = length of largest ship
5. Protection against wave action
6. Good soil conditions (firm & cohesive along the bottom of the anchorage area)

Shape and Size of Anchorage Area Depend on

1. Maximum number of ships to be served
2. Ship sizes
3. Mooring method (single or two anchors)
4. Maneuverability requirements: radius = ship length
5. Topographic condition at the proposed site

Rule of Thump:

Width of entrance = length of largest ship

Protective costal works

1. Offshore structures (breakwaters) to lessen wave heights and velocities

2. Structures that are built at an angle to the shore, such as jetties and groins to control littoral drift

3. Structures built at or near the shoreline to protect the shore from erosive forces of waves.

4. Natural costal features such as protective beaches to help controlling and dissipating waves without creating adverse environmental effects

Breakwaters and Jetties

Breakwaters:

built parallel to the shorelines to protect the shore area from waves

Jetties:

built perpendicular to the shoreline to maintain a protected entrance channel

Breakwater

Jetty

Breakwater Types:

1. Rubble mound (large stones): natural or artificial (concrete units)

2. Wall breakwaters, made of:
   a. Timber cribs filled with large stones
   b. Concrete caissons filled with sand or stones
   c. Sheet piling
3. Composite (both 1 and 2)

Port Planning

- The planning and size of port begins with an appraisal of present and future commerce types of shipping
- Estimate of number, type, and size of ships t be accommodated
- Estimating capacity of port, tons/year/terminal

- Ships arrive at a public port in accordance with a random pattern

- Poisson distribution may be used to predict the number of days on which a particular number of ships will be present