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A P P U N T I

STUDENTE: Raviglione

MATERIA: Progetto Infrastrutture. Prof. Bassani

PROGETTO di INFRASTRUTTURE

(Design of Transportation infrastructures)

Prof. Bassani

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Planning – plan typologies

RUP= responsabile unico procedimento -> only man responsable of the provediment

An infrastructure will be part of a Plan (or program) after the review and approval of a **Feasibility Study**.

The "Planning Document" is prepared by the Head of the Process (RUP), and establishes the functional and structural characteristics of the infrastructure.

Typologies:

- new construction (corridor studies)
- reconstruction

In future only reconstruction because the territory is full of road (350000 Km in Italy)

New construction plan

Many information are indicated in fesibility: all are necessary to do corridor (territory of land where infrastructure can be located)

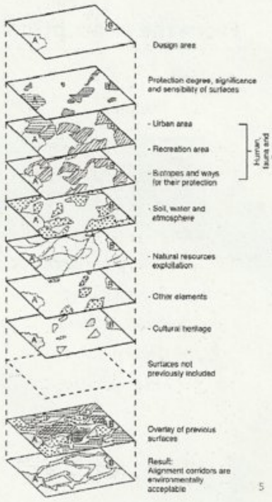
-> no cross on urban area

From FHWA (US). Types of Construction:

New construction: roadways that are built on new alignment = tracciato

From route location process, designers should be identifying **corridors** with sufficient width to enable full criteria to be met.

Corridor formation from environmental and land analysis →



there are several layer information -> in all of layer there is a different information (ex traffic layer or environment layer).

Reconstruction plans

intersection : in the same level +

interchanging : in a different layer ✕

Reconstruction: roadways that are **re-built** primarily along existing alignment.

Reconstruction normally involves:

- full-depth pavement replacement,
- new lanes adjacent to an existing alignment,
- roadway conversion (e.g., a two-lane highway to a multi-lane divided arterial),
- reconfiguration of intersections and interchanges.

This typically involves a major change to an existing highway within the same general right-of-way corridor.

Reconstruction may also include substantial alignment changes to an older highway to eliminate safety and accident problems.

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Example #2

rebuild the pavement
3R reconstruction -> no change

— Curb = cordolo is the same

Contents of a feasibility study

- **Environmental and corridor analysis:**
  - environmental assessment (noise, water, ground consumption..)
  - corridors of reduced environmental impact
  - the main obstacles that impose constraints
- **Network analysis** (see *Transportation Planning* course, 2nd semester)
  - traffic demand analysis and assignment
  - expected level of service
- **Geometric characteristics of the infrastructures**:
  - sezioni trasversali tipo
  - template transversal section and reference design speeds (in Italy the "design speed range" concept is used)
  - typologies of intersection and/or interchanges connecting to existing infrastructures

Design – who is the Designer?

Public bodies (see above) -> administration to provide design (ex anas)

Private bodies:

- single professional
- associated professionals
- engineering companies
  ↳ several types of it (geothecnical, structural ...)

Nowadays the design of a transportation infrastructure involves **civil engineers** experts in the field of:

- infrastructure design and traffic analysis
- structures, tunneling and geotechnics
- hydraulics, geology and environmental subjects

Design levels / stages

you can do attention to a particular aspect → cost and benefits

PLAN / PROGRAM - FS

Needs:

- gradual approach to design starting from general to particular aspects
- evaluation of minimum 3 alternatives
- selection of the best one
- progressively involvement of stakeholders in the design process

DESIGN

- Preliminary stage : it is stabilited who are paid for the infrastructure (ex agriculture owners)
- Definitive stage
- Executive stage

CONSTRUCTION

stakeholders = portatori di interesse (ex enti)
several entity that the project on the modify of infrastructure interest a lot.

Preliminary stage

It contains the same three solutions already studied in the Feasibility study. It explores the following topics:

- geometric and functional characteristics of the infrastructure
- preliminary cost estimation and contract specifications (*capitolato d'appalto - parte amministrativa*)
- **plans** (1:10000 – 1:5000), **profiles** (1:10000/1:1000 – 1:5000/1:500) and **template sections** (1:200) (*sezioni tipo*)

The expropriation process begins at the end of the Preliminary Project. It is necessary to know:

- maps with the occupation area of the infrastructure
- the list of owners to be compensated (*indennità*)

Definitive stage

→ best solution

It contains the only one solution considered in the Preliminary Study. It explores the following topics:

- geometric and structural characteristics of the infrastructure
- preliminary design reports of components (structures, pavements, barriers, ...)
- materials selections
- definitive cost estimation and technical specifications (*capitolato d'appalto – specifiche tecniche*)
- **plans** (1:2000), **profiles** (1:2000/1:200), **template** (1:50) **and cross** (1:200) **sections**

The expropriation process ends in the Definitive stage.

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Laws and technical norms

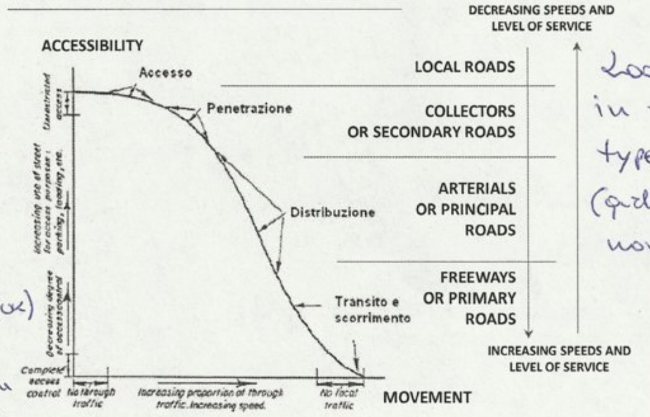
Please, download the documents from the web:

http://www.codiceappalti.it/

http://www.codiceappalti.it/Allegato_XXI_-_Allegato_tecnico_di_cui_all_art_164.htm

Two main function: accessibility / movement
Same infrastructure work in a both for the 2!
Undistributed access: many many access in roads.
Freeways: water way (ok) autostrade → here you can see "No local traffic"

Road classification



Look to the speed in the different type of roads. (quality for the movement).

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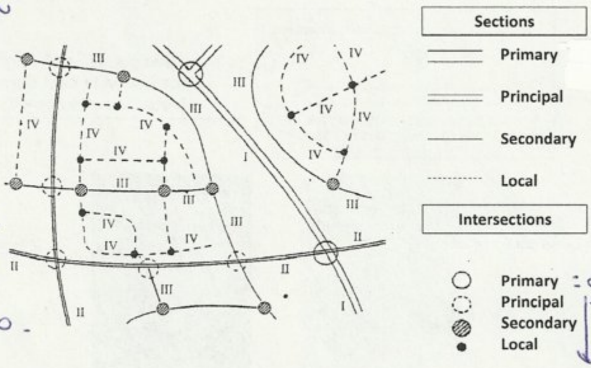
Road classification layout

Not all movement are allow → jump between road network is not allow

Homogeneo: ex II to II
not homogeneo: ex II to III
Local is always homogeneo.



connect primary road to second road and so on.

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Road classification and terminology

difference:
- street: urban area are used
- road: general name for all

A - Autostrade (extraurbane ed urbane)	Motorways / Freeways
B - Strade extraurbane principali	Rural multilane highways (rural arterials)
C - Strade extraurbane secondarie	Two-lanes rural highways
D - Strade urbane di scorrimento	Urban arterials
E - Strade urbane di quartiere	Urban collectors
F - Strade locali (extraurbane ed urbane)	Rural and urban local roads

There are two different environment: rural (extraurbano), urban divided in 4 level → 2·4 = 8 type of road.
Here you can see only 6, but A and F are divided in two!

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B, D are in the same level but different environment

Example – rural roads

high way: used in rural roads

multilane: section with two different carriageway

rilevato: embankment

trincea: trench

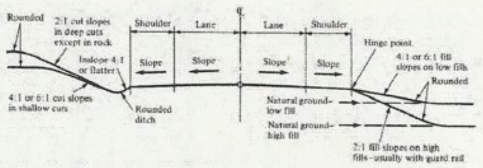


Figure 15.4 Typical Cross Section for Two-Lane Highways

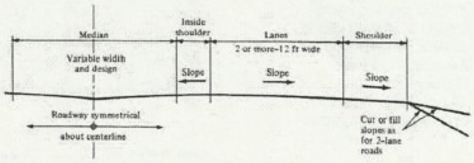
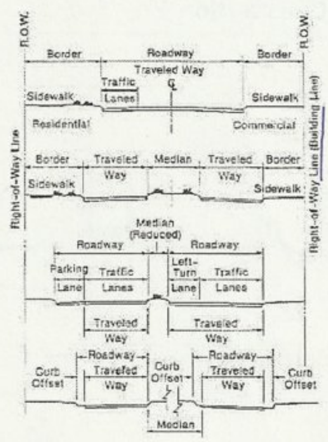


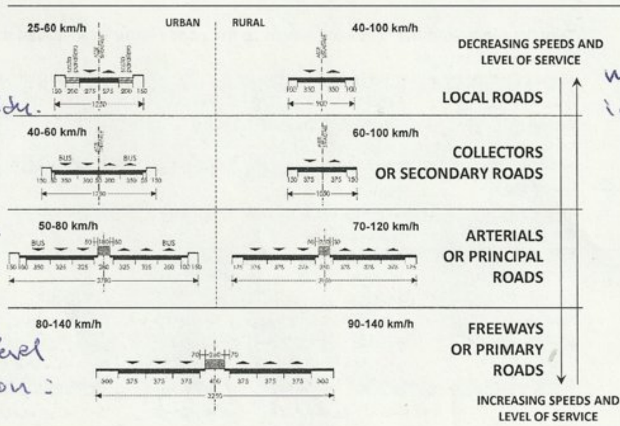
Figure 15.5 Typical Cross Section for Multilane Highways (half section)

Example
Urban roads



Building line: here it can be a contruction

General criteria – Template section



median: margine interno

Differences:
- presence of sidewalk: in italian's road it is allow walker on a shoulder.
- different lane width associated to the speed. 3,60 m is the maximum lane width in american roads.
- difference between the level of road → speed motivation: impact with other car
- last one is the number of lane: traffic and speed!

Design of new facilities

The Italian requirements for the design of new road sections are:

Tipo di strada		LOS minimo	
Autostrade	extraurbane	B	
	urbane	C	
Strade extraurbane principali		B	
Strade extraurbane secondarie		C	(*)
Strade urbane di scorrimento		E	
Strade urbane di quartiere		E	
Strade locali	extraurbane	C	(*)
	urbane	E	

Symbol (*) denotes fixed composition sections.

Level of service is designed
when you reach capacity : level of service is E (lower service - saturated lane or section)
↓
instable condition
stop and go

National road code : codice della strada

Slide 2 lecture #3
local system : moving system for the alignment → projection
3D planes but we use 2D image
horizontal reference surface : when we projected
Contour line : curve di livello
brown section is a 3D surface : model Terrain
Profile : cilindrical surface → move on the space ↑ since we interchected the 3D surface terrain
the black line is the intersection.
profile rappresent the stretch on a plane (allungamento su un piano)
Road centerline : the project of infrastructure

 Section : created in all infrastructure

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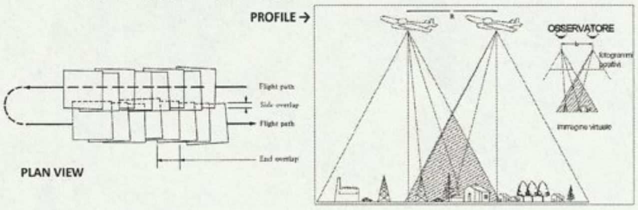
Terrain data

To build a DTM, spatial data need to be acquired. They can be obtained from:

- Official cartography (from Istituto Geografico Militare)
- Technical cartography (from local administrations)
- Maps (aerial or terrestrial surveys)

Aerophotogrammetry is widely used to collect territorial spatial data and produce cartography and maps.



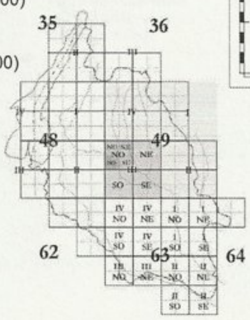
Official cartography

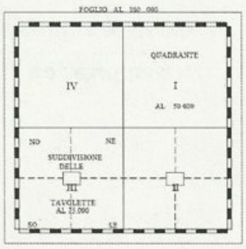
e-map: inquadramento where is the project, the general position of it.

Fogli (1:100.000)
A total of 227 covers the Italian territory

Quadranti (1:50.000)
I, II, III, IV

Tavolette (1:25.000)
NO, NE, SO, SE





Terrain data

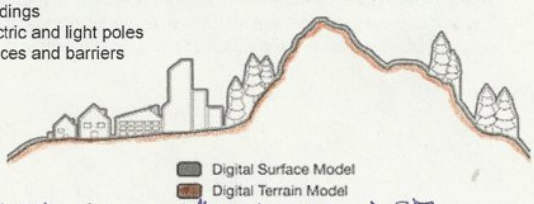
The terrain data includes:

- Land surface (without vegetation)
- Existing infrastructures (road and railways)
- Natural rivers and channels

They do not include artificial elements such as:

- Buildings
- Electric and light poles
- Fences and barriers

light pol = palo della luce
remove to DTM



DTM is different to DSM

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TIN Formation (phase II)

To import the terrain features into a road design software some manipulations to layers and objects inside the drawing are necessary (see above). The cleaning process is the first step that a road designer has to do before starting the alignment design.

Delete the heading and all the external content of the drawing (every element that is outside the cartography border, like labels, etc…)

Delete all the elements that are on the plane zero, so without the third coordinate. Then buildings, vegetation, …

CODICE	ENTITA'	SPESSORE TRATTO	GRAFICO ESPLICATIVO
1000	Limite elemento Pararecinzione	0,18	
1010	Strade asfaltate Strade urbane	0,18	
1020	Strade non asfaltate carreggiabile, sterrata, campestre	0,18	
1030	Mulattiera, Sentiero	0,25	
1040	Strade in costruzione	0,18	
1050	Ponte, Viadotto	0,18	
1060	Spartitraffico stradale Aiuola spartitraffico rilevante	0,13	
1070	Passerella pedonale	0,13	
1080	Scarpata, Rampa	0,18	
1090	Binario di ferrovia	0,35	
1100	Binario di ferrovia a scartamento ridotto	0,35	
1110	Binario in costruzione	0,35	
1120	Binario in disuso	0,35	
1130	Passaggio a livello		
1140	Trasporto a mezzo cavo Seggiovia, Cabinovia	0,13	
1150	Sostegni piloni, Altri elementi di sostegno nel trasporto a mezzo cavo	0,13	

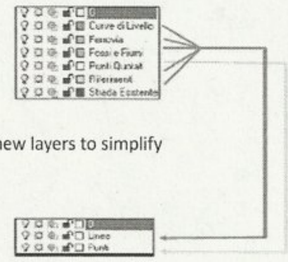
TIN formation (phase II)

Terrain data are normally available on *.dgn or *.dwg files. 3D entities are normally composed of:

- Lines
- Points

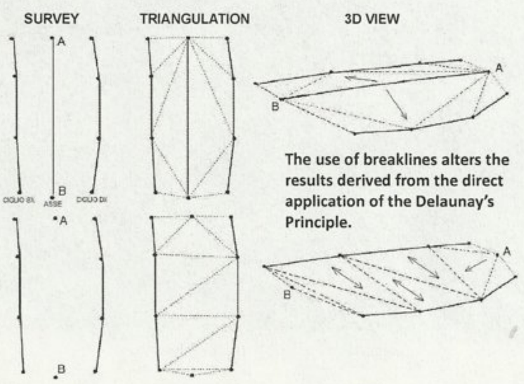
and located in several layers.

These data can be grouped into new layers to simplify the structure of data:



TIN Formation (phase II)

margin of existent board → breaklines (cigli stradali) → spigoli di superficie di un territorio
Se non considero l'asse perdo la pendenza trasversale



The use of breaklines alters the results derived from the direct application of the Delaunay's Principle.

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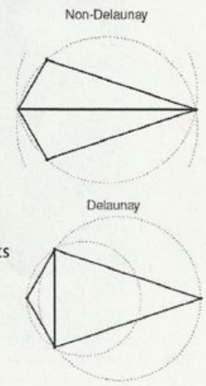
Terrain modeling

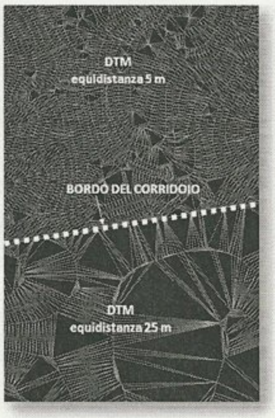
... (continue)

- the Delaunay triangulation maximizes the minimum angle. Compared to any other triangulation of the points, the smallest angle in the Delaunay triangulation is at least as large as the smallest angle in any other. However, the Delaunay triangulation does not necessarily minimize the maximum angle;
- if a circle passing through two of the input points doesn't contain any other of them in its interior, then the segment connecting the two points is an edge of a Delaunay triangulation of the given points.



Create triangle as much as possible similar to the reality of the terrain

TIN formation (phase III)



Contour line and contour interval (or *vertical interval*) of a map or a TIN.

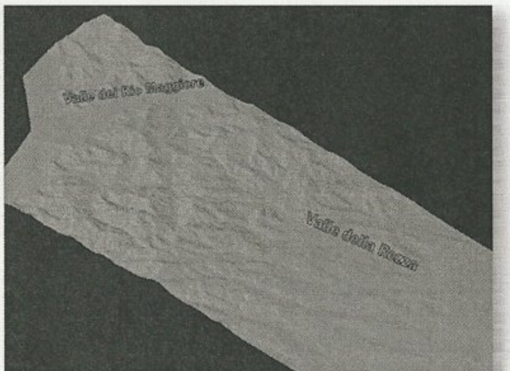
Remember that:

Terrain surface = the surface derived from survey (including existing infrastructures)

Project surface = the designed surface of the new infrastructure

Good DTM are when 3D details and triangles are near to each other.

TIN formation (phase IV)



3D rendering from DTM 1:5000

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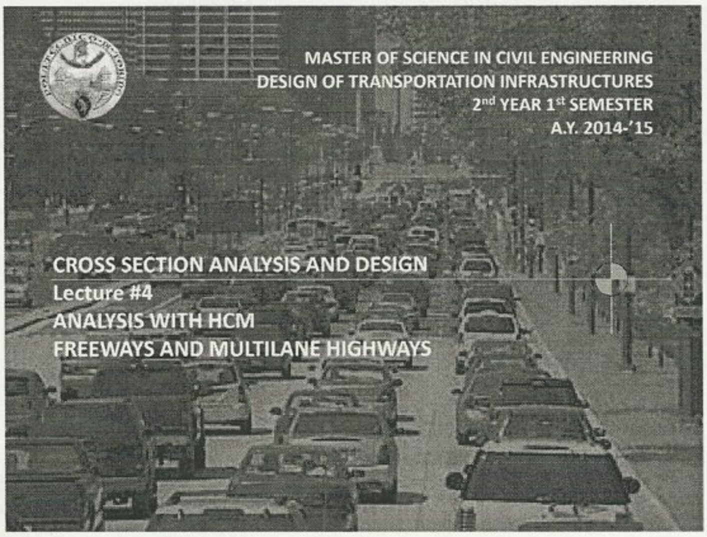


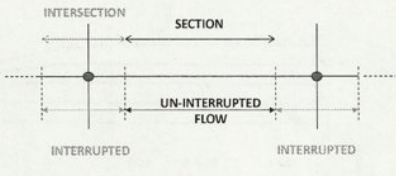
HCM 2010

functional design infrastructure

The objectives of the HCM are to

1. Define performance measures and describe survey methods for key traffic characteristics,
2. Provide methodologies for estimating and predicting performance measures, and
3. Explain methodologies at a level of detail that allows readers to understand the factors affecting multimodal operation.

Flow conditions



Un-interrupted flow conditions are typical of those facilities where traffic can be interrupted only by internal causes (i.e., accident, congestion), and in which there is no obstructions to the movement of vehicles along the road. Uninterrupted flow is possible in sections where signal spacing is sufficient to allow for uninterrupted flow.
Measure of effectiveness is <u>density</u> in freeways. <u>Speed</u> also becomes important in two-lane highways and multilane highways.

Stream = corrente stradale

/12

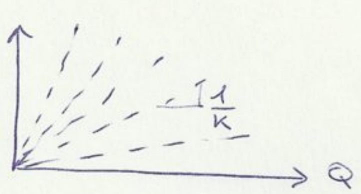
FFS = speed in free flow condition
we can measure it.
It is the medium speed of the stream (fifty percentile of a gaussian distribution).
Depend of geometrical characterist : distance of shoulder, number of lane, lane width...
Positioned on the vertical axis.

Capacity : depend only from the infrastructure characterist
Positioned on the orizontal axis. (Flow rate)

Density : measured in passengers car / miles / lane
it is what reduce the speed way.
it is represented by a bundle of straight lines (fascio di rette) centred on the origin of the axis.

The general equation is $Q = K \cdot V$
Q = flow rate
K = density
V = speed

If you derive : $V = \frac{1}{K} Q$



Equation of bundle of straight lines infact if you increase density, the cofficient $\frac{1}{K}$ decrease and the straight line is going to the orizontal axis.

Freeways SF_i (pc/h/ln)

FFS	LOS				
mi/h	A	B	C	D	E
75	820	1310	1750	2110	2400
70	770	1250	1690	2080	2400
65	710	1170	1630	2030	2350
60	660	1080	1560	2010	2300
55	600	990	1430	1900	2250

Base conditions

Models and equations refer to **base conditions** defined as the absence of restrictive geometric, traffic, or environmental factors.

Every situation in which some differences occur, correction factors must be adopted.

Base free-flow conditions include the following freeway characteristics:
- lanes are 12 ft wide,
- lateral clearance between the edge of a right lane and an obstacle is 6 ft or greater,
- there are no trucks, buses, or RVs in the traffic stream, ← RVs = recreation of veichles (capers, roulotte, touristic veichle).
- urban freeways are five lanes in each direction,
- interchanges are spaced at least 2 mi (3.2 km) apart,
- grades do not exceed 2%, → for flat terrain
- drivers are familiar with the freeway.

For condition base:
- $f_{HV} = 1$ when no heavy veicles but only passengers/car
- $f_P = 1$ when familiar drivers.

Freeway analysis and design

Methodologies include:

- **LOS analysis:**

$$v_p = \frac{V}{PHF \times N \times f_{HV} \times f_p}$$

where

- v_p = demand flow rate under equivalent base conditions (pc/h/ln),
- V = demand volume under prevailing conditions (veh/h),
- PHF = peak-hour factor,
- N = number of lanes in analysis direction,
- f_{HV} = adjustment factor for presence of heavy vehicles in traffic stream, and
- f_p = adjustment factor for unfamiliar driver populations.

v_p is used when we want calculate LOS of existent infrastructure
N is used for design a new infrastructure (how many lane are necessary to warranty a determinate LOS).

- **Section (# Lane) design**

$$N = \frac{V(v/h)}{PHF \cdot SF_i(pc/h/ln) \cdot f_{hv} \cdot f_p}$$

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Input data

Parameter	Domains		Corrective factors
Free flow speed (FFS)	55-75 mi/h	90-120 km/h	-
Lanes per direction (N)	≥ 2		-
Lane width (LW)	10-12 ft	3,00-3,60 m	f_{LW}
Shoulder width (*clearance*)	0-6 ft	0,00-1,80 m	f_{LC}
Ramp density (TRD)	0-6 ramps/mi	0-3,8 ramp/km	-
Terrain	Level-rolling-mountainous		f_{HV}
Traffic composition	tracks-/buses/RV		
Peak hour factor (PHF)	≤ 1,00		-
Drivers	0,85 – 1,00		f_P

Step #1: Free flow speed

75,4 is a constant value. Because Freeway are designed with high value of radius (so FFS not depend of the project). In opposite there are multi-lane highway that the value of radius are not too high. For this reason FFS depend only by 3 parameters.

In this type of facility speed is not affected by the alignment. Thus for base conditions the speed (BFFS) is always equal to 75.4 mi/h:

$$FFS = 75.4 - f_{LW} - f_{LC} - 3.22\,TRD^{0.84}$$

where

FFS = FFS of basic freeway segment (mi/h),
f_{LW} = adjustment for lane width (mi/h),
f_{LC} = adjustment for right-side lateral clearance (mi/h), and
TRD = total ramp density (ramps/mi).

Step #1: Free flow speed

Exhibit 11-8
Adjustment to FFS for Average Lane Width

Average Lane Width (ft)	Reduction in FFS, f_{LW} (mi/h)
≥12	0.0
≥11–12	1.9
≥10–11	6.6

Exhibit 11-9
Adjustment to FFS for Right-Side Lateral Clearance, f_{LC} (mi/h)

Right-Side Lateral Clearance (ft)	Lanes in One Direction 2	3	4	≥5
≥6	0.0	0.0	0.0	0.0
5	0.6	0.4	0.2	0.1
4	1.2	0.8	0.4	0.2
3	1.8	1.2	0.6	0.3
2	2.4	1.6	0.8	0.4
1	3.0	2.0	1.0	0.5
0	3.6	2.4	1.2	0.6

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Step #2: Flow rate

Exhibit 11-12
PCEs for RVs (E_R) on Upgrades

Upgrade (%)	Length (mi)	Proportion of RVs 2%	4%	5%	6%	8%	10%	15%	20%	≥25%
≤2	All	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
>2–3	0.00–0.50	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	>0.50	3.0	1.5	1.5	1.5	1.5	1.5	1.2	1.2	1.2
>3–4	0.00–0.25	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	>0.25–0.50	2.5	2.5	2.0	2.0	2.0	2.0	1.5	1.5	1.5
	>0.50	3.0	2.5	2.5	2.5	2.0	2.0	2.0	1.5	1.5
>4–5	0.00–0.25	2.5	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5
	>0.25–0.50	4.0	3.0	3.0	3.0	2.5	2.5	2.0	2.0	2.0
	>0.50	4.5	3.5	3.0	3.0	3.0	2.5	2.5	2.0	2.0
>5	0.00–0.25	4.0	3.0	2.5	2.5	2.5	2.0	2.0	2.0	1.5
	>0.25–0.50	6.0	4.0	4.0	3.5	3.0	3.0	2.5	2.5	2.0
	>0.50	6.0	4.5	4.0	4.0	3.5	3.0	3.0	2.5	2.0

Note: Interpolation for percentage of RVs is recommended to the nearest 0.1.

Exhibit 11-13
PCEs for Trucks and Buses (E_T) on Specific Downgrades

Downgrade (%)	Length of Grade (mi)	Proportion of Trucks and Buses 5%	10%	15%	≥20%
<4	All	1.5	1.5	1.5	1.5
4–5	≤4	1.5	1.5	1.5	1.5
	>4	2.0	2.0	2.0	1.5
>5–6	≤4	1.5	1.5	1.5	1.5
	>4	5.5	4.0	4.0	3.0
>6	≤4	1.5	1.5	1.5	1.5
	>4	7.5	6.0	5.5	4.5

Step #2: Flow rate

Adjustment for Driver Population

The base traffic stream characteristics for basic freeway segments are representative of traffic streams composed primarily of commuters, or drivers who are familiar with the facility. It is generally accepted that traffic streams with different characteristics (e.g., recreational drivers) use freeways less efficiently. Although data are sparse and reported results vary substantially, significantly lower capacities have been reported on weekends, particularly in recreational areas. It may generally be assumed that the reduction in capacity (LOS E) extends to service flow rates and service volumes for other LOS as well.

The adjustment factor f_p is used to reflect the effect of driver population. The values of f_p range from 0.85 to 1.00 in most cases, although lower values have been observed in isolated cases. In general, the analyst should use a value of 1.00, which reflects commuters or otherwise-accustomed drivers, unless there is sufficient evidence that a lower value should be used. Where greater accuracy is needed, comparative field studies of commuter and recreational traffic flow and speeds are recommended.

Step #3: Density and LOS

$$D = \frac{v_p}{S}$$

where

D = density (pc/mi/ln),

v_p = demand flow rate (pc/h/ln), and

S = mean speed of traffic stream under base conditions (mi/h).

LOS	Density (pc/mi/ln)
A	≤11
B	>11–18
C	>18–26
D	>26–35
E	>35–45
F	Demand exceeds capacity >45

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Input data

Parameter	Domains		Corrective factor
Free flow speed (FFS)	45-60 mi/h	70-100 km/h	-
Lane per direction (N)	2-3		-
Lane width (LW)	10-12 ft	3,00-3,60 m	f_{LW}
Right shoulder width (*clearance*)	0-6 ft	0,00-1,80 m	f_{LC}
Left shoulder width (*clearance*)	0-6 ft	0,00-1,80 m	
Type of median	Divided, undivided, TWLTL		f_M
Access points	0-40 ramps/mi	0-25 rampe/km	f_A
Terrain	Level-rolling-mountainous		f_{HV}
Traffic	tracks-/buses/RV		
Peak hour factor (PHF)	≤ 1,00		-
Drivers	0,85 – 1,00		f_P

MLH LOS analysis

BFFS depend by the infrastructure

$$FFS = BFFS - f_{LW} - f_{LC} - f_M - f_A$$

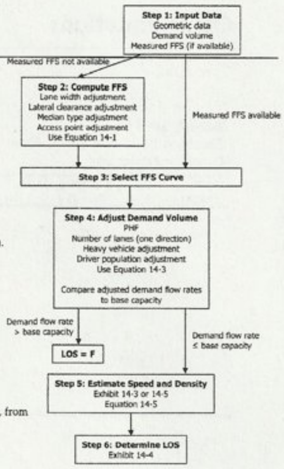
where

$BFFS$ = base FFS for multilane highway segment (mi/h);
FFS = FFS of basic freeway segment (mi/h);
f_{LW} = adjustment for lane width, from Exhibit 14-8 (mi/h);
f_{LC} = adjustment for TLC, from Exhibit 14-9 (mi/h);
f_M = adjustment for median type, from Exhibit 14-10 (mi/h); and
f_A = adjustment for access-point density, from Exhibit 14-11 (mi/h).

$$v_p = \frac{V}{PHF \times N \times f_{HV} \times f_p}$$

where

v_p = demand flow rate under equivalent base conditions (pc/h/ln);
V = demand volume under prevailing conditions (veh/h);
PHF = peak hour factor;
N = number of lanes (one direction);
f_{HV} = adjustment factor for presence of heavy vehicles in traffic stream, from Equation 14-4; and
f_p = adjustment factor for atypical driver populations.



Step #1: Free flow speed

Exhibit 14-8
Adjustment to FFS for Average Lane Width

Lane Width (ft)	Reduction in FFS, f_{LW} (mi/h)
≥12	0.0
≥11–12	1.9
≥10–11	6.6

TWLTL = two-way left turn lanes

Exhibit 14-10
Adjustment to FFS for Median Type

Median Type	Reduction in FFS, f_M (mi/h)
Undivided	1.6
TWLTL	0.0
Divided	0.0

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Step #2: Flow rate

Exhibit 14-13
PCEs for Trucks and Buses (E_T) on Upgrades

Percent Upgrade	Length (mi)	Proportion of Trucks and Buses 2%	4%	5%	6%	8%	10%	15%	20%	25%
≤2	All	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
>2 – 3	0.00 – 0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.25 – 0.50	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.50 – 0.75	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.75 – 1.00	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5
	>1.00 – 1.50	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	>1.50	3.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	2.0
>3 – 4	0.00 – 0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.25 – 0.50	2.0	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5
	>0.50 – 0.75	2.5	2.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	>0.75 – 1.00	3.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	2.0
	>1.00 – 1.50	3.5	3.5	3.0	3.0	3.0	3.0	2.5	2.5	2.5
	>1.50	4.0	3.5	3.0	3.0	3.0	3.0	2.5	2.5	2.5
>4 – 5	0.00 – 0.25	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.25 – 0.50	3.0	2.5	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	>0.50 – 0.75	3.5	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.5
	>0.75 – 1.00	4.0	3.5	3.5	3.5	3.0	3.0	3.0	3.0	3.0
	>1.00	5.0	4.0	4.0	4.0	3.5	3.5	3.0	3.0	3.0
>5 – 6	0.00 – 0.25	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	>0.25 – 0.30	4.0	3.0	2.5	2.5	2.0	2.0	2.0	2.0	2.0
	>0.30 – 0.50	4.5	4.0	3.5	3.0	2.5	2.5	2.5	2.5	2.5
	>0.50 – 0.75	5.0	4.5	4.0	3.5	3.0	3.0	3.0	3.0	3.0
	>0.75 – 1.00	5.5	5.0	4.5	4.0	3.0	3.0	3.0	3.0	3.0
	>1.00	6.0	5.0	5.0	4.5	3.5	3.5	3.5	3.5	3.5
>6	0.00 – 0.25	4.0	3.0	2.5	2.5	2.5	2.5	2.0	2.0	1.0
	>0.25 – 0.30	4.5	4.0	3.5	3.5	3.5	3.0	2.5	2.5	2.5
	>0.30 – 0.50	5.0	4.5	4.0	4.0	3.5	3.0	2.5	2.5	2.5
	>0.50 – 0.75	5.5	5.0	4.5	4.5	4.0	3.5	3.0	3.0	3.0
	>0.75 – 1.00	6.0	5.5	5.0	5.0	4.5	4.0	3.5	3.5	3.5
	>1.00	7.0	6.0	5.5	5.5	5.0	4.5	4.0	4.0	4.0

Note: Interpolation for percentage of trucks and buses is recommended to the nearest 0.1.

Step #2: Flow rate

Exhibit 14-14
PCEs for RVs (E_R) on Upgrades

Percent Upgrade	Length (mi)	Proportion of RVs 2%	4%	5%	6%	8%	10%	15%	20%	25%
≤2	All	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
>2 – 3	0.00 – 0.50	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	>0.50	3.0	1.5	1.5	1.5	1.5	1.5	1.2	1.2	1.2
>3 – 4	0.00 – 0.25	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	>0.25 – 0.50	2.5	2.5	2.0	2.0	2.0	2.0	1.5	1.5	1.5
	>0.50	3.0	2.5	2.5	2.5	2.0	2.0	2.0	1.5	1.5
>4 – 5	0.00 – 0.25	2.5	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5
	>0.25 – 0.50	4.0	3.0	3.0	3.0	2.5	2.5	2.0	2.0	2.0
	> 0.50	4.5	3.5	3.0	3.0	3.0	2.5	2.5	2.0	2.0
>5	0.00 – 0.25	4.0	3.0	2.5	2.5	2.5	2.0	2.0	2.0	1.5
	>0.25 – 0.50	6.0	4.0	4.0	3.5	3.0	3.0	2.5	2.5	2.0
	>0.50	6.0	4.5	4.0	4.0	3.5	3.0	3.0	2.5	2.0

Note: Interpolation for percentage of RVs is recommended to the nearest 0.1.

Exhibit 14-15
PCEs for Trucks and Buses (E_T) on Specific Downgrades

Percent Downgrade	Length of Grade (mi)	Proportion of Trucks and Buses 5%	10%	15%	20%
<4	All	1.5	1.5	1.5	1.5
4 – 5	≤4	1.5	1.5	1.5	1.5
	>4	2.0	2.0	2.0	1.5
>5 – 6	≤4	1.5	1.5	1.5	1.5
	>4	5.5	4.0	4.0	3.0
>6	≤4	1.5	1.5	1.5	1.5
	>4	7.5	6.0	5.5	4.5

Step #3: Density and Level of Service

$$D = \frac{v_p}{S}$$

where

D = density (pc/mi/ln),

v_p = demand flow rate (pc/h/ln), and

S = mean speed of traffic stream under base conditions (mi/h).

LOS	FFS (mi/h)	Density (pc/mi/ln)
A	All	>0–11
B	All	>11–18
C	All	>18–26
D	All	>26–35
E	60	>35–40
	55	>35–41
	50	>35–43
	45	>35–45
F	Demand Exceeds Capacity	
	60	>40
	55	>41
	50	>43
	45	>45

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A.Y. 2014 – '15
Master of Science in Civil Engineering

Design of Transportation Infrastructures
prof. Marco Bassani

Lecture #5 (Tutorial)

Reference: Roess, R.P., Prassas, E.S., McShane, W.R. (2011). *Traffic Engineering*. Pearson ed.

1) **Example 14-1: An Urban Freeway**

An old 6-lane urban freeway has the following characteristics: 11-foot lanes; frequent roadside obstructions located 2 feet from the right pavement edge; and a total ramp density of 3 ramps/mile. What is the free-flow speed of this freeway?

Solution: The free-flow speed of a freeway may be estimated using Equation 12-5:

$$FFS = 75.4 - f_{LW} - f_{LC} - 3.22 TRD^{0.84}$$

The following values are used in this computation:

f_{LW} = 1.9 mi/h (Table 14.5, 11-ft lanes)
f_{LC} = 1.6 mi/h (Table 14.6, 2-ft lateral clearance, 3 lanes)
TRD = 3 ramps/mi

Then:

$$FFS = 75.4 - 1.9 - 1.6 - 3.22(3^{0.84})$$
$$= 75.4 - 11.6 = 63.8 \text{ mi/h}$$

2) **Example 14-2: A Four-Lane Suburban Multilane Highway**

A four-lane undivided multilane highway in a suburban area has the following characteristics: posted speed limit = 50 mi/h; 11-foot lanes; frequent obstructions located 4 feet from the right pavement edge; 30 access points/mi on the right side of the facility. What is the free-flow speed for the direction described?

Solution: The free-flow speed for a multilane highway is computed using Equation 14-6:

$$FFS = BFFS - f_{LW} - f_{LC} - f_M - f_A$$

The base free-flow speed for a multilane highway may be taken as 60 mi/h as a default or may be related to the posted speed limit. In the latter case, for a posted speed limit of 50 mi/h, the base free-flow speed may be taken to be 5 mi/h more than the limit, or 50 + 5 = 55 mi/h. This is the value that will be used.

Adjustments to the base free-flow speed are as follows:

f_{LW} = 1.9 mi/h (Table 14.5, 11-ft lanes)
f_{LC} = 0.4 mi/h (Table 14.7, total lateral clearance = 10 ft, 4-lane highway)
f_M = 1.6 mi/h (Table 14.8, undivided highway)
f_A = 7.5 mi/h (Table 14.9, 30 access points/mi)

Then:

$$FFS = 55.0 - 1.9 - 0.4 - 1.6 - 7.5 = 43.6 \text{ mi/h}$$

Note that in selecting the adjustment for lateral clearance, the total lateral clearance is 4 feet (for the right side) plus an assumed value of 6.0 feet (for the left or median side) of an undivided highway.

3) **Example 14-3: Determination and Use of the Heavy-Vehicle Adjustment Factor**

Consider the following situation: A volume of 2,500 veh/h traverses a section of freeway and contains 15% trucks and 5% RVs. The section in question is on a 5% upgrade, 0.75 miles in length. What is the equivalent volume in passenger-car equivalents?

Solution: The solution is started by finding the passenger car equivalent of trucks and RVs on the freeway section described (5% upgrade, 0.75 miles). These are found in Tables 14.12 and 14.13, respectively:

E_T = 2.5 (Table 14.12, 15% trucks, >4–5%, >0.50–0.75 mi)
E_R = 3.0 (Table 14.13, 5% RV's, >4–5%, >0.50 mi)

In entering values from these tables, care must be taken to observe the boundary conditions.

The heavy-vehicle adjustment factor may now be computed as:

$$f_{HV} = \frac{1}{1 + 0.15(2.5 - 1) + 0.05(3.0 - 1)}$$

$$= \frac{1}{1.325} = 0.7547$$

and the passenger-car equivalent volume may be estimated as:

$$V_{pce} = \frac{V_{vph}}{f_{HV}} = \frac{2{,}500}{0.7547} = 3{,}313 \text{ pc/h}$$

The solution can also be found by applying the passenger-car equivalents directly:

Truck pces: 2,500*0.15*2.5 = 938
RV pces: 2,500*0.05*3.0 = 375
Pass Cars: 2,500*0.80*1.0 = 2,000
TOTAL pces: 3,313

Table 14.15: Spreadsheet Computation of Service Flow Rates and Service Volumes

Level of Service	MSF (pc/h/ln)	N	f_{HV}	f_p	SF (veh/h)	PHF	SV (veh/h)
A	770	3	0.863	1.000	**1,994**	0.92	**1,834**
B	1,250	3	0.863	1.000	**3,236**	0.92	**2,977**
C	1,690	3	0.863	1.000	**4,375**	0.92	**4,301**
D	2,080	3	0.863	1.000	**5,385**	0.92	**4,954**
E	2,400	3	0.863	1.000	**6,214**	0.92	**5,617**

Step 2: *Determine the Maximum Service Flow Rates for Each Level of Service* Maximum service flow (MSF) rates for each level of service are drawn from Table 14.3 for a freeway with a 70-mi/h free-flow speed. These values are A: 770 pc/h/ln, B: 1,250 pc/h/ln, C: 1,690 pc/h/ln, D: 2,080 pc/h/ln, and E: 2,400 pc/h/ln.

Step 3: *Determine the Heavy-Vehicle Factor* The heavy-vehicle factor is computed as:

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$$

where: P_T = 0.08 (given)
P_R = 0.00 (given)
E_T = 2.5 (Exhibit 14-11, rolling terrain)

Then:

$$f_{HV} = \frac{1}{1 + 0.08(2.5 - 1)} = \frac{1}{1.12} = 0.893$$

Step 4: *Determine the Service Flow Rates and Service Volumes for Each Level of Service* Service flow rates and service volumes are computed using Equations 14-2 and 14-3:

$$SF_i = MSF_i * N * f_{HV} * f_p$$
$$SV_i = SF_i * PHF$$

where: MSF_i = as determined in Step 2
N = 3 (given)
f_{HV} = 0.893 (as computed in Step 3)
f_p = 1.00 (regular users)
PHF = 0.92 (given)

These computations are shown in Table 14.15.

The service flow rates (SF) refer to the peak 15-minute interval; service volumes apply to peak-hour volumes.

Step 5: *Determine Target-Year Peak-Demand Volumes* The problem statement indicates that present demand is 3,600 veh/h and that this volume will increase by 6% per year for the foreseeable future. Future demand volumes may be computed as:

$$V_j = V_o\,(1.06^n)$$

where: V_j = peak-hour demand volume in target year j
V_o = peak-hour demand volume in year 0, 3,600 veh/h
N = number of years to target year

Then:

$$V_o = 3{,}600 \text{ veh/h}$$
$$V_5 = 3{,}600(1.06^5) = 4{,}818 \text{ veh/h}$$
$$V_{10} = 3{,}600(1.06^{10}) = 6{,}447 \text{ veh/h}$$
$$V_{15} = 3{,}600(1.06^{15}) = 8{,}628 \text{ veh/h}$$
$$V_{20} = 3{,}600(1.06^{20}) = 11{,}546 \text{ veh/h}$$

Step 6: *Determine Target Year Levels of Service* The target year demand volumes are stated as full peak-hour volumes. They are, therefore, compared to the *service volumes* computed in Table 14.15 to determine LOS. The results are shown in Table 14.16.

As indicated in Table 14.16, level of service F prevails in target years 10, 15, and 20. In each of these years, demand exceeds capacity. Clearly, the point at which capacity is reached occurs between years 5 and 10. Capacity, stated in terms of a full peak hour, is 5,617 veh/h (Table 14.15). The exact year that demand reaches capacity may be found as follows:

$$5617 = 3600(1.06^n)$$
$$n = 7.63$$

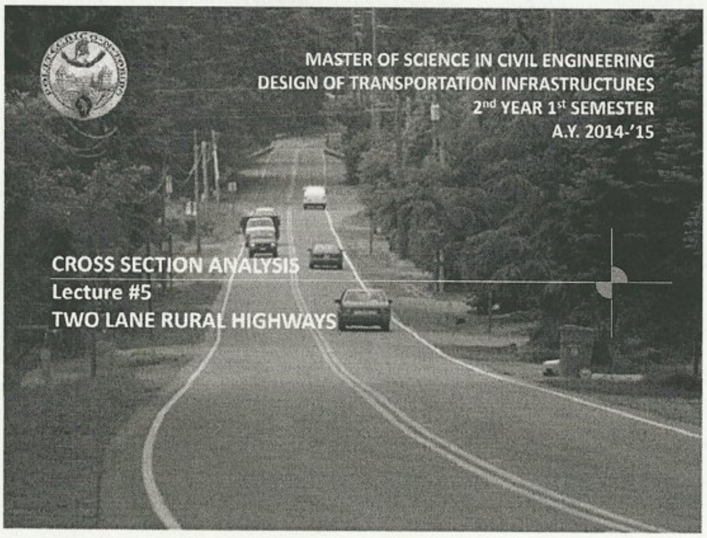
Table 14.16: Levels of Service for Sample Problem

Target Year	Demand Volume (veh/h)	Level of Service
0	3,600	C
5	4,818	D
10	6,447	F
15	8,628	F
20	11,546	F

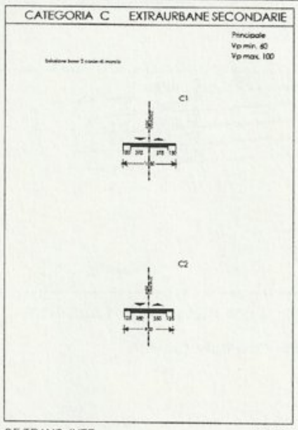
Analysis The results of this analysis indicate that demand will reach the capacity of the freeway in 7.63 years. If no action is taken, users can expect regular breakdowns during the peak hour in this freeway section. To avoid this situation, action must be taken to either reduce demand and/or increase the capacity of the section.

Increasing the capacity of the section suggests adding a lane. Computations would be redone using a four-lane, one-direction cross section to see whether sufficient capacity was added to handle the 20-year demand forecast. Reduction in demand is more difficult and would involve intensive study of the nature of demand on the freeway section in question. Reduction would require diversion of users to alternative routes or alternative modes, encouraging users to travel at different times or to different destinations, encouraging car-pooling and other actions to increase auto occupancy. Given the constraints of capacity on the current cross section, it is also unlikely that demand would grow to the levels indicated in later years because queuing and congestion would reach intolerable levels. In Year 20, the projected demand of 11,546 veh/h is more than twice the capacity of the current cross section.

As is the case in many uses of the HCM, this analysis identifies and gives insight into a problem. It does not definitively provide a solution—unless engineers are prepared to more than double the current capacity of the facility or modify alternative routes to provide the additional capacity needed. Even these options involve judgments. Capacity and level-of-service analyses of the various alternatives would provide additional information on which to base those judgments, but would not, taken alone, dictate any particular course of action. Economic, social, and environmental issues would obviously also have to be considered as part of the overall process of finding a remedy to the forecasted problem.



Two-lane rural highways



According to the Italian standard, such road typology has a fixed composition:

	LIVELLO DI SERVIZIO	Portata di servizio per corsia (autoveic. equiv./ora)
C1	C (1 corsia)	600 (e)
C2	C (1 corsia)	600 (e)

} LOS not lower than C

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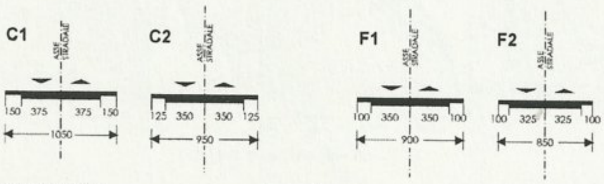
Rural highways

HCM considers three types of two lane rural highways:

- **Class 1**: high speed rural highways (cat.C1) with grade-separated intersections → staggered level (livelli sfalsati) → in this class high speed maintained for a long time.
- **Class 2**: rural highways (cat.C1 and C2) with at-grade intersections
  two road at the same level
- **Class 3**: local rural highways (cat.F1 e F2) with at-grade intersections

different width of embankment and shoulder.



Fixed composition of this kind of road, you cannot insert a new lane so you don't design but you can only performing LOS analysis.

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LOS for two-lanes rural highways

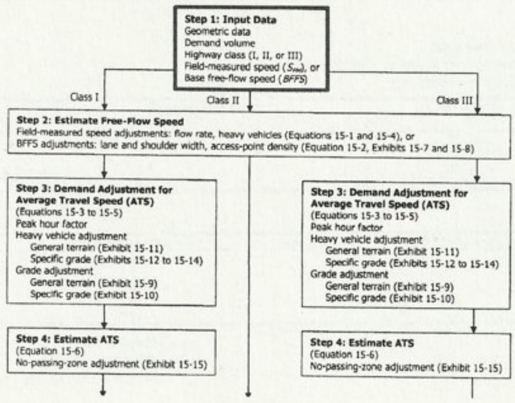
ATS = average travel speed
PTSF = percent-time spent following
PFFS = percent of free-flow speed

LOS	Class I Highways ATS (mi/h)	Class I Highways PTSF (%)	Class II Highways PTSF (%)	Class III Highways PFFS (%)
A	>55	≤35	≤40	>91.7
B	>50–55	>35–50	>40–55	>83.3–91.7
C	>45–50	>50–65	>55–70	>75.0–83.3
D	>40–45	>65–80	>70–85	>66.7–75.0
E	≤40	>80	>85	≤66.7

↳ class II and I

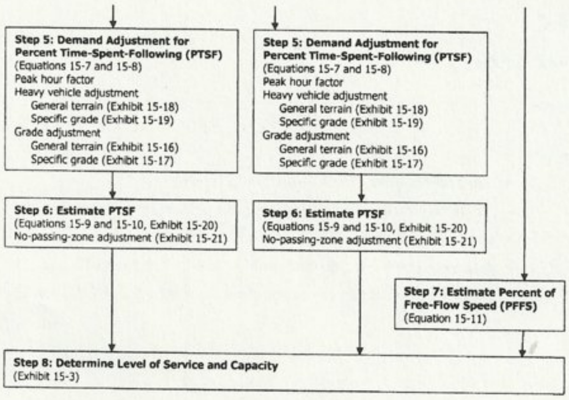
This column is also used to calculate Class I and Class III level of service

Rural highways



ATS: it is refered by space and time, both! Because we consider one section and the average speed and time to do this specific segment.

Rural highways



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Step #3. Demand flow rate evaluation

Exhibit 15-9
ATS Grade Adjustment Factor ($f_{g,ATS}$) for Level Terrain, Rolling Terrain, and Specific Downgrades

One-Direction Demand Flow Rate, v_{vph} (veh/h)	Adjustment Factor: Level Terrain and Specific Downgrades	Adjustment Factor: Rolling Terrain
≤100	1.00	0.67
200	1.00	0.75
300	1.00	0.83
400	1.00	0.90
500	1.00	0.95
600	1.00	0.97
700	1.00	0.98
800	1.00	0.99
≥900	1.00	1.00

Note: Interpolation to the nearest 0.01 is recommended.

I do an hypotesis for the demand value (if I don't know it). I take coefficient in the table and I see if my hypotesis was true. If not I check another value and I repeat the operations. It is an iterative calculation.

Step #3. Demand flow rate evaluation

$$f_{HV,ATS} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$$

where

$f_{HV,ATS}$ = heavy vehicle adjustment factor for ATS estimation,
P_T = proportion of trucks in the traffic stream (decimal),
P_R = proportion of RVs in the traffic stream (decimal),
E_T = passenger car equivalent for trucks from Exhibit 15-11 or Exhibit 15-12, and
E_R = passenger car equivalent for RVs from Exhibit 15-11 or Exhibit 15-13.

Step #3. Demand flow rate evaluation

Exhibit 15-11
ATS Passenger Car Equivalents for Trucks (E_T) and RVs (E_R) for Level Terrain, Rolling Terrain, and Specific Downgrades

Vehicle Type	Directional Demand Flow Rate, v_{vph} (veh/h)	Level Terrain and Specific Downgrades	Rolling Terrain
Trucks, E_T	≤100	1.9	2.7
	200	1.5	2.3
	300	1.4	2.1
	400	1.3	2.0
	500	1.2	1.8
	600	1.1	1.7
	700	1.1	1.6
	800	1.1	1.4
	≥900	1.0	1.3
RVs, E_R	All flows	1.0	1.1

Note: Interpolation to the nearest 0.1 is recommended.

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Step #4. ATS evaluation - $f_{np,ATS}$

Exhibit 15-15
ATS Adjustment Factor for No-Passing Zones ($f_{np,ATS}$)

Opposing Demand Flow Rate, v_o (pc/h)	Percent No-Passing Zones ≤20	40	60	80	100
FFS ≥ 65 mi/h					
≤100	1.1	2.2	2.8	3.0	3.1
200	2.2	3.3	3.9	4.0	4.2
400	1.6	2.3	2.7	2.8	2.9
600	1.4	1.5	1.7	1.9	2.0
800	0.7	1.0	1.2	1.4	1.5
1,000	0.6	0.8	1.1	1.1	1.2
1,200	0.6	0.8	0.9	1.0	1.1
1,400	0.6	0.7	0.9	0.9	0.9
≥1,600	0.6	0.7	0.7	0.7	0.8
FFS = 60 mi/h					
≤100	0.7	1.7	2.5	2.8	2.9
200	1.9	2.9	3.7	4.0	4.2
400	1.4	2.0	2.5	2.7	3.9
600	1.1	1.3	1.6	1.9	2.0
800	0.6	0.9	1.1	1.3	1.4
1,000	0.6	0.7	0.9	1.1	1.2
1,200	0.5	0.7	0.9	0.9	1.1
1,400	0.5	0.6	0.8	0.8	0.9
≥1,600	0.5	0.6	0.7	0.7	0.7
FFS = 55 mi/h					
≤100	0.5	1.2	2.2	2.6	2.7
200	1.5	2.4	3.5	3.9	4.1
400	1.3	1.9	2.4	2.7	2.8
600	0.9	1.1	1.6	1.8	1.9
800	0.5	0.7	1.1	1.2	1.4
1,000	0.5	0.6	0.8	0.9	1.1
1,200	0.5	0.6	0.7	0.9	1.0
1,400	0.5	0.6	0.7	0.7	0.9
≥1,600	0.5	0.6	0.6	0.6	0.7
FFS = 50 mi/h					
≤100	0.2	0.7	1.9	2.4	2.5
200	1.2	2.0	3.3	3.9	4.0
400	1.1	1.6	2.2	2.6	2.7
600	0.6	0.9	1.4	1.7	1.9
800	0.4	0.6	0.9	1.2	1.3
1,000	0.4	0.4	0.7	0.9	1.1
1,200	0.4	0.4	0.7	0.8	1.0
1,400	0.4	0.4	0.6	0.7	0.8
≥1,600	0.4	0.4	0.5	0.5	0.5
FFS ≤ 45 mi/h					
≤100	0.1	0.4	1.7	2.2	2.4
200	0.9	1.6	3.1	3.8	4.0
400	0.9	0.5	2.0	2.5	2.7
600	0.4	0.3	1.3	1.7	1.8
800	0.3	0.3	0.8	1.1	1.2
1,000	0.3	0.3	0.6	0.8	1.1
1,200	0.3	0.3	0.6	0.7	1.0
1,400	0.3	0.3	0.6	0.6	0.7
≥1,600	0.3	0.3	0.4	0.4	0.6

Note: Interpolation of $f_{np,ATS}$ for percent no-passing zones, demand flow rate, and FFS to the nearest 0.1 is recommended.

Step #5. PTSF - demand flow rate evaluation

$$v_{i,PTSF} = \frac{V_i}{PHF \times f_{g,PTSF} \times f_{HV,PTSF}}$$

$$f_{HV,PTSF} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$$

where

$v_{i,PTSF}$ = demand flow rate i for determination of PTSF (pc/h);

i = "d" (analysis direction) or "o" (opposing direction);

$f_{g,PTSF}$ = grade adjustment factor for PTSF determination, from Exhibit 15-16 or Exhibit 15-17; and

$f_{HV,PTSF}$ = heavy vehicle adjustment factor for PTSF determination, from Exhibit 15-18 or Exhibit 15-19.

Step #5. PTSF - demand flow rate evaluation

Exhibit 15-16
PTSF Grade Adjustment Factor ($f_{g,PTSF}$) for Level Terrain, Rolling Terrain, and Specific Downgrades

Directional Demand Flow Rate, v_{vph} (veh/h)	Level Terrain and Specific Downgrades	Rolling Terrain
≤100	1.00	0.73
200	1.00	0.80
300	1.00	0.85
400	1.00	0.90
500	1.00	0.96
600	1.00	0.97
700	1.00	0.99
800	1.00	1.00
≥900	1.00	1.00

Note: Interpolation to the nearest 0.01 is recommended.

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Step #6. PTSF - demand flow rate evaluation

$$BPTSF_d = 100\left[1 - \exp\left(a v_d^b\right)\right]$$

Exhibit 15-20
PTSF Coefficients for Use in Equation 15-10 for Estimating BPTSF

Opposing Demand Flow Rate, v_o (pc/h)	Coefficient *a*	Coefficient *b*
≤200	-0.0014	0.973
400	-0.0022	0.923
600	-0.0033	0.870
800	-0.0045	0.833
1,000	-0.0049	0.829
1,200	-0.0054	0.825
1,400	-0.0058	0.821
≥1,600	-0.0062	0.817

Note: Straight-line interpolation of *a* to the nearest 0.0001 and *b* to the nearest 0.001 is recommended.

Step #6. PTSF evaluation - $f_{np,PTSF}$

Exhibit 15-21
No-Passing-Zone Adjustment Factor ($f_{np,PTSF}$) for Determination of PTSF

Total Two-Way Flow Rate, $v = v_d + v_o$ (pc/h)	Percent No-Passing Zones 0	20	40	60	80	100
Directional Split = 50/50						
≤200	9.0	29.2	43.4	49.4	51.0	52.6
400	16.2	41.0	54.2	61.6	63.8	65.8
600	15.8	38.2	47.8	53.2	55.2	56.8
800	15.8	33.8	40.4	44.0	44.8	46.6
1,400	12.8	20.0	23.8	26.2	27.4	28.6
2,000	10.0	13.6	15.8	17.4	18.2	18.8
2,600	5.5	7.7	8.7	9.5	10.1	10.3
3,200	3.3	4.7	5.1	5.5	5.7	6.1
Directional Split = 60/40						
≤200	11.0	30.6	41.0	51.2	52.3	53.5
400	14.6	36.1	44.8	53.4	55.0	56.3
600	14.8	36.9	44.0	51.1	52.8	54.6
800	13.6	28.2	33.4	38.6	39.9	41.3
1,400	11.8	18.9	22.1	25.4	26.4	27.3
2,000	9.1	13.5	15.6	16.0	16.8	17.3
2,600	5.9	7.7	8.6	9.6	10.0	10.2
Directional Split = 70/30						
≤200	9.9	28.1	38.0	47.8	48.5	49.0
400	10.6	30.3	38.6	46.7	47.7	48.8
600	10.9	30.9	37.5	43.9	45.4	47.0
800	10.3	23.6	28.4	33.3	34.5	35.5
1,400	8.0	14.6	17.7	20.8	21.6	22.3
2,000	7.3	9.7	11.7	13.3	14.0	14.5
Directional Split = 80/20						
≤200	8.9	27.1	37.1	47.0	47.4	47.9
400	6.6	26.1	34.5	42.7	43.5	44.1
600	4.0	24.5	31.3	38.1	39.1	40.0
800	3.8	18.5	23.5	28.4	29.1	29.9
1,400	3.5	10.3	13.3	16.3	16.9	32.2
2,000	3.5	7.0	8.5	10.1	10.4	10.7
Directional Split = 90/10						
≤200	4.6	24.1	33.6	43.1	43.4	43.6
400	0.0	20.2	28.3	36.3	36.7	37.0
600	-3.1	16.8	23.5	30.1	30.6	31.1
800	-2.8	10.5	15.2	19.9	20.3	20.8
1,400	-1.2	5.5	8.3	11.0	11.5	11.9

Note: Straight-line interpolation of $f_{np,PTSF}$ for percent no-passing zones, demand flow rate, and directional split is recommended to the nearest 0.1.

Step #7. PFFS and capacity evaluation

$$PFFS = \frac{ATS_d}{FFS}$$

$$c_{dATS} = 1{,}700 f_{g,ATS} f_{HV,ATS}$$

$$c_{dPTSF} = 1{,}700 f_{g,PTSF} f_{HV,PTSF}$$

where

c_{dATS} = capacity in the analysis direction under prevailing conditions based on ATS (pc/h), and

c_{dPTSF} = capacity in the analysis direction under prevailing conditions based on PTSF (pc/h).

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Reference textbook: Roess, R.P., Prassas, E.S., McShane, W.R. (2011). *Traffic Engineering*. Pearson ed.

16.5.1 Analysis of a Class I Rural Two-Lane Highway in Rolling Terrain

A Class I two-lane highway in rolling terrain has a peak demand volume of 500 veh/h, with 15% trucks and 5% RVs. The highway serves as a main link to a popular recreation area. The directional split of traffic is 60-40 during peak periods, and the peak-hour factor is 0.88. The 10-mile section under study has 40% "No Passing" zones. The base free-flow speed of the facility may be taken to be 60 mi/h. Lane widths are 12 feet, and shoulder widths are 2 feet. There are 10 access points per mile along this 10-mile section.

Step 1: *Estimate the Free-Flow Speed.* The free-flow speed (*FFS*) is estimated from the base free-flow speed (*BFFS*) and applicable adjustment factors f_{LS} (Table 16.5) and f_A (Table 16.6). Then:

$$FFS = BFFS - f_{LS} - f_A$$

$$FFS = 60.0 - 2.6 - 2.5 = 54.9 \text{ mi/h}$$

where $f_{LS} = 2.6$ (for 12-foot lanes and 2-foot shoulders) and $f_A = 2.5$ (for 10 access points per mile)

Step 2: *Compute the Directional Demand Flow Rates for ATS and PTSF Determinations* Because each direction of the two-lane highway must be separately analyzed, it is necessary that the demand of 500 veh/h be separated by direction. Note that the two directional analyses may be done concurrently because the directional demand in one case is the opposing demand in the other. Given the specified 60-40 split:

$$V_1 = 500 * 0.60 = 300 \text{ veh/h}$$

$$V_2 = 500 * 0.40 = 200 \text{ veh/h}$$

Both of these values have to be converted to base passenger-car flow rates.

Four demand flows will be computed. Both the directional and opposing volumes must be separately converted for ATS determination and for PTSF determination. The initial selection of adjustment factors would be based on flow rates, which are found using the demand volume and the peak hour factor: $v_1 = 300/0.88 = 341$ veh/h and $v_2 = 200/0.88 = 227$ veh/h. Interpolation for the grade factor to the nearest 0.01 and passenger car equivalents to the nearest 0.1 is required. Table 16.18 summarizes the results of these determinations.

Using these values, the following heavy vehicle factors are computed:

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$$

$$f_{HV1}(ATS) = \frac{1}{1 + 0{,}15(2.1 - 1) + 0.05(1.1 - 1)} = 0.85$$

$$f_{HV1}(PTSF) = \frac{1}{1 + 0.15(1.7 - 1) + 0.05(1.0 - 1)} = 0.90$$

$$f_{HV2}(ATS) = \frac{1}{1 + 0.15(2.3 - 1) + 0.05(1.1 - 1)} = 0.83$$

$$f_{HV2}(PTSF) = \frac{1}{1 + 0.15(1.8 - 1) + 0.05(1.0 - 1)} = 0.89$$

Then:

$$v = \frac{V}{PHF * f_G * f_{HV}}$$

$$v_1(ATS) = \frac{341}{0.88 * 0.86 * 0.85} = 530 \text{ pc/h}$$

$$v_1(PTSF) = \frac{341}{0.88 * 0.87 * 0.90} = 495 \text{ pc/h}$$

$$v_2(ATS) = \frac{227}{0.88 * 0.77 * 0.83} = 404 \text{ pc/h}$$

$$v_2(PTSF) = \frac{277}{0.88 * 0.81 * 0.89} = 358 \text{ pc/h}$$

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16.5.2 Single-Direction Analysis of a Specific Grade

A Class II two-lane highway serving a rural logging area has a 1-mile grade of 4%. Peak demand on the grade is 250 veh/h, with a 70-30 directional split and a PHF of 0.82. Because of active logging operations in the area, demand contains 20% trucks. There are also 5% RVs using the facility. The grade has 100% "No Passing" zones. The free-flow speed of the facility has been measured to be 45 mi/h. Twenty percent of all trucks operate at a crawl speed that is 20 mi/h lower than other vehicles on the downgrade. At what LOS does the facility operate, assuming that 70% of the traffic is on the upgrade?

Step 1: *Compute Demand Flow Rates for PTSF Determination* Both the upgrade and downgrade must be analyzed in this case. Because this is a Class II facility, however, PTSF is the only parameter that need be established. It is necessary to divide the demand volume into the upgrade volume, V_u $(250 * 0.70 = 175 \text{ veh/h})$, and downgrade volume, V_d $(250 * 0.30 = 75 \text{ veh/h})$.

As the upgrade and downgrade are analyzed, these will serve as directional and opposing volumes.

Base passenger-car equivalent demand flows are computed as:

$$v = \frac{V}{PHF * f_G * f_{HV}}$$

Selecting values of f_G, E_T and E_R from the appropriate tables for PTSF determination results in the values shown in Table 16.19. All tables are entered with the flow rate: $v_{up} = 175/0.82 = 213$ veh/h; $v_{dn} = 75/0.82 = 91$ veh/h. Note that the fact that 20% of trucks travel at crawl speeds on the downgrade is not relevant to the predication of *PTSF*, and so this information is not used here.

Then:

$$f_{HV}\,(\text{up}) = \frac{1}{1 + 0.20(1.3 - 1) + 0.05(1 - 1)} = 0.943$$

$$f_{HV}\,(\text{dn}) = \frac{1}{1 + 0.20(1.1 - 1) + 0.05(1 - 1)} = 0.980$$

And:

$$v_{up} = \frac{175}{0.82 * 1.00 * 0.943} = 226 \text{ pc/h}$$

$$v_{down} = \frac{75}{0.82 * 1.00 * 0.980} = 93 \text{ pc/h}$$

Step 2: *Estimate the PTSF for the Specific Upgrade and Specific Downgrade* The percent time spent following is estimated as:

$$PTSF_d = BPTSF_d + f_{npP}\left(\frac{V_d}{V_d + V_o}\right)$$

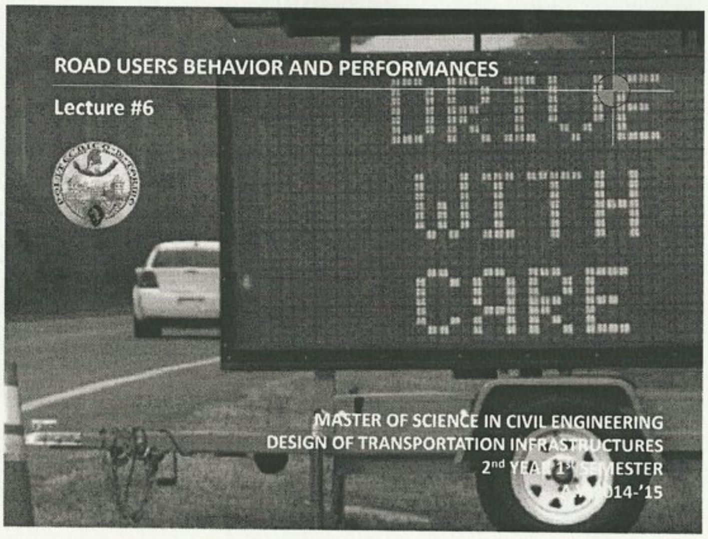
$$BPTSF_d = 100\left[1 - \exp\left(av_d^b\right)\right]$$

where:

f_{npP} (up and down) = 48.9% (Table 16.16, 100% "No Passing" zones, 70/30 split, and $v = 226 + 93 = 319$ pc/h, interpolated)

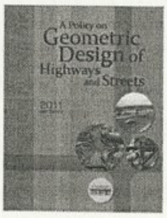
Table 16.19: Critical Values for Demand Flow Rate Computation

Direction	f_G	E_T	E_R
Upgrade	1.00 (Table 16.9)	1.3 (Table 16.13)	1.0 (Table 16.13)
Downgrade	1.00 (Table 16.7)	1.1 (Table 16.10)	1.0 (Table 16.10)



References

HSM
Highway Safety Manual

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Road users

Roadway design is affected by several variables.
Road users characteristics and performances are fundamental in the analysis and design of road geometrics.

Who are the road users?

Drivers. Some related topics: → they are the aggressive element into the road network
- Driving tasks
- Attention and information processing
- Vision
- Perception-reaction time
- Speed choice

... and **Vulnerable Road Users** (i.e., **bikers** and **pedestrians**) whose performance in terms of speed choice and occupancy are discussed herein.

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Driver's attention and information processing ability

neglect : trascurare

Consequently, drivers have a limited information processing capacity while driving, thus they subconsciously determine acceptable information loads that they can manage.
When the acceptable incoming information load is exceeded, they tend to neglect other information based on level of importance, and error is possible during this process.

accident = general terms
crash : phisic contact between two bodies

Driver's expectation

One way to accommodate for human information processing limitations is to design roadway environments in accordance with driver expectations.

When drivers can rely on **past experience** to assist with control, guidance, or navigation tasks there is less to process because they only need to process new information.

Drivers develop **long-** and **short-term expectancies.**

Driver's expectation

Examples of **long-term expectancies** that an unfamiliar driver will bring to a new section of roadway include:

- upcoming freeway exits will be on the right-hand side of the road;
- when a minor and a major road cross, the stop control will be on the road that appears to be the minor road;
- when approaching an intersection, drivers must be in the left lane to make a left turn at the cross street; and,
- a continuous through lane (on a freeway or arterial) will not end at an interchange or intersection junction.

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Driver's vision

Approximately 90 percent of the information that drivers use is visual.

While visual acuity is the most familiar aspect of vision related to driving, numerous other aspects are equally important. The following aspects of driver vision are described in this section:

- **Visual Acuity** – the ability to see details at a distance;
- **Contrast Sensitivity** – the ability to detect slight differences in luminance (brightness of light) between an object and its background;
- **Peripheral Vision** – the ability to detect objects that are outside of the area of most accurate vision within the eye;
- **Movement in Depth** – the ability to estimate the speed of another vehicle by the rate of change of visual angle of the vehicle created at the eye ; and,
- **Visual Search** – the ability to search the rapidly changing road scene to collect road information.

But not only vision:
- noises (rumori)
- perception (tatto)

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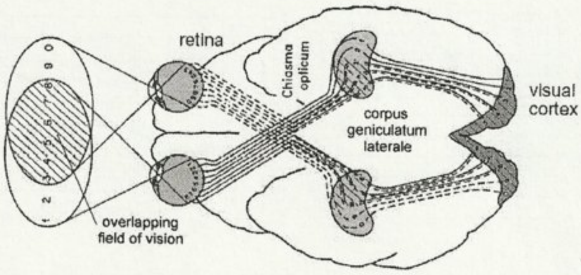
Human vision



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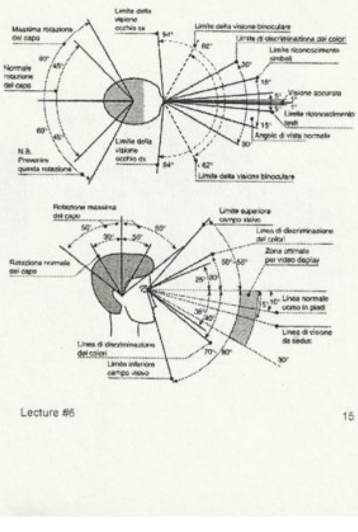
Human vision

The visual field of human eyes is large approximately:

- 55 degrees above the horizontal,
- 70 degrees below the horizontal,
- 90 degrees to the left, and
- 90 degrees to the right.



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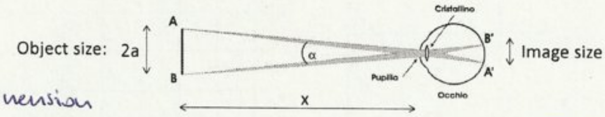
Driver's field of view at increasing speed

The primary cue that drivers use to determine their closing speed to another vehicle is the rate of change of the image size.



- object size: real dimension
- image size: perception dimension

$$\alpha = \frac{2a}{x}$$

$$\dot{\alpha} = \frac{d}{dt}\left(\frac{2a}{x}\right) = -\frac{2a}{x^2}\cdot\frac{dx}{dt} = -\frac{2a\cdot v}{x^2}$$

$$a = -\frac{\dot{\alpha}}{2v}x^2$$

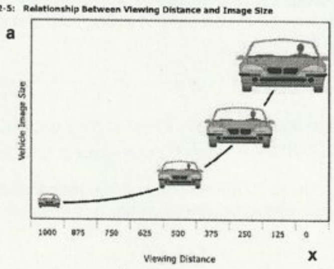
I derive for see how angle α change in time in function of the speed.
Variation about square distance so it is the motivation difficult to estimate the speed of the vehicle that I'm looking.

Driver's field of view at increasing speed

The figure illustrates the relative change of the size of an image at different distances from a viewer. The relationship between viewing distance (x) and image size (2a) is not a linear relationship.

The fact that it is a non-linear relationship is likely the source of the difficulty drivers have in making accurate estimates of closing speed.

Exhibit 2-5: Relationship Between Viewing Distance and Image Size



It's hard to understand relative speed to a car on the road.

Perception-reaction time

Perception-reaction time (PRT) includes time to detect a target, process the information, decide on a response, and initiate a reaction.

Values such as 1.5 or 2.5 s accommodates the vast percentage of drivers in most situations.

But **PRT** is not fixed.

PRT depends on human elements discussed in previous sections, including information processing, driver alertness, driver expectations, and vision.
Also include all the hydraulic component of brake to give effectively in function.

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Driver's speed choice – peripheral vision

Driver's speed choice – noise and adaptation

Noise level is also an important cue for speed choice. Several studies examined how removing noise cues influenced travel speed. While drivers' ears were covered (with ear muffs) they were asked to travel at a particular speed.

All drivers underestimated how fast they were going and drove 4 to 6 mph faster than when the usual sound cues were present.

With respect to lowering speeds, it has been counter-productive to progressively quiet the ride in cars and to provide smoother pavements.

Another aspect of speed choice is **speed adaptation**. This is the experience of leaving a freeway after a long period of driving and having difficulty conforming to the speed limit on an arterial road.

Driver's speed choice – road and env. effects

Drivers may interpret the roadway environment as a whole to encourage fast or slow speeds depending on the effects of the geometry, terrain, or other roadway elements.

Even though drivers may not have all the information for correctly assessing a safe speed, they respond to what they can see.

Low perception of risk, increase aggressive drive.

Drivers tend to drive faster on a straight road with several lanes, wide shoulders, and a wide clear zone, than drivers on a narrow, winding road with no shoulders or a cliff on the side.

Clear zone: without other roads.

For example, speeds on rural highway tangents are related to cross-section and other variables, such as the radius of the curve before and after the tangent, available sight distance, and general terrain.

Where drivers perceived the accident risk to be greater (e.g., sharp curves, limited sight distance), they reduced their travel speed.

Sharp → strette

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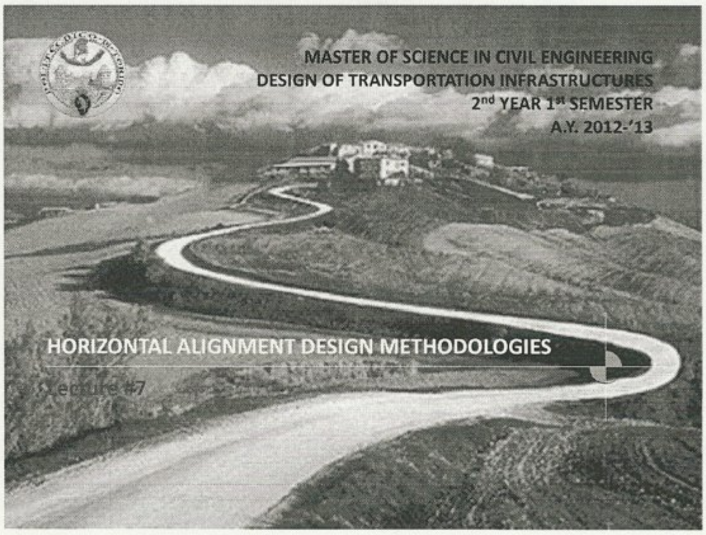
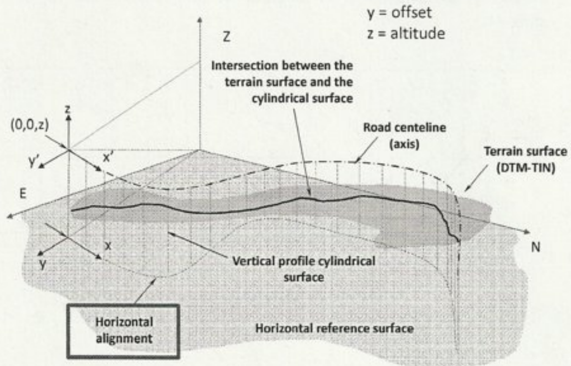


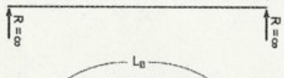
Horizontal and vertical alignment design

x = curvilinear abscissa
y = offset
z = altitude

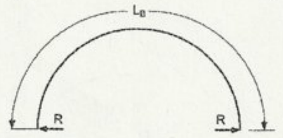


Elements for the horizontal alignment design

Design elements on the horizontal projection



Straight
L_0: Length of the straight
no curvature = $\frac{1}{radius}$ (infinite radius)



Circular arc
R: Radius of the circular arc
L_B: Length of the circular arc

Transition curve
L_C: Length of the transition curve
R: Radius at end of the transition curve

there are many transition curve (ex synusoidal) It is a way to change the radius.

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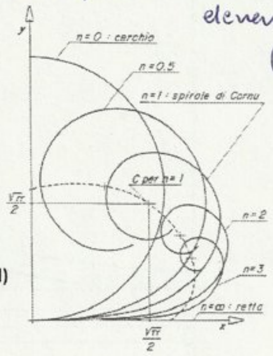
Transitions

Parametric equation of spirals: → general equations — we can represent all the element in road projectation. (tangent, clothoid, circular arct).

$$r \cdot s^n = A^{n+1}$$

where:
- A = scale factor ← govern the dimension of curve.
- n = shape factor
- s = curvilinear abscissa
- R = radius of the osculating circle

n = -1, r = s	**spiral**
n = 0, r = A	**circle**
n = 1, r s = A^2	**clothoid (Cornu's spiral)**
n ≥ 2, r s^n = A^{n+1}	**iper-clothoids**
n = ∞, r = ∞	**straight line**



R: circle that have the same curvature of the local circle point to point. Approximate an infinitesimal element of curve. They are as how as are the point on the curve.

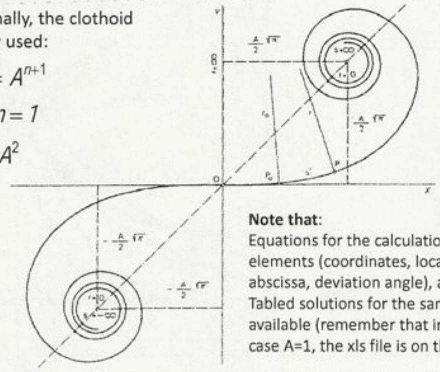
Clothoid

Traditionally, the clothoid is widely used:

$$R \cdot s^n = A^{n+1}$$

when $n = 1$

$$R \cdot s = A^2$$



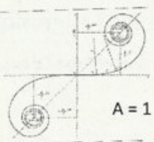
Note that:
Equations for the calculation of the elements (coordinates, local radius, abscissa, deviation angle), are available. Tabled solutions for the same are also available (remember that in the latter case A=1, the xls file is on the webpage).

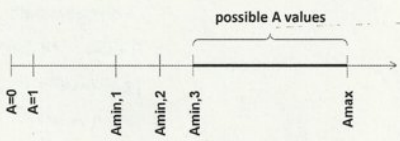
Equation to calculate the different value of A:
max(A_{min}) ≤ A ≤ A_{max}
A_{min}:
- maximum jerk
- rolling criteria (sopra-elevation of edge)
- perception (R/3)

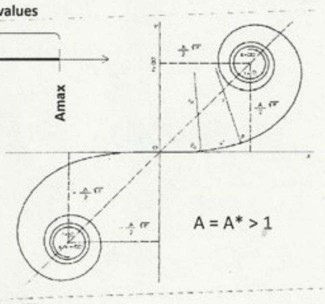
A_{max} = R

Clothoid's scale factor

Standards provide limits for the scale factor of a clothoid:







Q: Do you remember the criteria followed in the Amin and Amax evaluation?

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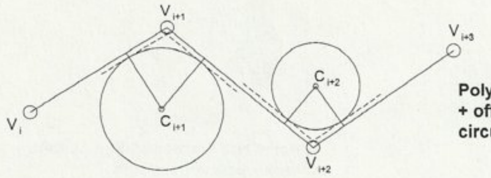
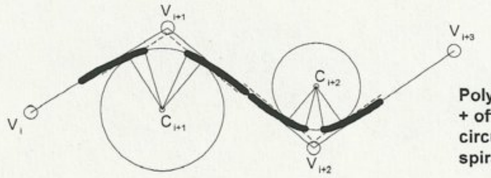
Horizontal alignment process (I)



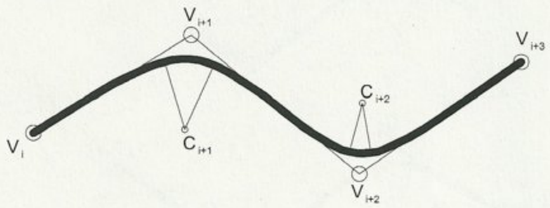
Polygonal path
+ offset +
circular arc



Polygonal path
+ offset +
circular arc +
spirals

Horizontal alignment process (I)

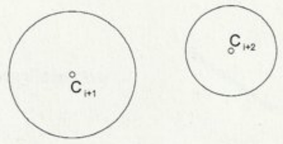
Polygonal path + offset + circular arc + spirals = horizontal alignment



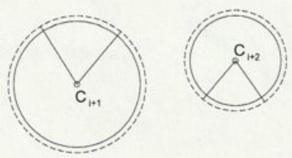
Horizontal alignment process (II)

New road design approach -> new thought school

- use the circle
- define the offset
- straight line must be tangent to offset circle, in the space remaining you have a clothoid.



Circles and
corresponding
centers



Circles and
corresponding
centers + offset

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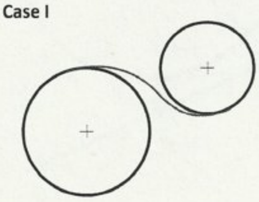
Inflected and continuity spirals

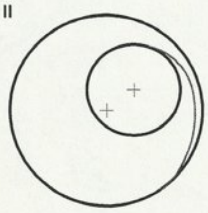
Inflected and continuity spirals are used to solve connections between circular arcs. Conditions are:

- non-intersecting circles
- the two centers of curvature do not coincide
- when the circles are external, then inflection (case I)
- when one circle in internal, then continuity (or egg-shaped, case II)

Case I



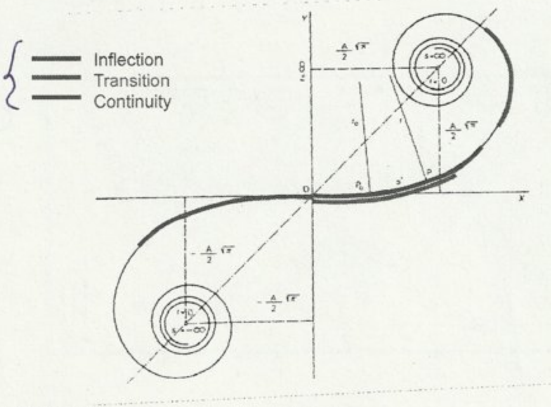
Case II



no straight are included between elements.

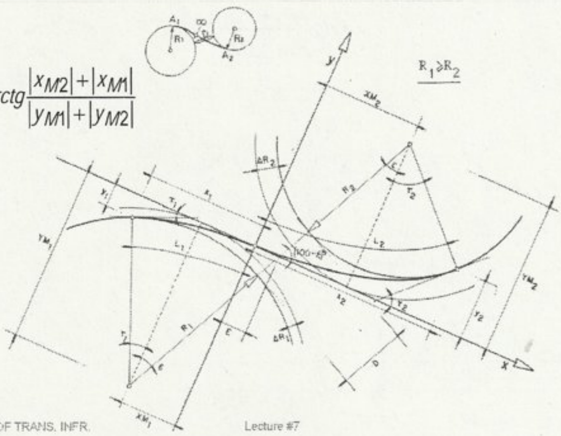
Transitional, inflected and continuity with spirals

Same circle can be used to draw



Inflected clothoid → two external circle

$$\varepsilon = arctg\frac{|x_{M2}|+|x_{M1}|}{|y_{M1}|+|y_{M2}|}$$



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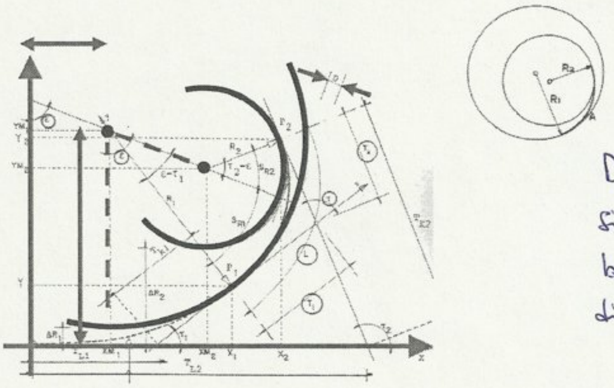
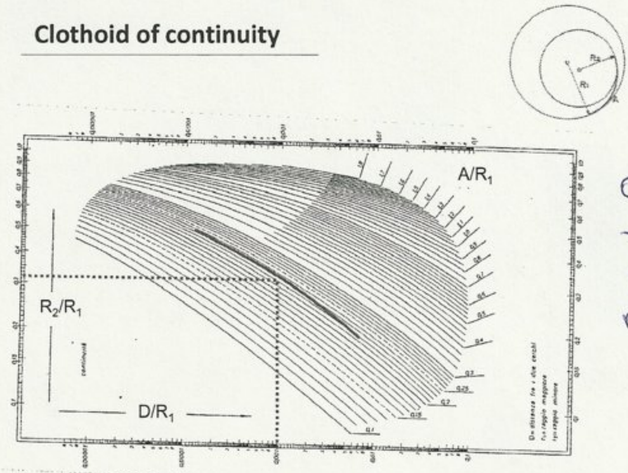
Clothoid of continuity



Draw method is very similar to the others, but this type is very difficult to adopte.

DES. OF TRANS. INFR. Lecture #7 25

Clothoid of continuity



Osterlock diagram → graphic method you calculate A and ricave D.

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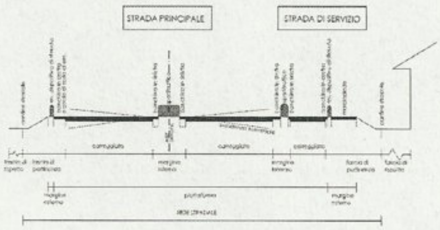
Speed interval approach selection

	Principal								Service			
Road cat.	A_e	A_u	B	C	D	E	F_e	F_u	A_e	A_u	B	D
V_{lim}	130	130	110	90	70	50	90	50	90	50	90	50
$V_{P,max}$	140	140	120	100	80	60	100	60	100	60	100	60
$V_{P,min}$	90	80	70	60	50	40	40	25	40	40	40	25



Design speed selection (US)

DHV = design hourly volume
volume orario di progetto
it is the equivalent volume of vehicle

Table 15.2 Minimum Design Speeds for Various Functional Classifications

Class		*Speed (mi/h)* 20	30	40	50	60	70
Rural principal arterial	Min 50 mi/h for freeways			x	x	x	x
Rural minor arterial				x	x	x	x
Rural Collector Road	DHV over 400			x	x	x	
	DHV 20-400			x	x	x	
	DHV 100-200		x	x	x		
	Current ADT over 400		x	x	x		
	Current ADT under 400	x	x	x			
Rural Local Road	DHV over 400		x	x	x		
	DHV 200-400		x	x	x		
	DHV 100-200		x	x	x		
	Current ADT over 400		x	x	x		
	Current ADT 250-400	x	x	x			
	Current ADT 50-250	x	x				
	Current ADT under 50	x	x				
Urban principal arterial	Minimum 50 mi/h for freeways		x	x	x	x	x
Urban minor arterial			x	x	x	x	
Urban collector street			x	x	x		
Urban local street		x	x				

SOURCE: *Road Design Manual*, Virginia Department of Transportation, Richmond, VA. (See www.virginiadot.org/business/locdes/rdmanual-index.asp for most current version.)

Reference design speed selection

Max speed depend also by grades!

Type of Terrain	Metric – Design Speeds (km/h) 80	90	100	110	120	130	US Customary – Design Speeds (mph) 50	55	60	65	70	75	80
	Grades (%)[a]						Grades (%)[a]						
Level	4	4	3	3	3	3	4	4	3	3	3	3	3
Rolling	5	5	4	4	4	4	5	5	4	4	4	4	4
Mountainous	6	6	6	5	–		6	6	6	5	5	–	–

[a] Grades 1% steeper than the value shown may be used for extreme cases in urban areas where development precludes the use of flatter grades and for one-way downgrades except in mountainous terrain.

Exhibit 8-1. Maximum Grades for Rural and Urban Freeways

Speed analysis and control, Italian standard

When $V_{P,max} \geq 100$ km/h:

- $\Delta V_P \leq 10$ km/h when speed pass from $V_{P,max}$ to $V_P < V_{P,max}$
- $\Delta V_P \leq 20$ km/h (better if lower than 15 km/h) when speed pass from values lower than $V_{P,max}$

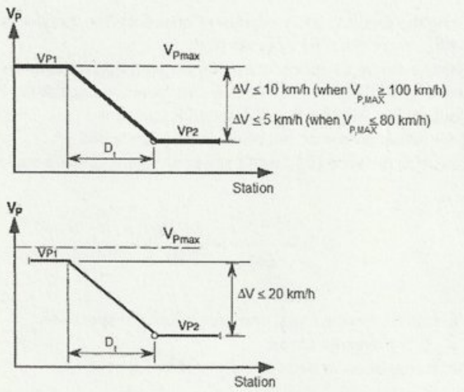
When $V_{P,max} \leq 80$ km/h:

- $\Delta V_P \leq 5$ km/h when speed pass from $V_{P,max}$ to $V_P < V_{P,max}$
- $\Delta V_P \leq 20$ km/h (better if lower than 10 km/h) when speed pass from values lower than $V_{P,max}$

Why speed value is different from 10 to 20?
For comfort and safety we want to reduce speed variation
↳ it is good when speed variation is slow.

Consistent = congruenza o omogeneità
Do consistent speed during the alignment → for make it true variation speed must be small.

Speed analysis and control, Italian standard



Effects of speed variation

Accident (crash) rate in horizontal curve versus the operating speed variation between tangent and curve in two lane rural highway (US).

From:
Glennon, J.C., Harwood, D.W., Free, S., Gray, C.W. (1978).
Highway Design Consistency and Systematic Design Related to Highway Safety.
Transportation Research Record, **681**, 77-88.

ΔV_{85}	Number of horizontal curve	Crash in three years (n)	Exposition factor ($10^6 \cdot v \cdot km$)	Crash rate ($n/10^6 \cdot v \cdot km$)
$\Delta V_{85} \leq 10$ km/h	4518	1483	3206,06	0,46
$10 \leq \Delta V_{85} \leq 20$ km/h	622	217	150,46	1,44
$\Delta V_{85} > 20$ km/h	147	47	17,05	2,76

Slide 13

Experiment: something that you control with a variable and you can modify it to see how depends to a characteristic variable.

observation: only see what happens, you cannot modify!

The distribution of speed in FF condition is a gaussian and we use a percentile of this distribution (85%) to make matches.

But it isn't a correct way because as you see for the same parameters I have two different distribution.

In US speed limit are put in base to V_{85}.

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OS models (I) – two-lane rural hw, curves

Autori	Rif.	Paese	Equazione	R^2
Lamm et al.	[5]	US	$V_{85} = 93{,}9 - 1{,}82 \cdot DC_{a}$	0,79
Passetti e Fambro	[44]	US	$V_{85} = 103{,}9 - 3020{,}5 \cdot (1/R)$	0,68
Ottesen e Krammes	[45]	US	$V_{85} = 102{,}4 - 1{,}57 \cdot DC_m - 0{,}012 \cdot L_C - 0{,}01 \cdot DC \cdot L_C$	0,81
Andueza	[46]	Venezuela	$V_{85} = 98{,}2 - 2795 \cdot (1/R) - 894 \cdot (1/R_p) + 7{,}486 \cdot \frac{S}{250} + 9{,}308 \cdot L_{rp}$	0,81
Marchionna et al.	[58]	Italia	$V_{85} = 124{,}1 - 583{,}78 \cdot (1/R)^{0{,}5}$, per CCR < 30 gon/km	0,40
			$V_{85} = 118{,}1 - 510{,}56 \cdot (1/R)^{0{,}5}$, per 30 ≤ CCR < 80 gon/km	0,58
			$V_{85} = 111{,}6 - 437{,}44 \cdot (1/R)^{0{,}5}$, per 80 ≤ CCR < 160 gon/km	0,80
			$V_{85} = 100{,}8 - 346{,}62 \cdot (1/R)^{0{,}5}$, per CCR ≥ 160 gon/km	0,89
Bird e Hashim	[47]	UK	$V_{85} = 119{,}1 - \frac{518{,}275}{\sqrt{R}} - \frac{125440}{L_{rm}^2} + \frac{413{,}181}{\alpha^2}$	0,88
Nie e Hassan	[48]	Canada	$V_{85} = 108{,}4 - 0{,}097 \cdot CCR$	0,86

Legenda:
L_C = sviluppo della curva [m]
L_{rp} = sviluppo del rettifilo precedente la curva [m]
L_{rm} = sviluppo medio dei due rettifili adiacenti alla curva [m]
R_p = raggio della curva precedente [m]
S = distanza di visibilità disponibile lungo la curva [m]
α = angolo di deviazione del raccordo (°)

OS models (II) – two-lane rural hw, tangents

Autori	Rif.	Paese	Modello	R^2
Cardoso	[49]	Portogallo	$V_{85} = 41{,}67 - 548{,}892 \cdot (1/R_{Cp}) + 0{,}0238 \cdot R_{Cp} + 0{,}0165 \cdot L_r - 0{,}0207 \cdot R_{Cs} + 5{,}95 \cdot L_C + 5{,}28 \cdot L_B$	0,90
Andueza	[46]	Venezuela	$V_{85} = 100{,}7 - 3420 \cdot (1/R_{cp}) + 0{,}027819 \cdot L_r$	0,78
Polus et al.	[42]	US	(a) $V_{85} = 101{,}11 - 3420 \cdot (1/GM_S)$	0,55
			(b) $V_{85} = 105{,}00 - 28{,}107 / e^{0{,}00108 \cdot GM_L}$	0,74
			(c) $V_{85} = 97{,}73 - 0{,}00067 \cdot GM_L$	0,20
			(d) $V_{85} = 105{,}00 - 22{,}953 / e^{0{,}00012 \cdot GM_L}$	0,84
Bird e Hashim	[47]	UK	(e) $V_{85} = 95{,}414 + 0{,}476 \cdot \sqrt{L_r} - 4{,}824 \cdot \sqrt{DC_m}$	0,56
Crisman et al.	[50]	Italia	$V_{85} = V_{85,Cp} + 0{,}081 \cdot L_r^{0{,}75}$	0,88

Legenda:
(a) valida per R_i e R_{i+1} ≤ 250 m, L_T < 150 m
(b) valida per R_i e R_{i+1} ≤ 250 m, 150 ≤ L_T ≤ 1000 m
(c) valida per R_i e R_{i+1} > 250 m, 150 ≤ L_T ≤ 1000 m
(d) valida per R_i e R_{i+1} qualunque, L_T > 1000 m
(e) in cui DC_m è il valore medio delle due curve adiacenti
$V_{85,Cp}$ = velocità operativa della curva precedente [km/h]
L_B = larghezza della banchina [m]
L_C = larghezza della corsia [m]
L_r = lunghezza del rettifilo [m]
R_{Cp} = raggio della curva che precede [m]
R_{Cs} = raggio della curva che segue [m]

OS models (III) – motorways

Autori	Rif.	Paese	Strada	Modello	R^2
Francia	[52]	Francia	Strade extraurbane principali a 4 corsie	$V_{85} = 120 / \left[1 + 346 \cdot (1/\sqrt{R})\right]$	-
Gong e Stamatiadis	[51]	USA		(a) $V_{85} = 1{,}609 \cdot \left[51{,}52 + 1{,}567 \cdot T_B - 2{,}795 \cdot T_M + -4{,}001 \cdot T_P - 2{,}150 \cdot T_i + +2{,}221 \cdot \ln(L_C/3{,}28)\right]$	0,65
				(b) $V_{85} = 1{,}609 \cdot \left[60{,}779 + 1{,}804 \cdot T_B - 2{,}521 \cdot T_M + -1{,}071 \cdot T_i - 1{,}519 \cdot F_C + +0{,}000143 \cdot R + 2{,}408 \cdot (L_C/R)\right]$	0,43
Bassani e Santagata	[53]	Italia	Autostrade urbane ed extraurbane	$V_{85} = 144{,}70 - 0{,}3086 \cdot CCR$	0,75

Legenda:
(a) valida per la corsia di sinistra
(b) valida per la corsia di destra
T_B = indicatore del tipo di banchina (1 per banchina pavimentata; 0 diversamente);
T_M = indicatore del tipo di margine interno (1 senza barriera di sicurezza; 0 diversamente);
T_P = indicatore del tipo di pavimentazione (1 in calcestruzzo; 0 in conglomerato bituminoso);
T_i = indicatore di pendenza (1 per pendenza assoluta ≥ 0.5 %; 0 diversamente)
L_C = lunghezza della curva orizzontale [m]
F_C = fattore di curva (1 se il tratto di avvicinamento è una curva; diversamente 0)

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Lamm criteria

1. $|V_d - V_{85,i}| \le \Delta V_{max}$ Design consistency

2. $|V_{85,i} - V_{85,i+1}| \le \Delta V_{max}$ Operating speed consistency

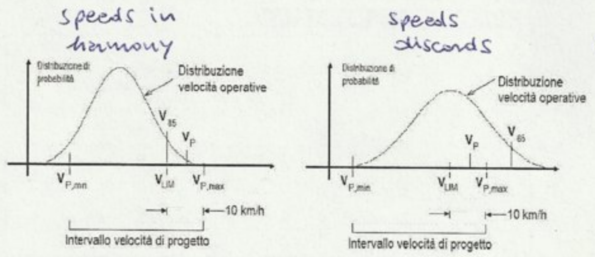
3. it is about contact friction (aderenza di contatto)

- good, con $\Delta V_{max} \le 10$ km/h;
- fair, con $10 < \Delta V_{max} \le 20$ km/h;
- pour, con $\Delta V_{max} > 20$ km/h.

} different level of design

Speed harmony and speed discord

The shape and the position of the operating speed distribution depend on the road geometrics.



$V_{85} > V_{max\ lim}$

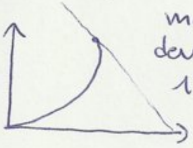
V_P = Speed project

Considerations:

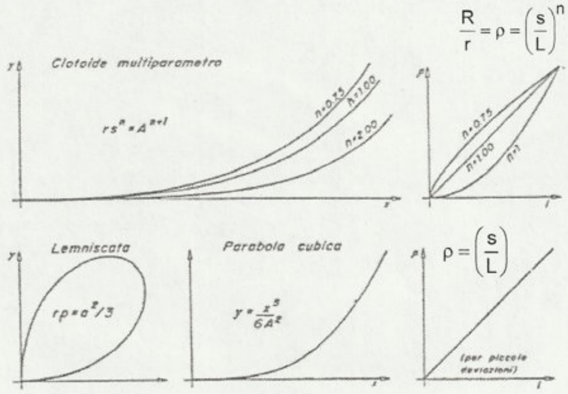
- in the second graph perhaps geometry is not able to support the speed, for example radius value is too high and drivers can go very fast (over speed limit) because don't receive perception of risk.

1st curve type

More curves are a good approximation of clothoid but only in a little portion of them.
For example lemniscata of Bernulli:



maximum deviation 135°



$$\frac{R}{r} = \rho = \left(\frac{s}{L}\right)^n$$

$$rs^n = A^{n+1}$$

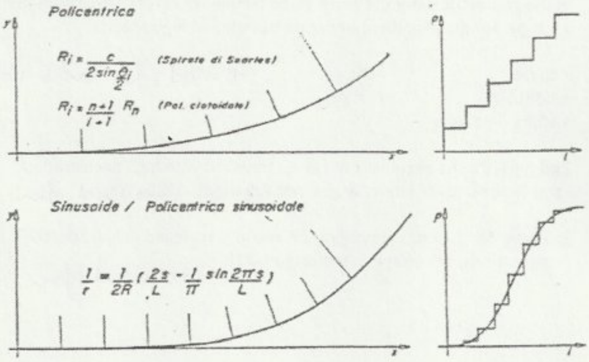
$$r\rho = a^2/3$$

$$y = \frac{x^3}{6A^2}$$

$$\rho = \left(\frac{s}{L}\right)$$

parabola cubica has the same problem!

1st curve type



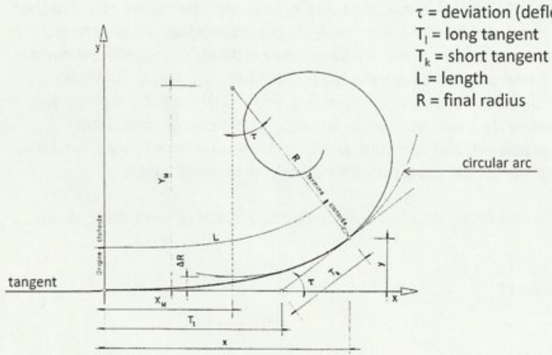
$$R_i = \frac{c}{2\sin\frac{\theta_i}{2}}$$

$$R_i = \frac{n+1}{i+1} R_n$$

$$\frac{1}{r} = \frac{1}{2R}\left(\frac{2s}{L} - \frac{1}{\pi}\sin\frac{2\pi s}{L}\right)$$

Clothoid

x_M = center abscissa
ΔR = arc-tangent offset
τ = deviation (deflection angle)
T_l = long tangent
T_k = short tangent
L = length
R = final radius



Offset of the clothoid

$\Delta R \cong y_n - R$
↳ $y + R\cos\tau$
↓
last point of clothoid
ΔR is an approximate solution so there is $\simeq$!

$$\Delta R = y_M - R = y + R \cdot \cos\tau - R = y + R \cdot (\cos\tau - 1)$$

LOOK AT SLIDE #6

$$\Delta R \cong A \cdot \frac{\tau}{3}\sqrt{2\tau} + R \cdot \left[\left(1 - \frac{\tau^2}{2}\right) - 1\right] = A \cdot \frac{\tau}{3}\sqrt{2\tau} - R \cdot \frac{\tau^2}{2}$$

Remind that: $\tau = \frac{s^2}{2 \cdot A^2} = \frac{s}{2R} = \frac{A^2}{2R^2}$

$$\Delta R = A \cdot \frac{\tau}{3}\sqrt{2\tau} - R \cdot \frac{\tau^2}{2}$$

$$\Delta R = A \cdot \frac{A^2}{6R^2}\sqrt{2\frac{A^2}{2R^2}} - R \cdot \frac{A^4}{8R^4} \cong \frac{A^4}{24R^3}$$

APPROXIMATED SOLUTION

Cubic parabola

→ The cubic parabola represents an approximation of the clothoid.

Demonstration:

$$\begin{cases} x = A \cdot \sqrt{2\tau} \cdot \left(1 - \frac{\tau^2}{10} + \frac{\tau^4}{216}\right) \\ y = A \cdot \sqrt{2\tau} \cdot \left(\frac{\tau}{3} - \frac{\tau^3}{42} + \frac{\tau^5}{1320}\right) \end{cases} \Rightarrow \begin{cases} x = A \cdot \sqrt{2\tau} \\ y = A \cdot \sqrt{2\tau} \cdot \frac{\tau}{3} \end{cases}$$

SHORTEST SERIES

$$y = A \cdot \tau^{\frac{3}{2}}\sqrt{\frac{2}{9}} \Rightarrow \tau^{\frac{3}{2}} = \frac{y}{A\sqrt{\frac{2}{9}}}, \quad \tau = \left(\frac{2}{9}\right)^{-\frac{1}{3}}\left(\frac{y}{A}\right)^{\frac{2}{3}}$$

Cubic parabola

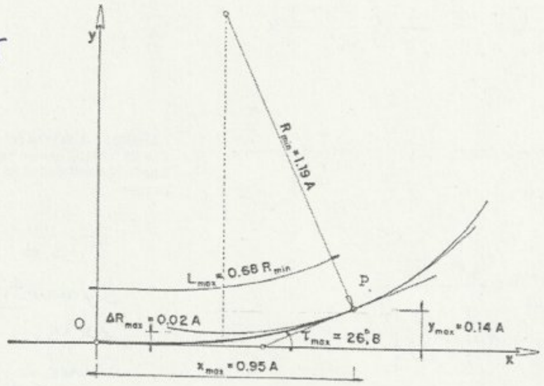
Substituting τ in the equation of x:

$$x = A \cdot 2^{\frac{1}{2}} \cdot \left(\frac{2}{9}\right)^{-\frac{1}{6}}\left(\frac{y}{A}\right)^{\frac{1}{3}} \Rightarrow x = A^{\frac{2}{3}} \cdot \frac{y^{\frac{1}{3}}}{\sqrt[6]{\frac{2}{72}}}$$

$$x^3 = \frac{A^2 y}{\frac{1}{6}} = 6A^2 y \quad \Rightarrow \boxed{y = \frac{1}{6A^2}x^3}$$

Limit values of cubic parabola parameters

Graph indicates limit of values.

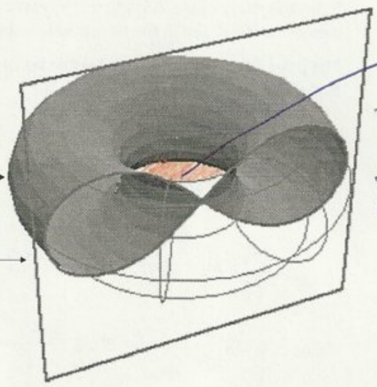


Lemniscate of Bernoulli

For small deviations the Lemniscate of Bernoulli is an approximation of the clothoid, but it requires easier equations.

Torus

Lemniscate of Bernoulli is the intersection of a plane tangent to the inner ring of a torus whose inner radius equals to its radius of generating circle



inner ring

Lemniscate of Bernoulli

Cartesian equation:

$$x^2 + y^2 + 2x^2y^2 - 2A^2xy = 0$$

Polar equation:

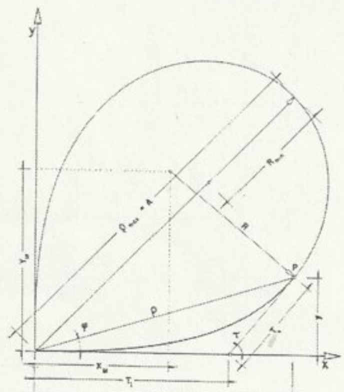
$$\rho^2 = A^2 \cdot sen(2\varphi)$$

Characteristic:

$$\tau = 3\varphi$$

Tabled solutions are available.

Maximum deviation angle 135°

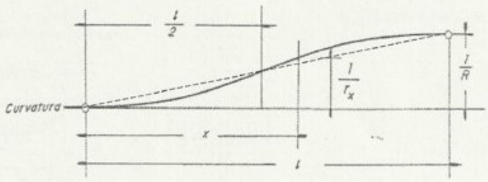


Sinusoidal curve

They exclude any discontinuity in the curvature diagram.
Characteristics are:

- curvature diagram with horizontal tangents;
- more comfort, since suspensions are continuously loaded with minor oscillations for the cabin.

Dashed line : how change curvature for clothoid or similar. Synusoidal is similar to straight for an initial point, at the final point is similar to curve next. Confort is better than clothoid.



Attention is a synusoidal diagram curvature not a single curve.

$$\rho_x = \frac{1}{r_x} = \frac{1}{2R} \cdot \left[2\frac{x}{l} - \frac{1}{\pi} \cdot \sin\frac{2\pi x}{l} \right]$$

Sinusoidal curve

Deviation angle:

$$\tau = \int_0^{\tau} d\tau = \int_0^{S} \rho ds = \frac{1}{2R}\int_0^{S}\left(\frac{2s}{L} - \frac{1}{\pi} sen\frac{2\pi s}{L}\right)\cdot ds =$$

$$= \frac{1}{2R}\cdot\left[\frac{s^2}{L} + \frac{L}{2\pi^2}\cdot\left(\cos\frac{2\pi s}{L} - 1\right)\right]$$

For s = L: ρ= 1/R ➡ $\tau = \frac{L}{2R}$

Sinusoidal curve

To derive the coordinates (x,y) of points, the following hypothesis are made:

- $y'^2 \ll 1$
- $x \cong s$

$$\rho = \frac{1}{r} = \frac{\frac{d^2y}{dx^2}}{\left[1+\left(\frac{dy}{dx}\right)^2\right]^{\frac{3}{2}}} = \frac{y''}{\left[1+(y')^2\right]^{\frac{3}{2}}}$$

$$y'' \cong \frac{1}{r} = \frac{1}{2R}\cdot\left(\frac{2x}{L} - \frac{1}{\pi} sen\frac{2\pi x}{L}\right)$$

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Comparison clothoids – sinusoidal curve

On a transition curve speed is a constant.

From the comfort point of view, it is interesting to evaluate the differences in terms of jerk.

For the clothoid it is equal to ...

$$c = \frac{da_C}{dt} = \frac{d\left(\frac{v^2}{r}\right)}{ds}\cdot\frac{ds}{dt} = v^3\cdot\frac{d\left(\frac{1}{r}\right)}{ds} = v^3\cdot\frac{d}{ds}\left(\frac{s^n}{A^{n+1}}\right) = \frac{v^3}{RL}\cdot n\cdot s^{n-1} = \frac{v^3}{RL}\cdot f(s)$$

$\frac{V^3}{RL}$ = variable part

$f(s)$ = costant part

is the same also for synusoidal.

... while for the sinusoidal curve ...

$$c = v^3\cdot\frac{d}{ds}\left(\frac{1}{2R}\left(\frac{2s}{L}-\frac{1}{\pi}sen\frac{2\pi s}{L}\right)\right) = \frac{v^3}{LR}\cdot\left(1-\cos\frac{2\pi s}{L}\right) = \frac{v^3}{LR}\cdot f(s)$$

ascissa curvilinea

I study the value of jerk to know differences of $f(s)$ between clothoid and synusoid

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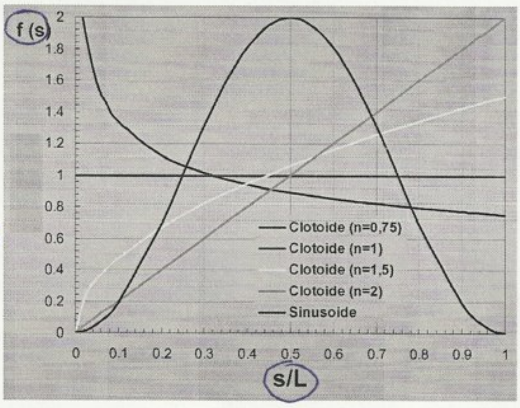
Comparisons clothoid – sinusoidal curve

S/L : normalized position on a transition curve → so I forget the real length of the transition.

n = 1 clothoid with constant jerk → on element before and after jerk is zero!



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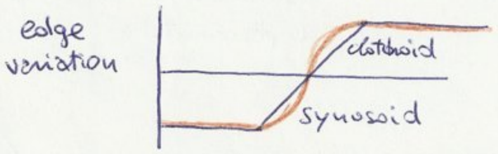
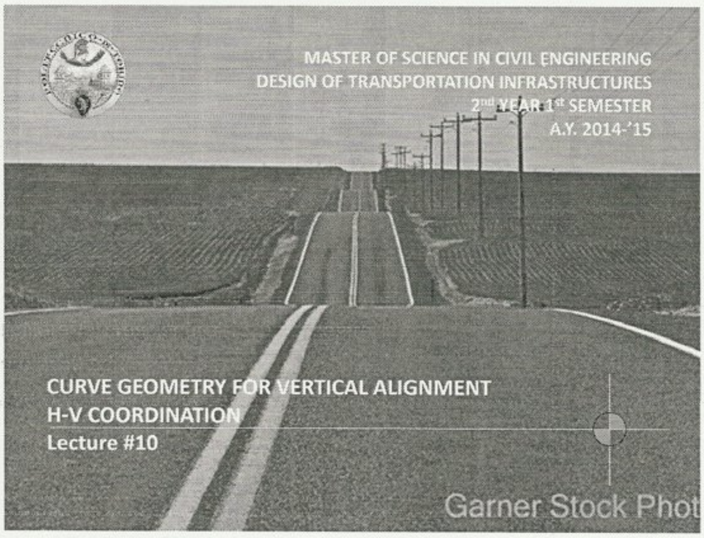
Synusoidal curve create a variable jerk on time → it is the reason for better confort. In addition this curve is longer than clothoid so it improve the gap.

Any defect? yes, the construction!

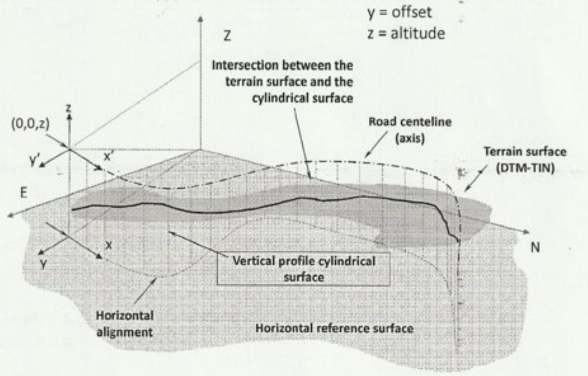
Because acceleration change with curvature $a_T = \frac{v^2}{R}$

On a clothoid, to contrast acceleration I change grades on road with a linear rule but with a synusoidal curve edge must change with a sinusoid rule ⌒ → it is very complex!

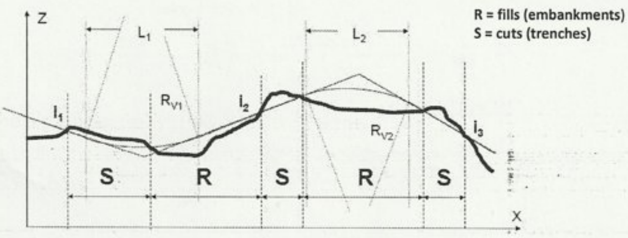




General approach to the geometric design of transportation infrastructures



Vertical alignment criteria



Criteria for the design of the vertical alignment:
1. Safe driving conditions (sight distances, V&H coordination)
2. Vehicle performances (maximum grade)
3. Respect of constraints (water table, rivers, interferences) → water table → falda
4. Minimum quantities of cuts and fills (R→Rmin e S → Smin)
5. Earthworks balance (R ≅ S).

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