WISE Requirements Analysis Framework for Automated Driving Systems

Operational World Model Ontology for Automated Driving Systems

Part 1: Road Structure

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Document history

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Abstract

This document is Part 1 of an ontology definition for specifying operational world models for an Automated Driving System (ADS). Part 1 defines a road structure ontology, which covers road types, road surface, road geometry, cross-section design, traffic control devices, pedestrian and cycling facilities, junctions, railroad level crossings, bridges and tunnels, driveways, and temporary road structure. The ontology can be used to define the Operational Design Domain (ODD) for an ADS. Other uses of the ontology are ADS behavior specification, test development and coverage assessment, labeling and indexing of datasets, and development of environment models used in an ADS.

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1. Scope

This document defines an ontology for specifying operational world models for an Automated Driving System (ADS). The ontology defines elements that occur in road environments, including their attributes, relationships, and if applicable, behaviors. Operational world models (OWMs) are used to define the Operational Design Domain (ODD) for an ADS or automated driving features. They provide context for specifying ADS driving behavior requirements and verifying and validating the implemented driving behavior. In particular, they can be used to specify simulation and field test environments. Other uses of the ontology are assessing the coverage of training data and validations tests, and labeling and indexing of datasets. Finally, the ontology can be used to design the operational world model inside the ADS, which is used for motion planning.

The ontology targets SAE J3016 levels of driving automation 4 and 5 [LA]. The ontology can also be used for lower levels of driving automation; however, the current scope of this document does not consider interaction with driver or a fallback-ready user, which is required for level 3 ADS. Further, as part of the operational environment, an ADS may need to interact with the driver for dual-use vehicles, remote driver (for vehicles with that capability), passengers, readying dispatcher, and scheduling dispatcher [LA]. Future versions of this document may include these aspects.

The document was developed with the intent to be consistent with prior art to the extent possible, including relevant industry standards and scientific literature. The road environment and, thus, the ontology are multi-disciplinary by nature. The document provides a structured and commented compilation of material from over 50 sources listed in the Reference section, which span the following disciplines:

1. road design;
2. traffic engineering;
3. traffic psychology;
4. behavioral modeling; and
5. traffic safety.

Whereas traffic engineers are likely to be familiar with most of the concepts covered in the ontology, other categories of engineers designing automated driving systems, such as mechanical, electrical, computer, and software engineers, are much less likely to know this material. They may use this document to get familiar with the domain.

2. Ontology Scope and Organization

At the top level, the ontology is organized into five areas:

1. **road structure;**
2. **road users,** including vehicles, cyclists, and pedestrians**;**
3. **animals;**
4. **other obstacles;** and
5. **environmental conditions.**

This document (Part 1) covers road structure (Section 4); the companion document (Part 2) covers road users, animals other obstacles, and environmental conditions (Sections 4, 5, 6, and 7). Each area is then refined in respective subsections, which provide structured lists of the concepts being defined and additional commentary and explanation. The objective of these two documents is to define and explain the concepts that occur in the road environment and are relevant to automated driving. Tools will require data formats to represent these concepts, however. Existing formats, such as OpenDrive and OpenScenario, may be used or adapted for this purpose, or new formats may need to be developed.

The ontology currently focuses on driving on paved, structured roads in North America. *Structured roads* are those with well-defined lane structure. It assumes right-hand traffic. The specific traffic rules and structural designs are drawn from the Province of Ontario, Canada, which is fairly representative of the driving environment in North America. While there are differences across jurisdictions in North America, the bulk of the rules and road structure are very similar. For example, the road design in the United States follows the ASHTO “Green Book” [AA11]; the Canadian equivalent, the TAC Design Guide [TAC17], was modeled largely after its U.S. counterpart. Similarly, the design of traffic signs and other traffic control devices across North America can be traced back to the Manual on Uniform Traffic Control Devices (MUTCD) [MUT], first released in 1935 in the U.S.

The current version of the ontology includes driving on non-access-controlled urban and rural roads. Access-controlled freeway driving and other types of driving, such as driving in parking lots and parking garages, will be addressed in future versions of this ontology.

Other types of driving environment that are not covered by this document include

1. Parking lots;
2. Parking garages;
3. Toll plazas;
4. Drive through businesses;
5. Ferries;
6. Gas or charging stations;
7. Carwash facilities; and
8. Other car maintenance facilities.

The following section introduces a general classification of objects found in the road environment by their physical properties; they can be seen as the top-level types that are specialized by the different objects in the road environment, that is, road structure elements, road users, animals, and other objects. Finally, Section 4 will cover the road structure and its elements.

3. Object Types

Objects that make up an operational world model may be fixed or non-fixed; non-fixed objects can be stationary or moving; object can also be static or dynamic. With respect to their shape, objects can be rigid or deformable. The reminder of this section defines each object type.

Fixed objects are attached to the ground and normally cannot change their position over time. Examples include traffic signs, guardrails, trees, etc. Fixed objects remain stationary during driving scenarios. Real-world fixed structure normally does change over time, such as the result of construction or natural forces. Some scenarios may test the behavior of an ADS with respect to relocation of fixed objects. Note that fixed structures may exhibit some forms of movements, such as vibration of a traffic sign or swaying of tree branches in the wind. However, these movements, although possibly relevant to perception functions, are normally abstracted in driving behavior scenarios. Also note that fixed objects may have moving parts relevant to driving, such as railway crossing gates. The property of being a fixed object is relevant to automated driving since fixed objects are normally expected to persist over time, and thus are typically included in high-definition semantic or localization maps. Further, collisions with many types of fixed objects, such as a tree or a utility pole, are usually severe because the reaction force is generated both by object's inertia and its rigid attachment to the ground.

Non-fixed objects are not attached to the ground and may change their position over time. Examples of non-fixed objects are vehicles, pedestrians, traffic cones, and debris.

Stationary objects are objects whose momentary speed with respect to ground is zero. Examples of stationary objects are fixed objects, standing pedestrians, and parked vehicles.

Moving objects are objects whose momentary speed with respect to ground is non-zero. Examples of moving objects are driving vehicles, walking pedestrians, and debris blown by the wind.

Static objects are fixed objects or non-fixed objects that do not have the propensity to change state on their own. In particular, *motion-static objects* do not have the propensity to move on their own. Motion-static objects are normally stationary, unless an external force moves them. Examples of motion-static objects are fixed objects, such as traffic signs, guardrails, and trees. Other examples are non-fixed objects such as traffic cones, garbage cans, and debris. Non-fixed motion-static objects can move when pushed by wind, a person, or some other force.

Dynamic objects are objects that have propensity to change state. Dynamic objects are endowed with deliberate or intentional behavior. *Motion-dynamic objects* are objects that have propensity to move. In a road environment, the main categories of motion-dynamic objects are vehicles, cyclists, pedestrians, and animals. Parked vehicles and standing pedestrians are motion-dynamic objects that are stationary. Traffic signals are fixed and motion-static, but they are dynamic in the sense of changing signal indication. Whenever it is clear from the context, motion-dynamic objects are referred to simply as dynamic objects. An ADS normally needs to track the state of dynamic objects over time and also predict their future state.

Note that non-fixed static objects can also have behavioral models, such as a model of a garbage bin rolling over the roadway, or a plastic bag being blown in the wind. In extreme cases, fixed structure may have movement relevant to driving, such as trees falling as a result of strong winds.

Objects can be *rigid*, that is, having a fixed shape, such as a rock, or *deformable*, that is, changing shape, such as a human body. For the purpose of driving automation, passenger cars can be considered as rigid while driving, but parked vehicles change shape when doors are opened or closed.

All objects have the following properties that are of interest to driving automation:

1. Position and orientation;
2. Extent;
3. Mass; and
4. Malleability.

Non-fixed objects may be moving and thus also have

1. Linear velocity;
2. Angular velocities;
3. Acceleration; and
4. Angular accelerations.

4. Road Structure

Road refers to the entire *right-of-way* (also known as *trafficway*), that is, the area of land devoted to the provision of the road. It comprises a common or public thoroughfare and any other structure incidental thereto, including medians and sidewalks [GDS85]. *Roadway* is the part of the road that is used for passage of vehicles, including shoulders and bicycle lanes [GDS85,AA11]. *Travelled way* refers to that part of the roadway intended for vehicular use excluding shoulders and bicycle lanes [GDS85,AA11].

Road structure includes

1. Road type and capacity;
2. Road surface type and quality;
3. Road geometry;
    a. Horizontal alignment;
    b. Vertical alignment;
4. Cross-section design;
    a. Lane structure;
    b. Roadside structure;
5. Traffic control devices;
    a. Traffic signs;
    b. Traffic signals;
    c. Pavement markings;
    d. Vertical deflections;
6. Pedestrian crossing facilities;
7. Cycling facilities;
8. Junctions;
    a. Intersections;
    b. Interchanges;
9. Railroad level crossings;
10. Bridges;
11. Tunnels;
12. Driveways; and
13. Temporary road structure.

The road structure follows road design guidelines, which are established at federal, state or provincial, and municipal levels. At the federal level, comprehensive manuals codify road design guidelines in the U.S. [AA11] and in Canada [TAC17]. An example of provincial guidelines, which supplement the federal ones, are the geometric design standards for Ontario highways (GDSOH) [GDS85] and the Ontario Traffic Manual (OTM) series [OMT1], which cover traffic signs [OMT2,5,6,8,10] and signals [OMT12], pavement marking [OMT11], pedestrian crossings [OMT13], cycling facilities [OMT14], and temporary structure [OTM7]. Additional guidebooks may exist at municipal or regional level. Examples include the City of Toronto lane width guidelines [LWG17] and road classification system [CTR13]. Finally, all roads are classified in the regional or municipal official plans.

Several data alternative formats exist to model road structure for use in ADS navigation and simulation, including OpenDrive [Dup15], Navigational Data Standard (NDS) Open Lane Model [NDS16], and the lanelet format [BZS14]. These formats normally cover at least lane structure and traffic control devices, but may or may not include many of the other concepts and attributes discussed in this document.

The following subsections cover the main aspects of road structure. Additional elements and detailed characteristics of road structure can be found in the design guides listed earlier in the section.

4.1 Road Type and Capacity

Roads can be classified according to their function in a road network and the zone type they are located in. Road capacity is concerned with providing sufficient level of service for the road function and the expected traffic volumes.

4.1.1 General Road Classification

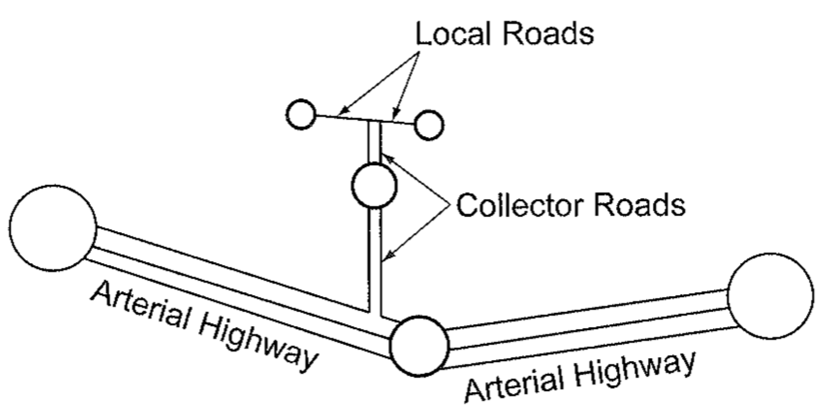


Figure 1 Channelization of trips (Figure 1-2(B) from [AA11])

The four main classes of public roads by function are local roads, collector roads, arterial roads, and freeways (Figure 1). Classification by function corresponds to stages of a road trip: main movement, transition, distribution, collection, access, and termination [AA11]. Each of the main four road classes is defined as follows:

1. *Local roads* are intended to provide access to local developments, like residential properties and businesses. They are typically low traffic volume

and carry mostly local residents. A special type of local road is *cull de sac*, also known as a *dead end*.
2. *Collectors* distribute traffic from arterials to local roads. Similar to local roads and unlike arterials, they also can provide access to residential properties. They are normally low-to-moderate capacity roads. Collectors may be subdivided into *minor* and *major collectors*.
3. *Arterials* are high-capacity roads that move traffic between urban centers and between collector roads and freeways and expressways. Arterials are typically divided by a median, possibly into two adjacent roadways. Arterials may be subdivided into *minor* and *major arterials*.
4. *Freeways* are fully controlled roads limited to through traffic, with access through interchanges.

At least three additional road classes are worth mentioning:
1. *Expressways* are similar to freeways but may have partially controlled access. In many parts of North America, expressways and freeways are synonymous, however.
2. *Local access roads*, such as *driveways*, connect a property or a business to a local or collector road. They are typically private roads.
3. *Highway ramps* are access roads connecting highways, arterials, or collectors to highways. They correspond to the transition stage of a road trip.

4.1.2 Road Capacity

The design of the different classes of roads reflects the traffic volumes, desired speeds, and the mix of vehicles that should be supported. This aspect of road design is referred to as *capacity*. Capacity of a facility is defined as "the maximum hourly flow at which road users are can be reasonably expected to pass a point or uniform section of a lane or roadway during a given time period under prevailing roadway, traffic, and control conditions" [GDS85].

The key measures related to capacity include [GDS85]:
1. *Traffic density* is "the number of vehicles occupying a given length of a lane or roadway, averaged over time, expressed as vehicles per kilometer (v/km)."
2. *Traffic volume* is "the total number of vehicles that passes over a given point or section of a lane or roadway during a given time interval, expressed in terms of annual, daily, hourly, or subhourly periods."
3. *Traffic flow* is the equivalent hourly rate at which vehicles pass over a given point or section of a lane or roadway during a given time interval less than an hour, usually 15 min."

The distinction between traffic volume and flow is subtle but important. As the GDSOH points out, "volume is the actual number of vehicles observed passing or predicted to be passing a point during a time interval", and "flow represents the number of vehicles passing a point during a time interval less than one hour, but expressed as an equivalent hourly rate." [GDS85]

The most commonly used measure of traffic volume is *Annual Average Daily Traffic (AADT)*. AADT is defined as the total annual traffic observed in a year but expressed as an equivalent daily rate, that is, total number of vehicles passing a location within a year divided by 365 [GDS85]. Hourly traffic volumes, that is, the number of vehicles observed passing a point or section, vary throughout the day, week, month, and season. The 30th highest hourly volume occurring in one year, expressed as a percent of AADT, is often used for capacity design, and is referred to as *design hourly volume (DHV)*. Service flow reflects peaking within the design hour, which is defined as four times the highest 15-minute volume. The maximum service flow is the maximum flow a roadway can carry at a given level of service.

Levels of service (LOS) are defined with respect to traffic flow characteristics (level definitions from [GDS85]):

1. *Level-of-service A* represents free flow. Individual users are virtually unaffected by the presence of others in the traffic stream. Freedom to select desired speed and to maneuver within the traffic stream are extremely high. The general level of comfort provided to the driver, passenger, or pedestrian is excellent.
2. *Level-of-service B* is in the range of stable flow, but the presence of users in the traffic stream begins to be noticeable. Freedom to select desired speed is relatively unaffected, but there is a there is a slight decline in the freedom to maneuver within the traffic stream compared to LOS A. The level of comfort and convenience provided is somewhat less that LOS A, because the presence of others in the traffic stream begins to affect individual behavior.
3. *Level-of-service C* is in the range of stable flow, but marks the beginning of the range of flow in which the operation of individual users becomes significantly affected by interactions with others in the traffic stream. The selection of speed is now affected by the presence of others, and maneuvering within the traffic stream requires substantial vigilance on the part of the user. The general level of comfort and convenience declines noticeably at this level.
4. *Level-of-service D* represents high-density, but stable, flow. Speed and freedom to maneuver are severely restricted, and the driver or pedestrian experiences a generally poor level of comfort and convenience. Small increases in traffic flow with generally cause operational problems at this level.
5. *Level-of-service E* represents operating conditions at or near the capacity level. All speeds are reduced to a low, but relatively uniform value. Freedom to maneuver within the traffic stream is extremely difficult, and is generally accomplished by forcing a vehicle or pedestrian to “give way” to accommodate such maneuvers. Comfort and convenience levels are extremely poor, and driver or pedestrian frustration generally high. Operations at this level are usually unstable, because small increases in flow or minor turbulence within the traffic stream cause breakdowns.

6. *Level-of-service F* is used to define forced or breakdown flow. This condition exists whenever the amount of traffic approaching a point exceeds the amount that can traverse the point. Queues form behind such locations. Operations within the queue are characterized by stop-and-go waves, and they are extremely unstable. Vehicles may progress at reasonable speeds for several hundred meters or more, then be required to stop in a cyclic fashion. Level-of-service F is used to describe the operating conditions within the queue, as well as the point of the breakdown. Nevertheless, it is the point at which arrival flow exceeds discharge from which causes the queue to form and level-of-service F is an appropriate designation for such points.

There are several vehicle speed measures used for traffic stream measurement and road capacity planning [GDS85]. Two of them are "spot speeds", i.e., vehicle speeds observed at a point:

- *Operating speed* is the speed at which a driver is observed operating an individual vehicle passing a point.
- *Average operating speed,* or *time mean speed*, "is the arithmetic average of vehicle speeds observed passing a point on a highway."

The following speeds are based on the observation of the vehicle travel times travelling a road section of known length [GDS85]:

- *Average running speed* is "the length of the section divided by the average running time of vehicles to travel this section. Running time includes only time which vehicles spend in motion, and does not include stopped delays."
- *Average travel speed* is "the length of the section divided by the average travel time of vehicles to travel this section, which includes stopped delay times."

The following speeds describe vehicle speeds to be continuously applied throughout a section of a road:

- *Desired speed* is "the speed at which a driver wishes to travel, determined by a combination of motivation and comfort. Motivation is heavily influenced by the length and urgency of the trip: as these factors increase, desired speed also increases." [TAC07] Driver comfort has also to do with driving task difficulty, and thus desired speed will reflect driver's expectations of the characteristics and quality of the road ahead. Expectations are, in turn, based on "the driver's perception of the prevailing topographic, environmental, traffic and climatic conditions." [TAC07]
- *Free flow speed* is "the average speed of all vehicles over those portions of arterial segments that are not close to signalized intersections and are at low traffic volumes in which vehicles are not constraint by other vehicles." [GDS85] The idea is that the free flow speed largely reflects the average desired speed.

- *Design speed* is “the speed selected for a section of a road for the purposes of design and correlation of the geometric features of the road section. It is the highest continuous speed at which an individual vehicle can travel safely on road section when weather conditions are favorable and traffic density is so low that safe speed is determined by the geometric features of the road.” [GDS85] The design speed is typically chosen to be the 85^{th} percentile of the desired speed within the driver population in good driving conditions, which is “only achievable for roads which the primary function is mobility and where severe physical constraints do not exist.” [TAC07]
- *Legal speed limits* are limits on the operating speed of a vehicle within a given section of a road imposed by traffic regulations. Statutory speed limits are default speed limits set for different types of roads, such as maximum speeds on freeways or on non-access controlled roads in developed vs. undeveloped areas. Posted speed limits are those displayed by speed control signs. Legal speed limits are selected for good driving conditions. They typically do not exceed the design speed of a given road section. When they do, it is not necessarily unsafe because of considerable margins of safety typically applied to design speeds [TAC07]. Further, additional advisory speed limits can and should be posted at critical locations.

4.1.3 Road Classification Criteria

Federal and state or provincial guidelines provide general criteria used in road classification. For example, the GDSOH manual [GDS85] classifies rural (Table 1) and urban (Table 2) roads according to their service function (mobility vs. land access), expected traffic volumes (expressed as Annual Average Daily Traffic or AADT), design speed, types of vehicles supported (passenger cars, trucks), and the percentage of road length in the network classified under the given type. As the tables indicate, local roads make up about 70% of the total length in a network.

Table 1 Criteria of rural road classification (Table A5-4 from [GDS85])

FUNCTIONAL CLASSIFICATION	RURAL FREEWAYS	RURAL ARTERIALS	RURAL COLLECTORS	RURAL LOCALS
Traffic Service	optimum mobility	traffic movement primary consideration	traffic movement & land access equal importance	traffic movement secondary consideration
Land Service	no access	land access secondary consideration	traffic movement and land access equal importance	land access primary consideration
Range of Traffic Volume A.A.D.T	more than 10,000	1,000 - 20,000	200 - 10,000	not applicable
Traffic Flow	free flow	uninterrupted flow except at signals	interrupted flow	interrupted flow
Design Speed	100 - 120 km/h	80 - 110 km/h	60 - 100 km/h	60 - 80 km/h
Average Running Speed Off-peak Conditions	80 - 120 km/h	60 - 100 km/h	60 - 90 km/h	50 - 80 km/h
Vehicle Type	all types heavy trucks average 20 - 30%	all types up to 20% trucks	all types up to 30% trucks mostly single unit type	predominantly passenger cars and light to medium trucks and occasional heavy trucks
Percentage of Total Length	up to 5	5 - 10	10 - 20	75 approx.
Connects to	freeways arterials collectors	all classifications	all classifications	arterials collectors locals

Table 2 Criteria of urban road classification (Table A5-5 from [GDS85])

FUNCTIONAL CLASSIFICATION	URBAN FREEWAYS	URBAN ARTERIALS	URBAN COLLECTORS	URBAN LOCALS
Traffic Service	optimum mobility	traffic movement primary consideration	traffic movement & land access equal importance	traffic movement secondary consideration
Land Service	no access	land access secondary consideration	traffic movement and land access equal importance	land access primary consideration
Range of Traffic Volume A.A.D.T	more than 75,000	5,000 - 50,000	1,000 - 20,000	not applicable
Traffic Flow	free flow	uninterrupted flow except at signals and cross walks	interrupted flow	interrupted flow
Design Speed	80 - 120 km/h	80 - 110 km/h	60 - 90 km/h	60 - 80 km/h
Average Running Speed Off-peak Conditions	60 - 110 km/h	50 - 90 km/h	40 - 70 km/h	40 - 60 km/h
Vehicle Type	all types up to 20% trucks	all types up to 20% trucks	all types	passenger and service vehicles
Percentage of Total Length	up to 10	up to 30	up to 30	70 approx.
Connects to	freeways arterials	freeways artetials collectors	arterials collectors locals	collectors locals

Municipalities typically define the most refined road classification criteria and provide a plan of the public road network located in their jurisdiction that assigns a class to each road. For example, Table 3 shows the road classification system used by the City of Toronto [CTR13]. In addition to the general criteria mentioned earlier, the system also specifies pedestrian and cyclist accommodation and spacing between traffic control devices such as traffic lights, pedestrian cross-overs, and stop signs. For the City of Waterloo, the concrete assignment of classes to all the roads within the municipality is specified in an appendix to the Official Plan [WRC17].

Table 3 City of Toronto Road classification criteria (Table 1 from [CTR13])

Characteristic	Locals	Collectors	Minor Arterials	Major Arterials	Expressways
Traffic movement versus property access	Property access primary function	Traffic movement and property access of equal importance	Traffic movement primary consideration; some property access control	Traffic movement primary consideration; subject to property access control	Traffic movement primary consideration; no property access
Typical daily motor vehicle traffic volume (both directions)	<2,500	2,500 – 8,000	8,000 - 20,000	> 20,000	> 40,000
Minimum number of peak period lanes (excluding bicycle lanes)	One (one-way streets) or two	One (one-way streets) or two	Two	Four	Four
Desirable connections	Locals, collectors	Locals, collectors, arterials	Collectors, arterials	Collectors, arterials, expressways	Major arterials, expressways
Flow characteristics	Interrupted flow	Interrupted flow	Uninterrupted except at signals and crosswalks	Uninterrupted except at signals and crosswalks	Free-flow (grade separated)
Legal speed limit, km/h	40 - 50	40 - 50	40 - 60	50 – 60[2]	80 – 100
Accommodation of pedestrians	Sidewalks on one or both sides	Sidewalks on both sides	Sidewalks on both sides	Sidewalks on both sides	Pedestrians prohibited
Accommodation of cyclists	Special facilities as required		Wide curb lane or special facilities desirable		Cyclists prohibited
Surface transit	Generally not provided	Permitted	Preferred	Preferred	Express buses only
Surface transit daily passengers	Not applicable	<1,500	1,500 - 5,000	> 5,000	Not applicable
Heavy truck restrictions (e.g. seasonal or night time)	Restrictions preferred	Restrictions permitted	Generally no restrictions	Generally no restrictions	No restrictions
Typical spacing between traffic control devices[3], m	0 - 150	215 - 400	215 - 400	215 - 400	Not applicable
Typical right-of-way width, m	15 - 22	20 - 27	20[4] – 30[5]	20[4] – 45[5]	> 45[5]

Notes:
1. Private roads and lanes (public or private) are not part of this classification system.
2. A number of major arterial roads have speed limits which fall outside this range, as noted in Table 2: Speed Limit.
3. Traffic control devices refer to traffic control signals, pedestrian crossovers and 'Stop' signs.
4. 20 m rights-of-way exist on many downtown or older arterial roads. New arterial roads should have wider rights-of-way.
5. Wider rights-of-way (within the ranges given) are sometimes required to accommodate other facilities such as utilities, noise mitigation installations, bicycle facilities, and landscaping. For new streets, wider rights-of-way (upper end of ranges given) should be considered to accommodate such facilities.

4.1.4 Road Location by Zone

Roads are located on lands that have expected use. The most basic distinction is whether the land is within an urban or rural area, which gives rise to urban vs. rural roads. Municipalities and regions regulate land use through *zoning*, which is specific to each local jurisdiction. Normally, zones reflect the type of development, such as residential, business, industrial, conservation, and agricultural, and the population density. For example, the Official Plan of the City of Waterloo defines the following types and subtypes of zones [WOP16]:

- *Residential*: Low Density, Mixed-Use Medium/Medium-High/High Density;
- *Commercial*: City Center, Commercial Center, Community Commercial, Neighborhood Commercial, Convenience Commercial, and Office;
- *Employment*: Flexible Industrial, Business Employment, and Academic;
- *Open Space*: Parks and Other Green Areas, Cemeteries, Golf Course, Landfill;
- *Natural System*; and
- *Other*: Water Body.

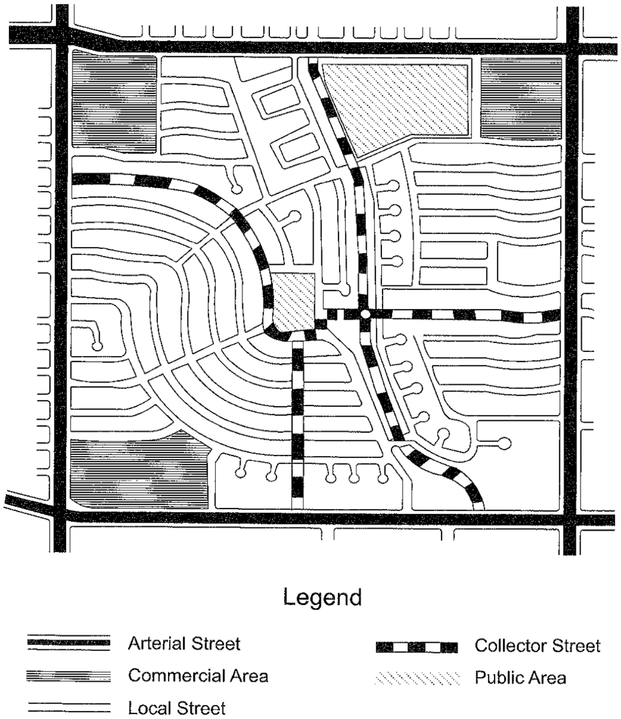


Figure 2 Schematic illustration of a portion of a Suburban Street Network [AA11]

Figure 2 illustrates a portion of a Suburban Street Network with local streets, collectors, and arterials in residential, public, and commercial zones.

In combination with road class, zones set expectation for types of road users and traffic patterns, including traffic volumes and their fluctuations over time, type of vehicular traffic (passenger cars, commercial vehicles, presence of farming equipment on the road, etc.), volumes of pedestrian and cyclist traffic, presence of children (especially in school zones), pedestrian activities (road crossing, roadside work, roadside play, etc.), and presence of wildlife (especially in conservation areas).

4.2 Road Surface Type and Quality

4.2.1 Road Surface Type

The most salient aspect of paved road surface is *pavement type*. Two main types of pavement are commonly used in road construction today [Nik17]:

1. *bituminous surface*, also known as *asphalt concrete*, which is a *flexible pavement surface* used in most non-freeways and some more-lightly-used rural freeways.

2. *Portland cement concrete surface*, which is a *rigid pavement surface* used in most urban freeways and heavily travelled rural freeways. Sometimes the cement concrete is overlaid with an asphalt layer.

Other less common types of road surface are *cobblestone*, *granite setts*, and *gravel*.

The specific material mix used in asphalt or cement concrete pavements varies regionally and is often standardized at State or Provincial and municipal level. For example, the City of Calgary's road construction standards [CRC12] specify the properties of asphalt or cement concrete to be used for paving its municipal roads.

Pavement designers traditionally try to enhance [WS05]:

1. friction characteristics (for safety),
2. noise characteristics (for comfort and environmental noise protection),
3. rutting resistance (for safety and durability), and
4. structural performance (for durability).

Key functional and non-functional properties of pavement-tire interaction are determined by the *pavement texture* (Figure 3). *Microtexture*, wavelengths of 1μm to 0.5mm, and *macrotexture*, wavelengths of 0.5mm to 50mm, are responsible for tire-road friction. Other important properties such as vehicle external and internal noise development, splash and spray, tire wear, rolling resistance, and potential of tire or suspension damage depend on surface features of different spatial frequency.

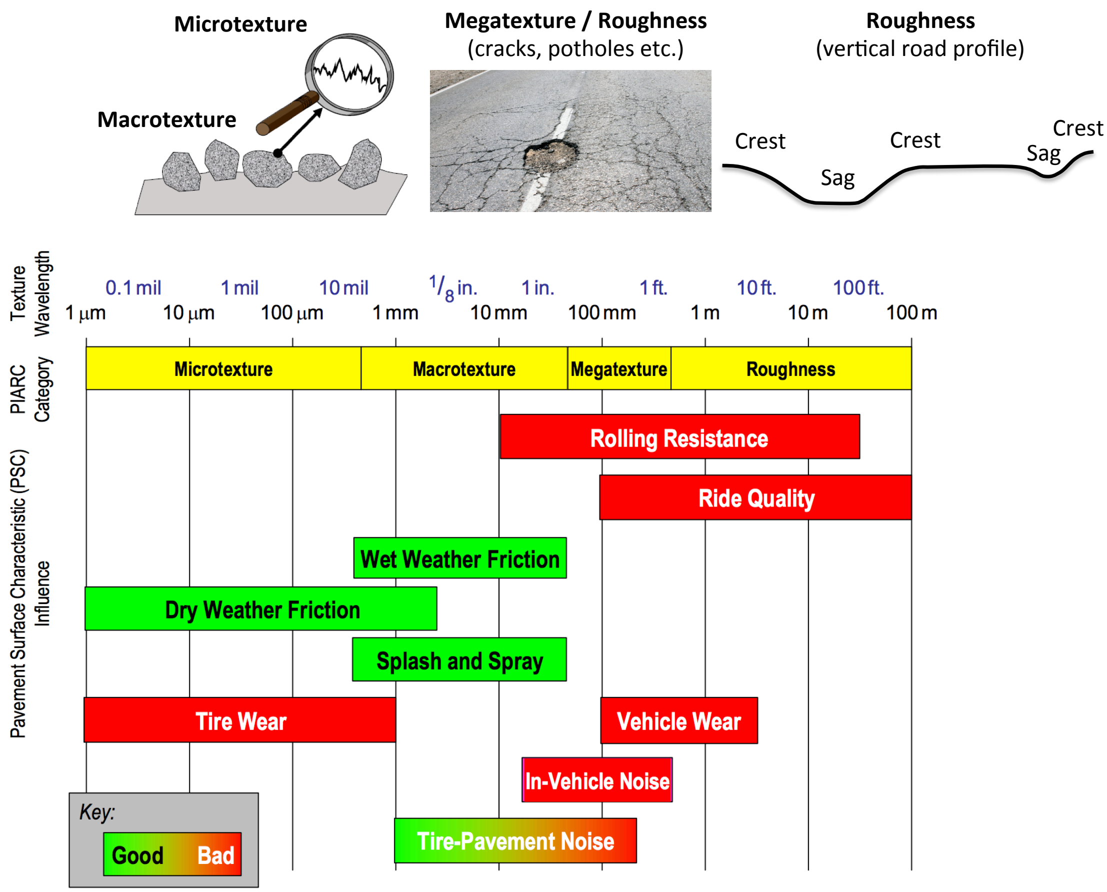


Figure 3 Texture wavelength influence on pavement-tire interaction (Figure A.2 in [Cac06]; Permanent International Association of Road Congresses (PIARC) categories from [PIA95])

4.2.2 Road Surface Friction

Pavement friction is the force that resists the relative motion between a vehicle tire and a pavement surface [Hal08]. The friction force between tire and pavement is generally characterized by a dimensionless coefficient known as *coefficient of friction* (μ), which is the ratio of the tangential force at the contact interface between the tire and pavement to the normal force on the wheel [FMI12]. The friction coefficient peaks at a critical tire slip ratio and then flattens off as slip reaches 100%, that is, locked wheel condition (Figure 4). The *Skid Number* (*Friction Number* or *Skid Resistance*) is the friction coefficient of a locked, standardized wheel expressed in percent and measured across a test interval at a reference speed [Hal08]. Road friction measurement can also involve measuring the friction coefficient across a range of slip values as well as the side force for different sideslip angles. Hall et al. [Hal08] give a comprehensive survey of measurement equipment and methods used.

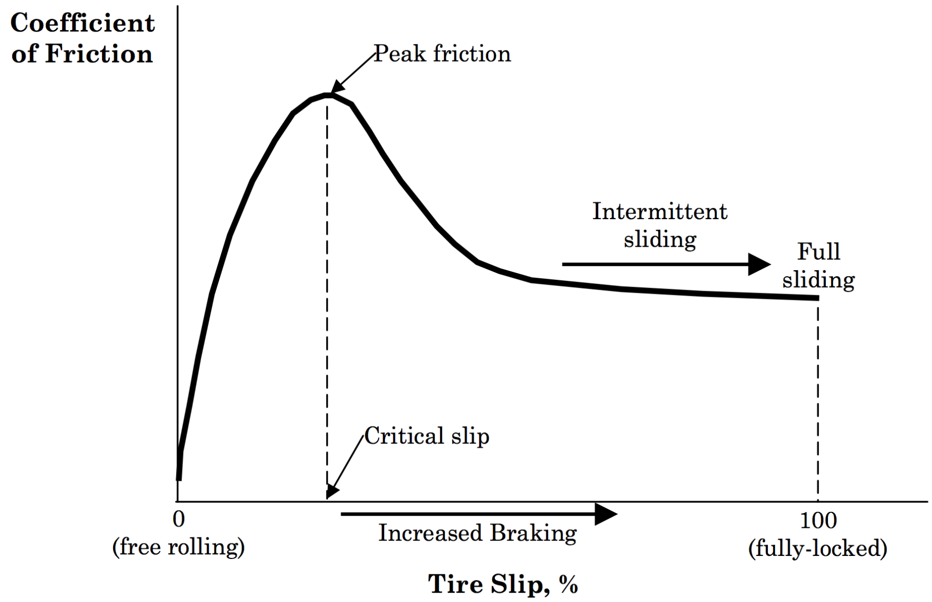


Figure 4 Pavement friction vs. tire slip (from [Hal08])

Table 4 Factors affecting pavement friction (Table 2 from [Hal08])

Pavement Surface Characteristics	Vehicle Operating Parameters	Tire Properties	Environment
• **Micro-texture** • **Macro-texture** • Mega-texture/ unevenness • **Material properties** • Temperature	• **Slip speed** ➢ Vehicle speed ➢ Braking action • Driving maneuver ➢ Turning ➢ Overtaking	• Foot Print • **Tread design and condition** • Rubber composition and hardness • **Inflation pressure** • Load • Temperature	• Climate ➢ Wind ➢ **Temperature** ➢ **Water (rainfall, condensation)** ➢ **Snow and Ice** • **Contaminants** ➢ Anti-skid material (salt, sand) ➢ Dirt, mud, debris

Note: Critical factors are shown in bold.

The pavement friction is influenced by pavement properties, including micro- and macrotexture, but also vehicle operating parameters, tire properties, and contaminants of the pavement surface (Table 4). Good pavement friction can be achieved with either asphalt or cement concrete; the key is proper construction and maintenance techniques that ensure adequate surface texture, which include gradation (sizing) of the particles used in the pavement mix and various surface texturing treatments, such as grooving and cold milling [NYK05]. Contaminants may be precipitation-related, such as rain, snow, and ice, or otherwise, such as mud, anti-skid material (salt, sand), or spilled oil.

Table 5 Typical skid number value ranges [NYK05]

Skid Number	Recommendations
< 30	Take measures to correct
≥ 30	Acceptable for low volume roads
31 - 34	Monitor pavement frequently
≥ 35	Acceptable for heavily traveled roads

Table 5 shows representative value ranges of skid numbers obtained with a skid trailer. It also shows associated recommendation for each value range. Table 6 shows friction coefficient values during braking in winter conditions and the effect of different anti-skid treatments: chloride, sand, and a mix of both. Finally, Table 7 shows how skid numbers were changing for different weather related pavement conditions observed on roads in Wisconsin.

Table 6 Friction coefficient values during braking [NYK05]

Snow or Ice Conditions	Friction Coefficient
Ice	0.1 – 0.2
New Snow	0.2 – 0.25
Old Snow	0.25 – 0.30
Refrozen snow	0.30 – 0.40
Chloride-Treated Snow	0.35 – 0.45
Sand-Treated Snow	0.30 – 0.40
Chloride-Sand Mix	0.30 – 0.50

Table 7 Skid number measurements from Wisconsin (Winter 1994-1995) [FHW98]

Pavement Condition	Friction Value		
	Median	25th percentile	75th percentile
Dry	47	44	51
Wet	45	42	47
Slush	30	26	34
Loose snow	26	23	28
Packed snow	21	19	22
Black ice	22	19	27

4.2.3 Road Surface Roughness

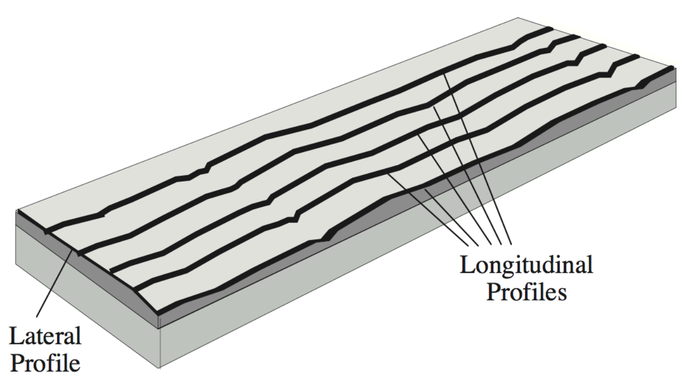


Figure 5 Longitudinal and lateral road surface profiles over a road section [SK98]

An important quality of road surface is its *roughness*, which describes the deviation of the road surface from planar and smooth surface that affect vehicle dynamics, ride quality, and dynamic loads [AST12]. Different types of roughness are associated with different spatial wavelengths (Figure 3). For example, heaving motions of the vehicle body that mainly involve suspension are due to wavelengths on the order of 15 meters, whereas noise involving acoustics of the body is generated by wavelengths shorter than 1 meter [SK98]. Roughness is measured along a section of a profile, which is an imaginary line, typically in either longitudinal or transverse (lateral) direction of the road (Figure 5).

The most common measure of roughness is International Roughness Index (IRI). The index is calculated as a filtered response of an idealized quarter-car vehicle model traveling at a reference speed of 80 km/h over the measured road profile [SK98,Say98]. IRI is designed to be highly correlated with the ride quality of a wide range of automobiles and is typically tuned into the wavelengths that cause humans to feel discomfort. IRI is measured in units of slope, e.g., m/km, which express the accumulated motion of suspension per length of travel. Its values range from 0, which is equivalent to driving on a plate of glass, upwards to several m/km, which corresponds to a very rough road. The Federal Highway Administration (FHWA) defines road roughness as *good* for IRI of less than 1.5 m/km, and *acceptable* for IRI of less than 2.7 m/km (Table 8).

Table 8 FHWA pavement condition criteria [FHW90]

Roughness Category	**IRI (inches/mile)**	**IRI (m/km)**
Good	≤ 95	≤ 1.5
Acceptable	≥ 95 and ≤ 170	≥ 1.5 and ≤ 2.7

Since roughness affects both comfort and safety, it often affects driver behavior. For example, roughness may influence the selection of travel speed, e.g., to avoid uncomfortable frequencies or excessive excitation, and travelled lane, if available lanes have different roughness. Drivers may also perform swerve maneuvers to avoid potholes and other undesirable road surface features.

4.2.4 Road Surface Damage

Road surface becomes damaged as a result of wear and distress, mainly caused by adverse weather, ground subsidence, and heavy truck traffic. The resulting damage is typically perceivable as roughness.

Road damage takes a range of appearance. Examples of include (see [AI17] for photographs):

1. *Cracks*, which are linear openings of different types including longitudinal or transverse, block, edge, Alligator, and slippage type;
2. *Potholes*, which are round openings from distress or poor base;

3. *Utility cuts or patch failures*, which are deteriorating portions of the pavements that have been removed and replaced;
4. *Ruts*, which are linear depressions created following a permanent deformation of the layers of bitumen caused by heavy trucks;
5. *Depressions*, which are dips in the surface such as caused by ground subsidence
6. *Sinkholes*, which are large openings in the surface such as caused by erosion, flooding, or water main brakes;
7. *Upheavals or swells*, which are large bumps in the surface such as caused by expansive soil or frost heaves; and
8. *Warped surface*, which are major deformations of the surface such as caused by tectonic movements.

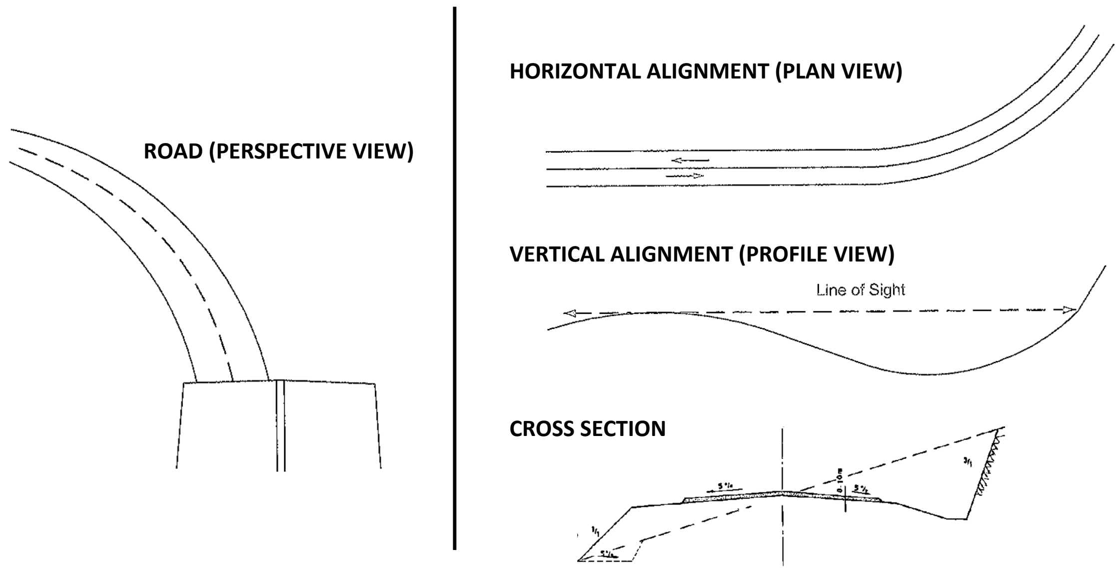
Damaged surface affects ride comfort and safety. On dry road surface, small surface features such as minor cracks, potholes, depressions, and bumps mainly contribute to reduced ride comfort. Some surface damage may pose immediate safety risk, however. For example, ruts are known to cause increased risk of aquaplaning in wet conditions. Sinkholes and surface warping pose obvious risks, but large potholes may damage tires and suspension, and may even affect vehicle stability at higher speeds.

Surface features such as manholes and gutters, although they are not artifacts of road surface damage, may cause roughness and interfere with traffic flow in similar ways as surface damage, especially if they were improperly installed.

The International Roughness Index (IRI) can be used to capture both (1) the impact of systematic surface damage on ride comfort and (2) the presence of occasional potholes in an otherwise smooth road. For the latter case, a *continuous IRI* is used, which is defined by a short moving average window of 25 foot. For example, a manhole may cause the continuous IRI to peak at close to 1000 in/mile in an otherwise smooth road, whose IRI fluctuates between 100 and 200 in/mile [MDT07].

4.3 Road Geometry

The key aspects of geometric design of roads are horizontal alignment, vertical alignment, and cross-section design.



4.3.1 Horizontal Alignment

Horizontal alignment is the configuration of a road or roadway as seen in plan, that is, a projection onto a horizontal plane. Horizontal alignment shows the horizontal curvature of a road and is normally designed as a composition of

1. tangents (straight lines);
2. circular curves; and
3. spiral or transition curves, which are most commonly clothoids.

4.3.1.1 Circular Curves

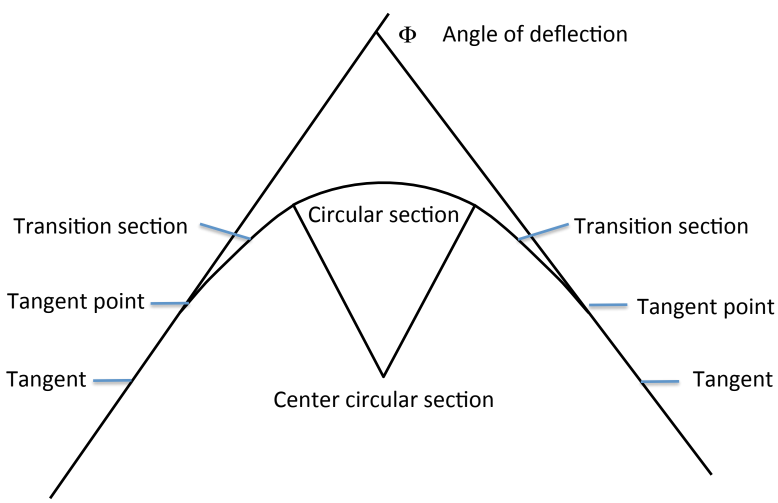
When traveling on a circular curve at a constant speed, a vehicle is subject to lateral acceleration towards the center of the circle. This centripetal force providing this acceleration is the tire-pavement friction, and if the travelled road is superelevated, that is, banked inwards the curve, the friction force is supplemented by a component of gravity due to the weight of the car. This can be expressed by the formula [GDS85]:

$e + f = v^2 / 127R$

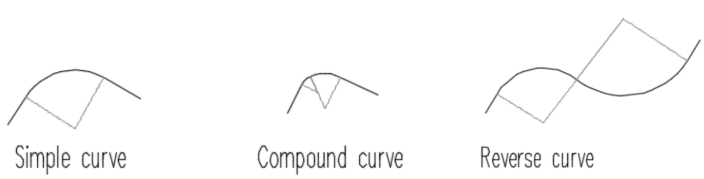
where e is the pavement superelevation, which is the amount of rise per lateral distance and is positive when sloping towards the center of the curve; f is the friction coefficient; v is the vehicle speed in km/h; and R is the curve radius in meters. Superelevation normally ranges from 0 to 0.06 m/m (i.e., 6%), and is selected based on multiple factors including climate conditions, terrain, type of development (rural or urban), and maintenance. Most roads in Ontario adopt maximum superelevation of 0.06 m/m. Curve radii are selected both for safety and comfort assuming the design speed. In order to accommodate both requirements with an ample margin, curve radii calculation assumes maximum friction coefficient between 0.122 (for high speeds) and 0.165 (for low speeds) [GDS85].

4.3.1.2 Spiral Curves

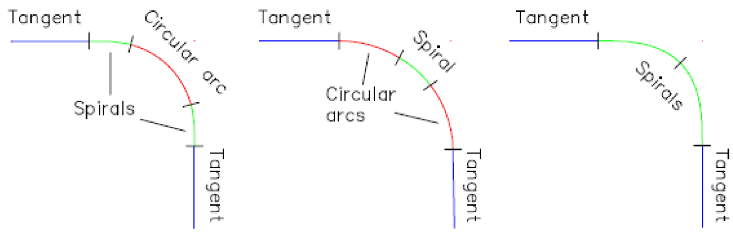
Spiral curves provide transitions between different radii. A tangent has an infinite radius. A circular curve has a constant radius. A vehicle traveling directly from a tangent onto a circular curve would require the application of an instant centripetal force to keep it on the circular curve, which would be experienced as a sudden jerk. A spiral provides a transition that gradually increases the required centripetal force (Figure 6.A).



A) Horizontal road curve with a circular section and two spiral transition sections



B) Horizontal road curves with circular sections



C) Horizontal road curves with spiral sections

Figure 6 Horizontal road curve design patterns

Clothoids are the most commonly used type of spirals in road design. A clothoid is a spiral whose radius is reciprocal of curve length, i.e., its curvature is linear with curve length. A vehicle traveling along a clothoid at constant speed experiences a centripetal force that varies at a constant rate along the length of the transition. The spiral parameters are selected such as to limit the amount of jerk for a given design speed to a comfortable level, which is normally less than 0.6 m/s^3 [GDS85].

Horizontal curves can use different combinations of circular and spiral sections depending on the radii required at the different points of the curve (Figure 6 B and C).

4.3.2 Vertical Alignment

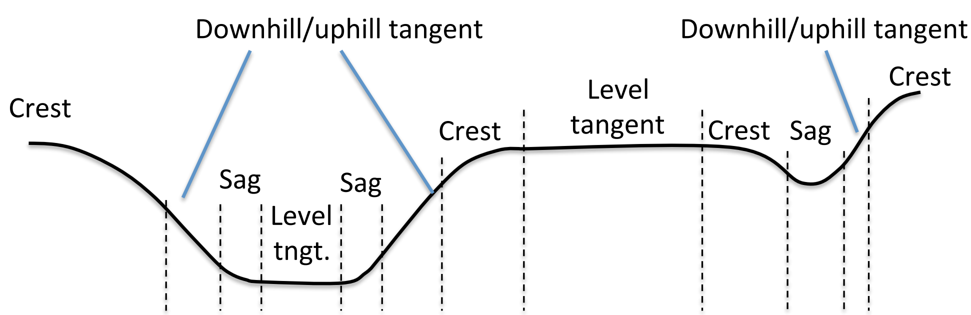


Figure 7 Vertical alignment with tangents, crests, and sags

Vertical alignment is the vertical configuration of a road or roadway in a longitudinal section. It consists of *tangents*, which have constant grade, and *crest* and *sag* curves, which are parabolas and provide transitions between adjacent grades (see Figure 7). *Crest vertical curves* are those between tangent sections (constant grade) in which either a positive grade is followed by negative grade, a positive grade is followed by a lesser positive grade, or a negative grade is followed by steeper negative grade [GDS85]. *Sag vertical curves* are those in which a negative grade is followed by a positive grade, a negative grade is followed by a lesser negative grade, and a positive grade is followed by a steeper grade [GDS85].

Parabolas with vertical axes are used as crest and sag vertical curves to provide smooth transition between adjacent grades (see Figure 7). The rate of change of grade with the length of a parabola is constant, and as a result, the sight distance when travelling on a crest is constant throughout the vertical curve length.

Road grade is typically less than 6%. Grades up to 3% affect passenger cars usually only to a small degree. On 5% grade passenger cars will usually have no problem operating, but trucks will experience significant loss of speed and may experience difficulty on icy road [GDS85]. Truck climbing and passing lanes are helpful in this case.

4.4. Cross section design

Cross section design is the configuration of the road across its transverse profile, from right-of-way (r.o.w.) line to right-of-way line (Figures 8, 9 and 10).

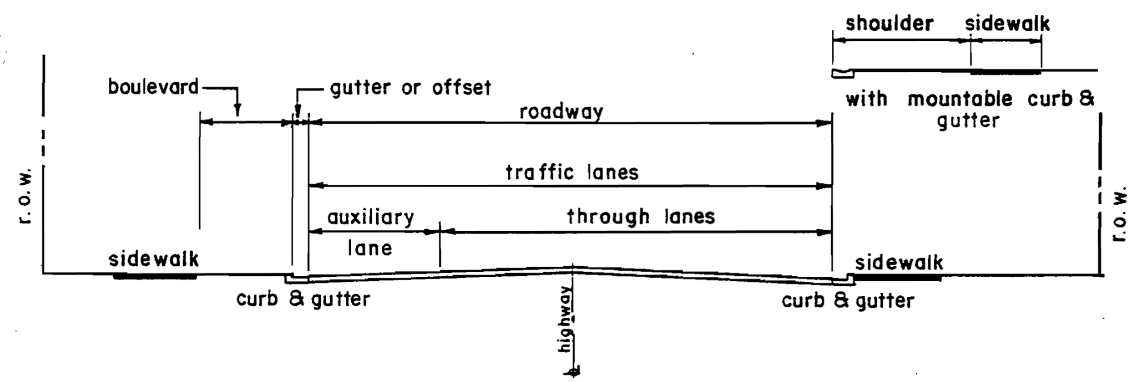


Figure 8a Example cross section design of a typical urban two-lane, undivided road (urban local road or collector) (part of Figure D1-2 [GDS85])

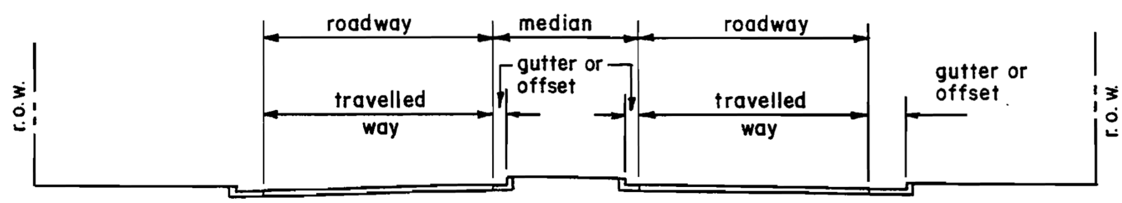


Figure 8b Example cross section design of a typical urban divided road (urban arterial) (part of Figure D1-2 [GDS85])

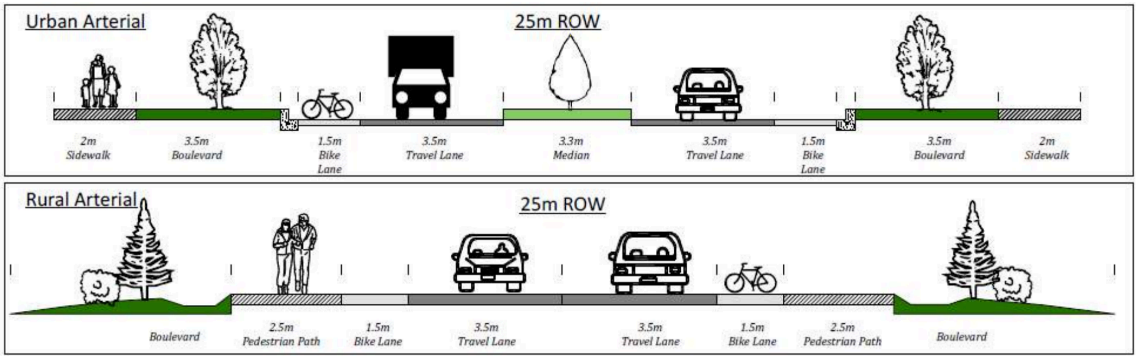


Figure 9 Example cross-section design of an urban arterial and a rural arterial ([CS11])

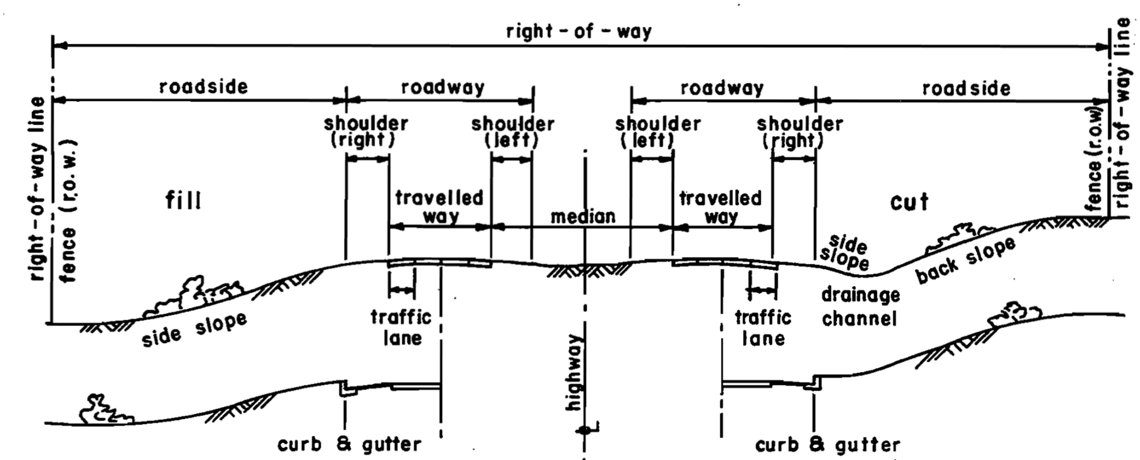


Figure 10 Example cross section design of a typical freeway (part of Figure D1-2 [GDS85])

A major aspect of cross section design is the *roadway configuration*:

1. *undivided roads* have a single roadway (Figure 8); and
2. *divided roads* have two separate roadways (Figures 9 and 10), one for each traffic direction, typically separated by a wide and depressed median, which may house median barriers.

Elements of the cross section design include

1. *vehicular lanes* are used by motor vehicles;
2. *vehicle turnouts* are paved areas adjacent to traffic lanes for temporarily stopping motor vehicles or for passing (they are kind of vehicular lane);
3. *bus bays* are turnouts for stopping buses;
4. *bikeways* are parts of the right-of-way set aside for preferential treatment of bicycle traffic; a bikeway is made up of one or more *bicycle lanes*; [GDS85]

5. *shoulders* are areas of pavement, gravel, or hard surface placed adjacent to traffic lanes and intended for emergency stopping and travel by emergency vehicles only; [GDS85]
6. *urban shoulders* are areas of pavement placed between traffic lanes and curb and delineated by an edge line from the adjacent vehicular lane that a cyclist may choose to ride in instead the vehicular shared vehicular lane where dedicated cycling facilities are not provided. An urban shoulder may also be used for snow or fall leaves storage. [LWG17]
7. *medians* are areas that laterally separate traffic lanes that carry traffic in opposite directions; a median may be *flush*, *raised*, or *depressed*, in relation to vertical position with respect to the adjacent traffic lanes [GDS85]; median width may vary anywhere from 1 m to 30 m;
8. *median openings* are openings in non-traversable medians that provide for crossing and turning traffic;
9. *traffic islands* are separations placed between lanes to channelize traffic, such as at intersections, or to provide refuge for pedestrians. Traffic islands can be placed between lanes carrying traffic in same or opposite directions. Traffic islands are usually short; long separations of lanes carrying traffic in opposite directions are called medians.
10. *outer separation* is a reserve which separates traffic travelling in the same direction, and includes shoulders, if any; [GDS85]
11. *traffic barriers* are placed adjacent to a roadway to protect traffic from hazardous objects fixed or moving (other traffic); [GDS85]
12. *median barriers* are traffic barriers placed in medians; [GDS85]
13. *sidewalk* is a travelled way intended for use by pedestrians only; [GDS85]
14. *boulevard* is a reserve which separates roadway and sidewalk; it normally accommodates roadside infrastructure such as traffic signs and hydrants, and may also be used for snow storage; [GDS85]
15. *curb and gutter* is placed adjacent to an outside lane or shoulder and is intended to control and conduct storm water and provides delineation for traffic; [GDS85] and
16. *drainage channel* is placed adjacent to an outside lane or shoulder and is intended to control and conduct storm water. [GDS85]

Cross-section design of a horizontal tangent section of a roadway will feature *cross-fall*, which is transversal grade designed to drain rainwater to the side(s) of the roadway. Two-lane and four-lane undivided roads are typically *crowned*, that is, they have cross-fall from the centerline to down to each side (Figure 8). The roadways in a divided road may have also crown (Figure 10) or be superelevated uniformly across the transversal profile (Figure 9). Typical cross-fall is -0,02m/m or -2%, where a negative value indicates downward slope from the centerline towards a side [GDS85]. Curved roadway sections are superelevated as described in the Section on Horizontal Alignment. The part of a tangent section of a crowned roadway adjacent to a curved section has a so-called *runout*, where the outside cross-fall of the crowned tangent section is gradually increasing until it aligns with the superelevation of the curved section.

4.4.1 Lane Structure

Lane structure varies in the number, type, width, and arrangement of lanes along the cross section.

Based on the number of lanes, roads are classified into:

1. *Two-lane roads* have one *through lane* of traffic in each direction [GDS85].
2. *2+1 roads* have two lanes of traffic in one direction and one in the other direction; consecutive road sections alternate between one and two lanes in a given direction [AA11].
3. *Four-lane roads* have two through lanes of traffic in each direction [GDS85].
4. *Multi-lane roads* have more than two through lanes of traffic in each direction [GDS85].

4.4.1.1 Lane Types

Vehicular lanes are classified into [GDS85]:

1. *Traffic lanes*, also known as *travel lanes*, are intended for the movement of a single line of vehicles.
2. *Parking lanes* are intended for parking vehicles, either *curb-parallel* or *angled*, which is typically between 45-60 degrees.
3. *Vehicle turnouts*, including *bus bays*, are paved areas, typically located on the left edge of the roadway, used for temporarily stopping vehicles, such as for vista locations for sightseeing, or for passing.

Traffic lanes are classified into:

1. *Through lanes* are those lanes intended for normal through travel of vehicles [GDS85].
2. *Express lanes* are through lanes used for faster moving traffic. They usually have less access to exits.
3. *Reversible lanes*, also known as *contraflow lanes*, are lanes where the direction of traffic can be changed to match peak flow.
4. *Auxiliary lanes* are lanes in addition to and placed adjacent to through lanes, intended for specific maneuvers such as turning, merging, diverging and weaving, or to accommodate slow-moving vehicles, but not parking [GDS85].
5. *Curb lanes* are outermost traffic lanes of an urban road that are not auxiliary lanes. Sometimes curb lanes are distinguished from through lanes. *Shared curb lanes* are curb lanes that are shared between vehicles and bicycles; they may be adjacent to an urban shoulder.

Axillary lanes are classified into [GDS85]:

1. *Dedicated right turn lanes* are lanes added to the right of through lanes ahead of intersections to allow right-turning traffic to slow down before making the turn, without interfering with following through traffic, and to provide

additional capacity at intersections. The lane may or may not lead directly into an exclusive right-turning roadway.

2. *Dedicated left turn lanes* are lanes added to the left of through lanes to provide a refuge for left-turning traffic waiting to make the turn at intersections and occasionally driveways. Left-turning traffic typically will move into the left-turning lane, slow down and wait for a suitable gap in oncoming traffic to make the turn. Left-turn lanes are used with and without medians.
3. *Two-way left turn lanes*, also known as *continuous left-turn lanes*, are introduced between through lanes in both directions to provide storage for left-turning vehicles from either direction and are usually designated for left turns only through out their length. These lanes are well suited to four-lane and multi-lane urban arterials where running speeds are relatively low, in the range of 40 km/h to 70 km/h.
4. *Slip* or *bypass lanes* are applied at crossings and roundabouts to channel traffic without interference with traffic at these junctions, such as right-turn slip lanes at roundabouts.
5. *Transfer lanes* are lanes that provide transfer between freeway express lanes and a collector-distributor road or a service road.
6. *Acceleration* and *deceleration lanes* are auxiliary lanes on freeways and arterial roads at interchanges for vehicles changing speeds at entrances and exists.
7. *Weaving lanes* are auxiliary lanes introduced between an entrance followed by an exit in close succession, usually less than 1000 m, to minimize turbulence in the traffic stream and to maintain adequate capacity.
8. *Truck-climbing lanes* are introduced on steep upgrades to provide a lane for trucks and other slow-moving vehicles whose speed drops more than 15 km/h because of the grade.
9. *Passing lanes* are similar to truck-climbing lanes, but are not necessarily in upgrades. They are applied to two-lane roads carrying large volumes of slow-moving vehicles, for example, recreational routes. Passing lanes are introduced at intervals.

Dedicated lanes are traffic lanes set aside for particular type of traffic; for example:

1. *Bus lanes* are lanes restricted to buses, possibly on certain days and times.
2. *High occupancy vehicle lanes* are lanes reserved for carpooling.

A *lane drop* is defined as a location on a road where the number of through lanes decreases. Lane drops are further classified as *lane exits*, *lane splits*, and *lane terminations*. Lane exits correspond to through lanes that become *mandatory exit lane* on a freeway or through lanes that become a *mandatory turn lane* on a non-access controlled road. The termination of an acceleration lane is not considered a lane drop.

4.4.1.2 Lane Widths

Lane width typically ranges from 3 m to 3.75 m and varies depending on traffic volume, types of vehicles, type of lane, and design speed. Through lanes on low volume urban roads (Design Hourly Volume less than 60 vehicles per hour) are typically 3 m wide. The width increases to 3.5 m for moderate traffic volumes, and to 3.75 when truck traffic is significant. On narrow urban streets, lanes can be as narrow as 2.75 m. Continuous left-turn lanes for speeds higher 60 km/h should be 4 m wide. Typical paved shoulder width is 0.5 m. An urban shoulder delineated by an edge line is a minimum width of 1.2m and may be as wide as 2.3m where space is available [LWG17]. Typical lane width on rural roads is 3.5 m and on freeways is 3.75 m.

Lanes are sometimes widened on road curves. Widening is often applied to improve visibility and reduce the risk of runoffs [AA11]. Further, widening of sharp corners is needed to accommodate overhang, especially where large vehicles are expected. Figure 12 illustrates the area swept by a passenger car design vehicle (Figure 11) travelling a curve with a minimum turning radius of the vehicle.

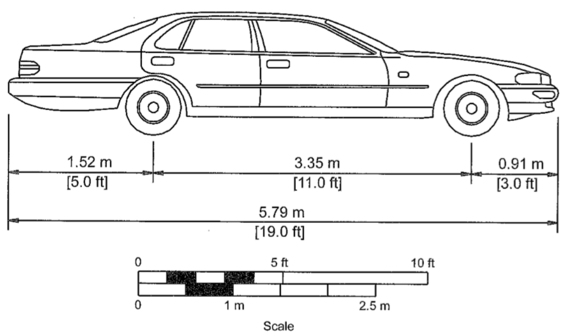


Figure 11 Passenger car design vehicle (Figure 2-1 from [A11])

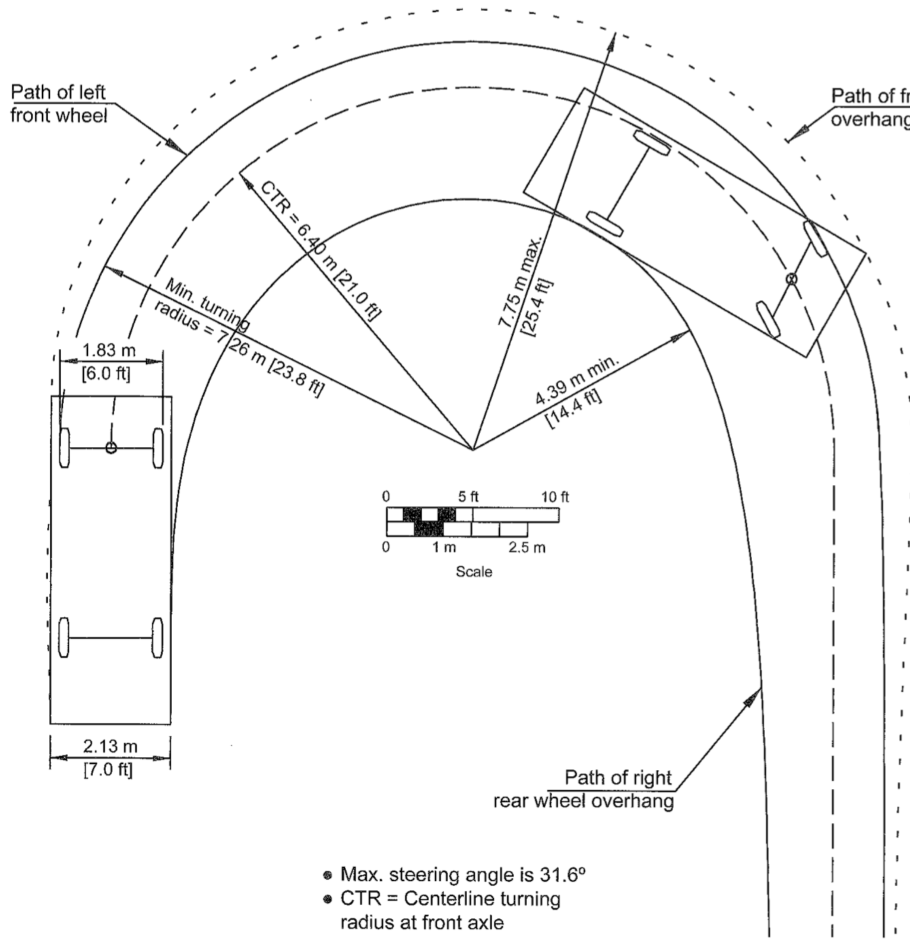


Figure 12 Minimum turning path for passenger car design vehicle (Figure 2-1 from [A11])

4.4.2 Roadside Structure

Roadside structure is the structure of the road area outside the traveled way [RDG11]. Major roadside elements include medians, traffic islands, sidewalks, boulevards, and drainage channels. These areas may house *roadside vegetation*, such as trees and shrubs, and *roadside furniture*, which includes [Wikipedia: Street Furniture]:

- benches,
- traffic barriers,
- bollards,
- fire hydrants,
- post boxes,
- phone boxes,
- streetlamps,
- utility poles,
- traffic lights,

- traffic signs,
- bus stops,
- tram stops,
- taxi stands,
- public lavatories,
- billboards,
- commercial property entrance signs,
- electric transformers,
- telecommunication service area interface cabinet,
- fountains,
- watering troughs,
- memorials,
- public sculptures, and
- waste receptacles.

4.5 Road Traffic Control Devices

Road traffic control devices are devices used to inform, guide, and control traffic. They include

1. traffic signs,
2. traffic signals,
3. pavement markings,
4. vertical deflections (speed bumps, humps and tables), and
5. channelization devices, such as traffic islands.

Control devices are usually used in combination forming larger systems. For example, a stop sign is usually supplemented with a stop bar pavement marking. Similarly, an intersection usually combines traffic signals, traffic signs, pavement marking, and channelization devices to control the traffic passing through the intersection.

Traffic can also be controlled by *traffic control persons*, such as school crossing guards, contraction zone guards, or police.

The Manual on Uniform Traffic Control Devices (MUTCD), first released in 1935, provides standard guidelines on the design of road traffic control devices used in the U.S. [MUT]. Many countries in Americas, but also outside, including Australia, Ireland, Japan, and New Zealand, use traffic devices that were greatly influenced by the MUTCD. This observation also applies to Canada, which has its own Manual of Uniform Traffic Control Devices for Canada (MUTCDC) [MUC]. However, there is considerable variation with countries, including Canada; for example, Quebec uses traffic control devices with substantially different symbology than the rest of the Canada. The standards for traffic control devices in Ontario are defined in the Ontario Traffic Manual book series.

4.5.1 Traffic Signs

Traffic signs are divided into three major classes:

1. *Regulatory traffic signs* are used to indicate or reinforce traffic laws, regulations, or requirements [OMT5];
2. *Warning traffic signs* are used to provide an advance notice of hazardous conditions ahead on or near the road; these signs are advisor only [OMT6]; and
3. *Guide and information* and traffic signs are used to provide directions and information about services and points of interest [OMT8].

Dynamic message signs are reprogrammable signs used to provide warning and information to road users about temporary conditions. They are usually part of an *advanced traffic management system* (ATMS) [OMT10].

Traffic signs can have different installations. They can be *overhead-mounted* or ground-mounted; further, they can be *permanent* or *portable*.

4.5.1.1 Regulatory Traffic Signs

Regulatory signs are intended to instruct road users on what they must or should do (or not do) under a given set of circumstances [OTM5]. The disregard of regulatory signs may constitute a traffic violation. In Ontario, "regulatory signs have different levels of legal status, enforcement regime and penalties for violation, depending on their individual governing authority. Some signs are enforceable directly under specific sections of the Highway Traffic Act (HTA) or other legislation, others under more general provisions of the HTA and its Regulations and still others only under duly enacted municipal by-laws. Some of the regulatory signs in this Book are not directly enforceable themselves but are used to reinforce regulatory conditions contained in legislation, such as HTA Part X (Rules of the Road). A final group of signs is not enforceable at all." [OTM5]

Table 9 summarizes the regulatory signs used in Ontario. Detailed description of each sign is provided in the OMT Book 5 [OMT5].

Table 9 Classification of Regulatory Traffic Signs used in Ontario [OMT5]

Type of Control	**Subcategory**	**Regulatory Traffic Signs**
Right of Way Control	STOP Sign	STOP, ALL-WAY (Tab Sign)
	YIELD Sign	YIELD, YIELD (Tab Sign)
Road Use	Pedestrian Crossing Sings	CROSS ON GREEN LIGHT ONLY, CROSS ON WALK SIGNAL ONLY, CROSS ONLY AT CROSSOVER, CROSS OTHER SIDE, PEDESTRIAN

Control		PUSHBUTTON, ...
	Pedestrian Crossover Sign	PEDESTRIAN X, STOP FOR PEDESTRIANS (Tab Sign), NO PASSING HERE TO CROSSING, ...
	Speed Control Signs	MAXIMUM SPEED, MAXIMUM SPEED with KM/H included, BEGINS (Tab Sign), MAXIMUM SPEED BEGINS, KM/H (Tab Sign), MAXIMUM SPEED AHEAD, SCHOOL ZONE MAXIMUM SPEED, SCHOOL ZONE MAXIMUM SPEED WHEN FLASHING
	Turn Control Signs	NO STRAIGHT THROUGH, NO STRAIGHT THROUGH, NORIGHTTURN, NO RIGHT TURN, NO LEFT TURN, NO LEFT TURN (specified times), NO STRAIGHT THROUGH OR RIGHT TURN, NO STRAIGHT THROUGH OR LEFT TURN, NO TURNS Sign, NO U-TURNS, BUSES EXCEPTED (Tab Sign)
	One-Way Traffic Control Signs	ONE-WAY, DO NOT ENTER, DO NOT ENTER (Tab Sign), DO NOT ENTER / WRONG WAY
	Two-Way and Multi-Lane Traffic Control Signs	TWO-WAY TRAFFIC, KEEP RIGHT, THROUGH TRAFFIC KEEP RIGHT, DO NOT PASS, PASSING PERMITTED, PASS WITH CARE (Tab Sign), KEEP RIGHT EXCEPT TO PASS, SLOWER TRAFFIC KEEP RIGHT, PASSING LANE 2 KM AHEAD, YIELD CENTRE LANE TO OPPOSING TRAFFIC, STOP FOR SCHOOL BUS WHEN SIGNALS FLASHING, BOTH DIRECTIONS (Tab Sign)
	Turn Lane Designation	LEFT TURN ONLY, LEFT LANE (Tab Sign), RIGHT TURN ONLY, RIGHT LANE (Tab Sign), STRAIGHT THROUGH OR LEFT TURN ONLY, STRAIGHT THROUGH OR RIGHT TURN ONLY, LEFT OR RIGHT TURN ONLY, ALL MOVEMENTS PERMITTED, STRAIGHT THROUGH ONLY, TWO-WAY LEFT-TURN LANE; TWO-WAY LEFT-TURN LANE, CENTRE LANE ONLY
	Reserved Lane Signs	RESERVED BICYCLE LANE (overhead or ground-mounted), RESERVED LANE (one vehicle class or multiple vehicle classes, overhead or ground-mounted, no days and times), 3 OR MORE PERSONS, Reserved Lane BEGINS (Tab Sign), Reserved Lane ENDS (Tab Sign)
	Parking Control Signs	NO PARKING Sign, NO PARKING Sign (with days), NO PARKING Sign (with days and times); NO PARKING, SNOW ROUTE; NO PARKING, EMERGENCY PARKING ONLY; PARKING RESTRICTED (with days, times and duration), NO STANDING, NO STANDING Sign (with days and times), DISABLED PARKING PERMIT, DISABLED STANDING EXEMPTION, DISABLED STOPPING EXEMPTION
	General Truck Control Signs	TRUCK ROUTE, MOVEMENTS PERMITTED, NO HEAVY TRUCKS, ...
	Dangerous Goods Carrier Control Signs	DANGEROUS GOODS ROUTE, DANGEROUS GOODS ROUTE (Tab Sign), NO DANGEROUS GOODS, DANGEROUS GOODS CARRIERS PROHIBITED (Tab Sign)
	Control of Other Specific Vehicle Classes	SCHOOL BUS LOADING ZONE, NO TRACTORS, BICYCLE ROUTE, NO BICYCLES, NO PEDESTRIANS OR BICYCLES, SNOWMOBILE ROUTE, NOS NOWMOBILES
	Supplementary Traffic Signal Control Signs	NO RIGHT TURN ON RED, NO LEFT TURN ON RED, STOP HERE ON RED SIGNAL, ADVANCED GREEN WHEN FLASHING, LEFT-TURN SIGNAL
	Regulatory Construction Traffic Control Signs	CONSTRUCTION ZONE BEGINS/ENDS, YIELD TO ONCOMING TRAFFIC, ROAD CLOSED
	Community Safety Zone Signs	COMMUNITY SAFETY ZONE, CONSTRUCTION ZONE BEGINS/ENDS

Miscellaneous Control Signs		WALK ON LEFT FACING TRAFFIC, NO FISHING FROM BRIDGE, VEHICLES WITH LUGS PROHIBITED, NO LITTERING, MAXIMUM FINE FOR LITTERING (Tab Sign), NO LITTERING AND MAXIMUM FINE FOR LITTERING, NO IN-LINE SKATING, KEEP OFF MEDIAN, NO PEDESTRIANS, FASTEN SEATBELT, COMPULSORY TAB

4.5.1.2 Warning Traffic Signs

Warning signs typically advise that road users exercise caution, and may require that drivers slow down, in order to travel safely in the presence of a hazard. Table 10 summarizes the warning signs used in Ontario. Detailed description of each sign is provided in the OMT Book 6 [OMT6].

Table 10 Classification of Warning Traffic Signs used in Ontario [OMT6]

Warning Sign Category	**Warning Traffic Signs**
Roadway Alignment Signs	TURN, SHARP CURVE, SHARP REVERSE CURVE, ADVISORY SPEED, DOUBLE ARROW, CHECKERBOARD – one direction or both directions
Intersection Warning Signs	INTERSECTION (uncontrolled or controlled and X, T or Y); DISTANCE, MERGE, DIVIDED ROAD INTERSECTION AHEAD, CROSS TRAFFIC DOES NOT STOP, DO NOT BLOCK INTERSECTION
Specific Roadway Feature Signs	SEEP HILL, USE LOWER GEAR, BUMP AHEAD, SPEED HUMP, NARROW STRUCTURE, ONE LANE, NARROW BRIDGE, LANE ENDS, etc.
Divided Road Transition Signs	DIVIDED ROAD BEGINS, DIVIDED ROAD ENDS, RIGHT LANE EXITS, etc.
Traffic Regulations Ahead Signs	STOP AHEAD, YIELD AHEAD, TRAFFIC SIGNALS AHEAD, PREPARE TO STOP WHEN FLASHING, etc.
Pedestrian Warning Signs	SCHOOL AREA, SCHOOL CROSSING, PLAYGROUND AHEAD, PEDESTRIANS AHEAD, etc.
Intermittent Hazards Signs	RAILWAY CROSSING AHEAD, SLIPPERY WHEN WET, ADVISORY SPEED, FALLEN ROCK, TRUCK ENTRANCE, CATTLE CROSSING, DEER CROSSING, MOOSE CROSSING, NIGHT DANGER, HORSE WITH RIDER, etc.

4.5.1.3 Guide and Information Signs

Table 11 summarizes the guide and information signs used in Ontario. Detailed description of each sign is provided in the OMT Book 8 [OMT8].

Table 11 Classification of Guide and Information Signs used in Ontario [OMT8]

Guide and Information Sign Category	**Guide and Information Traffic Signs**
Markers	route identification, distance markers, trailblazing "TO" signs, etc.
Freeway Interchanges Signs	destinations, interchange numbers, boundary signs, on-ramp signs, off-ramp signs, etc.

Emergency Detour Route (EDR) Signs	EDR trailblazer signs
Highway Intersection Signs	destination signs, boundary sings, service marker boards, etc.
Emergency Services Identification Signs	hospital markers, police markers, etc.
Public Transportation Services Signs	bus stop markers, subway and train station markers, airport sigs, carpool markers, etc.
Safety Message Sign	community safety program signs, speed fine messages, etc.
Major traffic generators	university and college markers, special events, major attraction sings
Special Signs	Adopt-A-Highway Sign

4.5.2 Traffic Signals

Traffic signals are electrically operated control devices (except signs and pavement markings) that are recognized in legal traffic rules and by which traffic is warned or directed to take some specific actions [OMT12]. The design of traffic signals varies from jurisdiction to jurisdictions. This section covers signals in Ontario, as defined in the Ontario Traffic Manual (OMT) Book 12 on Traffic Signals [OMT12].

Traffic signals are classified into *traffic control signals* and *flashing beacons*. Traffic control signals are defined as those that alternate vehicular and/or pedestrian right-of-way and include the following [OMT12]:

1. *Full Intersection Traffic Control Signals*,
2. *Intersection Pedestrian Signals*,
3. *Midblock Pedestrian Signals*,
4. *Bicycle Control Signals*,
5. *Movable Span Bridge Signals*,
6. *Transit Priority Signals*,
7. *Ramp Metering Signals*,
8. *Portable Lane Control Signals*,
9. *Train Approach Signals*, and
10. *Lane Direction Signals*.

Flashing beacons are used at intersections and to warn of other special hazards.

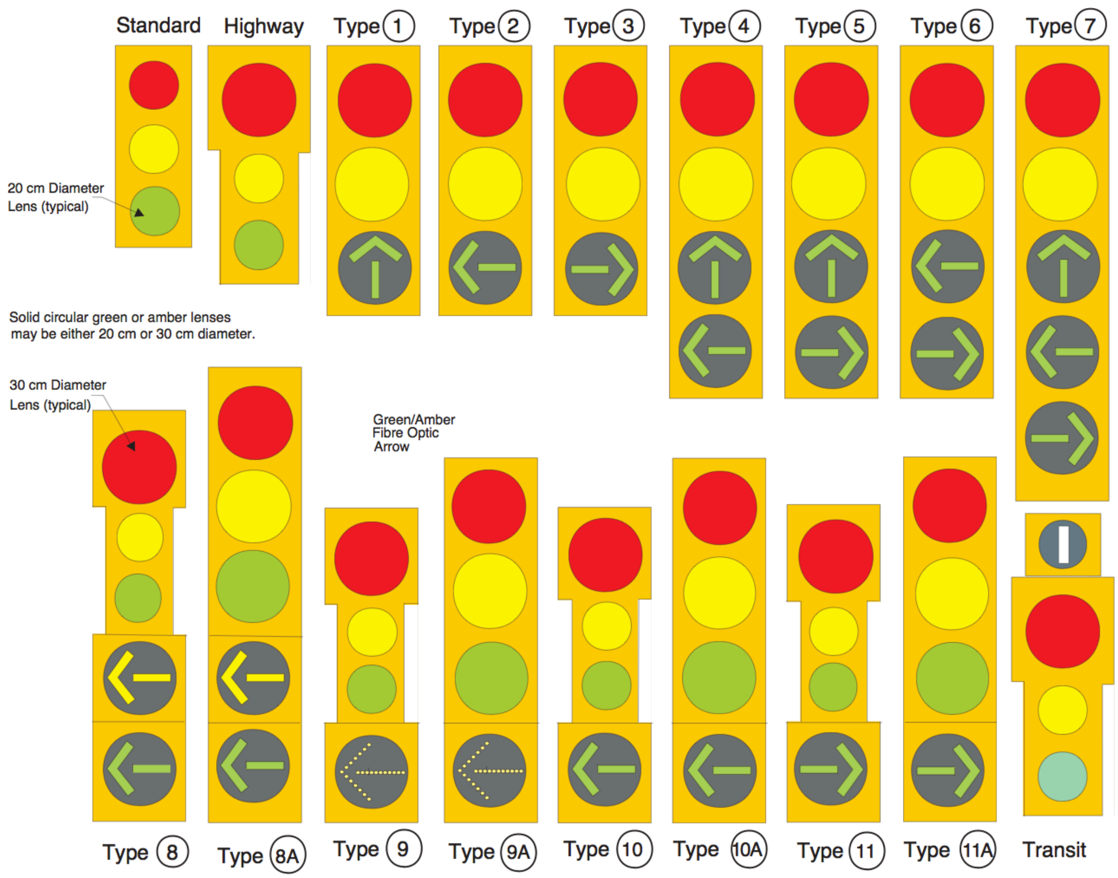


Figure 13 Traffic Control Signal Heads in Ontario [B12]

The design of the traffic control signal heads used in Ontario is shown in Figure 13. Each signal head features *green* (right-of-way), amber (change), and red (clearance) lights. The light shape is either circular or an arrow. Arrows signal turn permissions. The standard head applies to all intersection movements of vehicles facing the head at the movement origin, except right turns on red if they are permitted. Heads with four or five signal lenses may have multiple lights on simultaneously. For example, simultaneous red circle and green arrow for type 10 indicates clearance for through traffic and right-of-way for left turns. The green arrow may be flashing for better visibility.

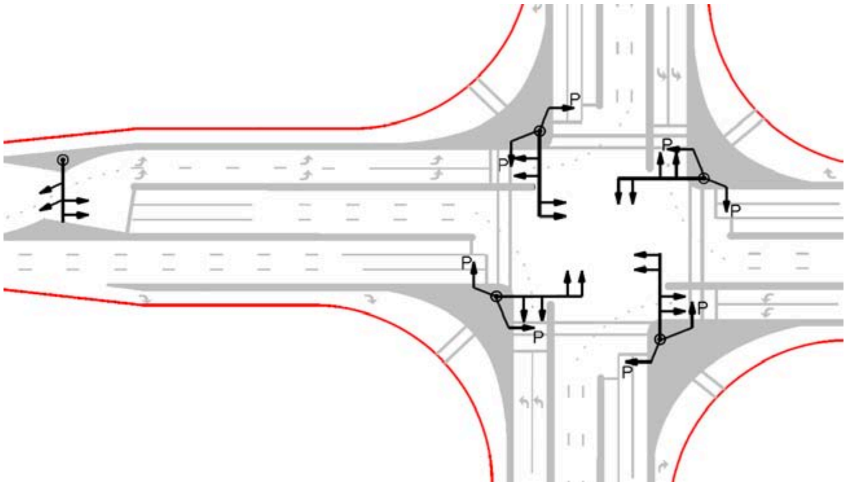


Figure 14 Placement of signal lights at a multilane four-leg, displaced left turn (DLT) intersection (Figure 22 from [AII10]).

The OMT Book 12 provides guidance on the number, size, mounting alternatives, physical arrangement, and placement of the signal heads [OMT12]. Figure 14 shows an example placement diagram. Each black arrow represents a signal head facing oncoming traffic that it regulates. Intersection pedestrian signals are marked by P. The intersection features *displaced left turns (DLT)*, which the relocation of the left-turn movement on an approach to the other side of the opposing roadway, which consequently eliminates the left-turn phase for this approach at the main intersection [AII10]. The crossing of conflicting oncoming through and left turning streams is controlled by additional traffic control signals, such as the one shown on the west leg in Figure 14. Also note the four bypass lanes that allow right-turning traffic to proceed without entering the main intersection.

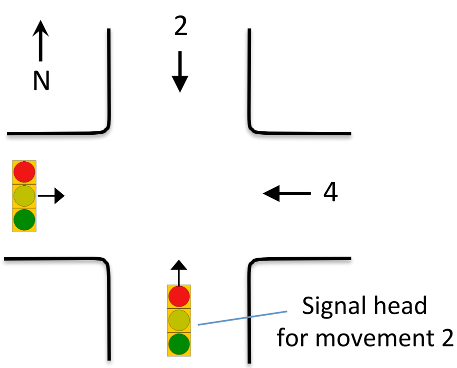


Figure 15 A signalized four-leg intersection of two one-way roads with no turns allowed and no pedestrian crossings. The intersection has two possible movements denoted by 2 and 4.

The behavior of traffic control signals at intersections can be specified using *phase diagrams*. There are different types of phase diagrams. For explanation purposes, consider a four-leg intersection of two one-way roads with no turns allowed and no pedestrian crossings (Figure 15). This intersection has only two possible phases:

traffic moves in either the north-south direction (Phase 2 in Figure 16) or the east-west direction (Phase 4 in Figure 16).

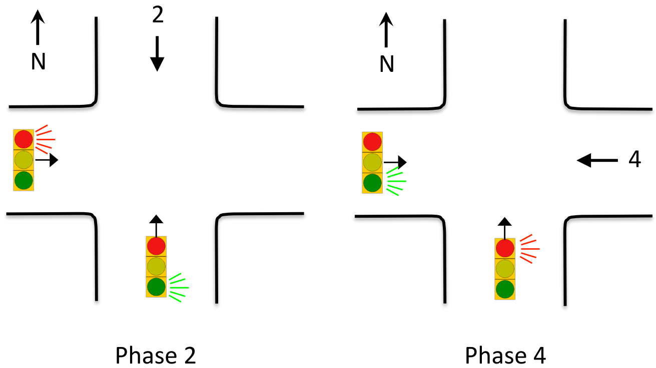


Figure 16 Two phases for the intersection from Figure 15

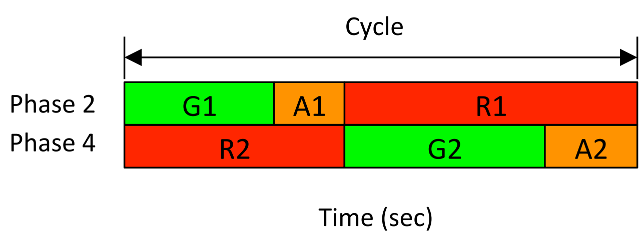


Figure 17 Phase timing diagram for the intersection from Figure 15

Figure 17 shows a *phase timing diagram* for the intersection from Figure 15. The diagram illustrates the following concepts:

1. A *signal indication* for a given movement is one of the three possible states — green (right-of-way), amber (change), and red (clearance). In Figure 15, a single lit circle gives an indication for a single movement. Depending on the number and design of the signal heads and the possible movements, the encoding of a signal indication for a movement may be more complex. The timing diagram (Figure 17) specifies the signal sequence for each of the two phases.
2. An *interval* is a time period during a signal indication does not change. For example, interval G1 in Figure 17 is the green interval for Phase 2.
3. A *cycle* is one complete repetition of all of the signal indications at the intersection.

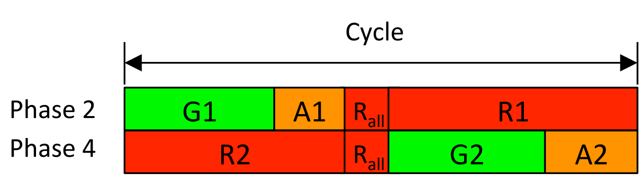


Figure 18 Modification of phase timing diagram from Figure 17 to include all-red interval

The interval sequence is often programmed to have a so-called *all-read interval* (see R_{all} in Figure 18). The purpose of the all-read interval is to ensure that the intersection is clear before switching between conflicting phases.

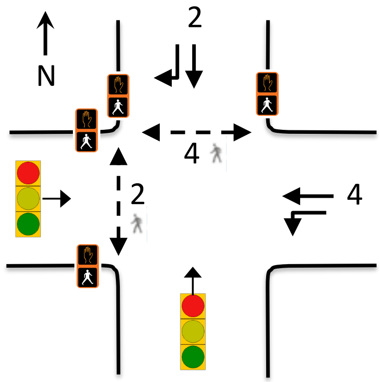


Figure 19 A signalized four-leg intersection of two one-way roads

A phase can include multiple movements. For example, Figure 19 shows the sample intersection from Figure 15 but now with allowed right turns and with pedestrian crossings. Figure 20 shows the two phases of the intersection.

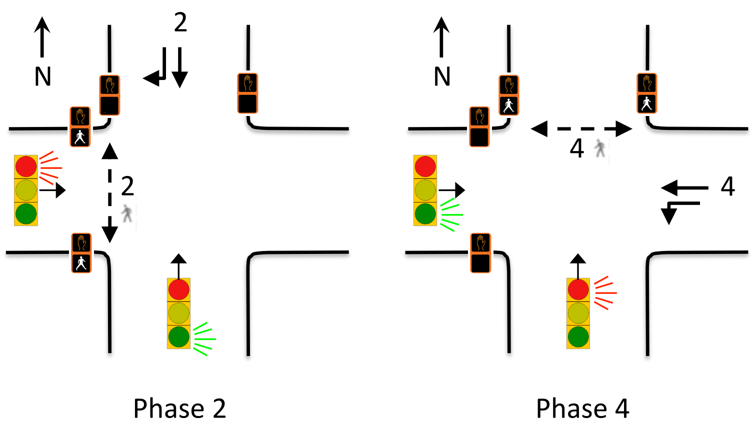


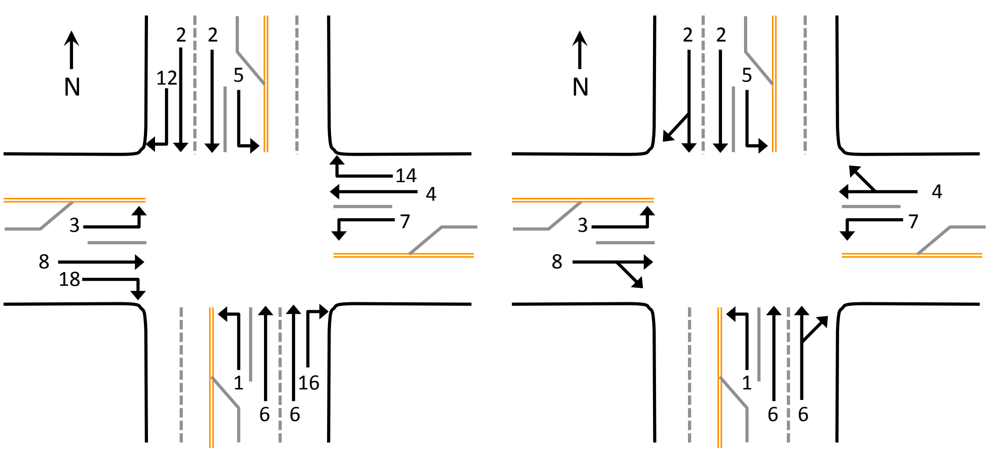
Figure 20 Two phases of the intersection from Figure 19

The key concepts of movements and phases are defined as follows:

1. A *movement* is a pattern of movement of a single road user at an intersection, such as southbound vehicle arriving at an intersection and turning left or pedestrians crossing the west leg of an intersection.
2. A *movement numbering scheme* assigns a unique number to a single movement or a combination of movements. Figure 21 (left) shows a common numbering scheme for all the possible vehicular movements at a four-leg intersection. The scheme is compatible with the National Electrical Manufacturers Association (NEMA) scheme, shown in Figure 21 (right), except that the NEMA scheme combines through and right-turn movements and gives them single number. Both schemes give *even* numbers (2, 4, 6, and

8) to through movements and *odd* numbers (1, 3, 5, and 7) to left-turn movements. Movements 2 and 6 correspond to the through movements on the major road, whereas movements 4 and 8 correspond to through movements on the minor road (that is, the major road should be aligned with the north-south direction on the diagram). Right-turn movements are given "1" as a prefix to distinguish them from the through movements.

3. A *phase* is the largest set of movements at an intersection that has a unique signal indication. A phase combines movements that will be occurring concurrently; thus, the movement combination should avoid potential conflicts. One strategy is to allow some conflicts, such as the so-called *permissive left-turn phasing*, where left-turn movements and opposite traffic through movements are part of the same phase, e.g., 1 and 2. Another strategy is to disallow conflicts, such as in the so-called *protected left-turn phasing*, where the two conflicting movements cannot be part of the same phase. *Fully-protected left-turn phasing* not only separates the conflicting movements, but assigns dedicated Type 2 signal head to the left turn, rather than sharing the signal with the through direction (e.g., when using Type 10 signal head) [OMT12]. Additional permissive/protective phase types dealing with turns and pedestrian traffic exist (see [OMT12]). The most restrictive case is *exclusive phasing*, which allows only one traffic approach to the intersection to proceed while the traffic on all other approaches is stopped.
4. A *phase numbering scheme* assigns a unique number to each phase. Phases that include through movements are assigned the same number as the through movement with the lowest number. For example, the though phase on the major street could consist of movements 12, 2, 6, and 16; this phase would then be assigned the number 2. Similarly, left-turn phases that have no through movements are assigned the same number as the left-turn with the lowest number. For example, protected left-turn phase could consist of movements 1, 5, 14, and 18; this phase would have the number 1. Figure 20 uses this standard phase numbering.



Movement numbers NEMA phase numbers

Figure 21 Movement numbering schemes on a four-leg intersection

Figure 20 illustrated a simple *two-phase operation*. In general, intersections can be operated with three or more phases. The phase sequencing can be represented by state machines (e.g., see Figure 5 in [OTM12]) or so-called *ring-and-barrier diagrams* (see Exhibit 5-3 in [STM15]). The interval timing may be either *pre-timed mode*, where fixed times for each interval are set, or *actuated mode*, where the intervals can be triggered and terminated by road user arrivals [OTM12]. Actuated mode requires vehicle detection sensors, such as inductive loops in the pavement, and push buttons for pedestrians. A traffic-actuated controller can provide means for traffic actuation on one or more but not all approaches to the intersection (*semi-actuated mode*), or on all approaches (*fully actuated mode*).

Table 12 shows a sample timing table for pre-timed mode for a four-leg intersection. This representation illustrates another common encoding of intersection movements using four letters per movement. The first two letters indicate the direction of traffic arriving at the intersection, which is northbound (NB), or southbound (SB), westbound (WB), or eastbound (EB). The last two letters indicate the maneuver, which is left turn (LT), through movement (TH), or right turn (RT). Table 12 shows the corresponding movement number (1-8) under each four-letter code in parenthesis.

Table 12 Sample pre-timed intervals for a four-leg intersection (from [STT])

Interval	Time (sec)	NBLT (M1)	NBTH (M6)	SBLT (M5)	SBTH (M2)	WBLT (M7)	WBTH (M4)	EBLT (M3)	EBTH (M8)
1	12	R	R	R	R	G	R	G	R
2	4	R	R	R	R	A	R	A	R
3	1	R	R	R	R	R	R	R	R
4	25	R	R	R	R	R	G	R	G
5	4	R	R	R	R	R	A	R	A
6	1	R	R	R	R	R	R	R	R
7	14	G	G	G	G	R	R	R	R
8	3	A	A	A	A	R	R	R	R
9	1	R	R	R	R	R	R	R	R

4.5.3 Roadway Pavement Markings

Pavement markings are visual markers on the roadway pavement that provide guidance and advisory information for road users. In Ontario, "pavement markings alone have no regulatory function. Pavement markings may be used to provide regulatory information to the road user, but associated signage must be in place as outlined in OTM Book 5 (Regulatory Signs).” [OTM11]

Different types of pavement marking used in Ontario include [OTM11]:

1. *Directional Dividing Lines* are used to separate traffic lanes that move in opposite directions (Figure 22 (a)). They are typically placed to coincide with the geometric center of the pavement, but may be placed off-center if the number and width of lanes for each direction is different (Figure 23, bottom). Directional dividing lines are yellow. Yellow broken lines are permissive, and indicate that adequate passing sight distance is available and passing is permitted where traffic allows (Figure 22 (c)). Solid yellow lines are restrictive, and indicate that passing is unsafe and is not permitted (Figure 22 (a) and (e)). Double line markings are only required where permissive passing opportunities must be indicated by direction of travel, where the posted speed limit is 70 km/h or more, or where additional emphasis of a passing prohibition is required (Figure 22 (e)). Single, solid, yellow line paired with a single, broken, yellow line denote no overtaking allowed for vehicles traveling in the lane adjacent to the solid line (Figure 23, bottom-right). The solid yellow lines denoting no-passing zones in single, double, or single-sided directional driving lines are also referred to as *barrier lines*.
2. *Lane Lines* are used to separate traffic lanes that move in the same direction. Lane lines are white and single. Broken white lines allow lane changes (Figure 22 (d)), and solid white lines prohibit lane changes (Figure 22 (f)).
3. *Edge Lines* delineate the outside edges of the traveled pavement. Edge lines to the right of a travel lane (when viewed by the driver) must be white (Figure 23 (h)); edge lines to the left of the travel lane must be yellow (Figure 23 (g)).
4. *Transition and Continuity Lines* are used to indicate changes in pavement width such as at offset or terminated lanes (Figure 23 (i)).
5. *Interchange Ramps and Channelization Lines* are edge lines and continuity line markings for single-lane on ramps, off ramps, and auxiliary lanes.
6. *Intersection Markings* are used at intersections to reduce vehicle and pedestrian conflicts, improve the capacity of the intersection, and clarify information used in driver decision-making; examples include *stop lines* (Table 13), *yield lines* (a row of solid white isosceles triangles pointing toward approaching vehicles), and no passing zones.
7. *Reserved Facility Markings* are used to mark facilities reserved for exclusive or priority use of certain road users, such as pedestrian crossings, cycling facilities, bus bays, bus lanes, high-occupancy vehicle lanes, etc.
8. *Parking Markings* are used for marking parallel and angle parking stalls and potential restrictions, such as stalls reserved for disabled drivers.
9. *Colored Pavements* are used to supplement other traffic control devices, such as marking channelizing traffic islands, crosswalks, and disabled parking spaces.

10. *Words and Symbols* may be used alone or as a supplement to other lines; examples are word messages (such as STOP or SLOW) and lane-use arrows.

Table 13 Road Marking Lines in Ontario (Figure 3 in [OMT11]); Note: Name of the line denotes the line marking appearance and the use denotes the role a line with this appearance may play in terms of traffic control.

	NAME OF LINE	DIMENSIONS (m)	USE
LONGITUDINAL	SOLID	0.10	EDGE LINES (WHITE OR YELLOW), DIRECTIONAL DIVIDING LINES (YELLOW), LANE LINES PROHIBITING LANE CHANGES (WHITE)
	DOUBLE SOLID	0.10 0.10 0.10	DIRECTIONAL DIVIDING LINES (YELLOW)
	SIMULTANEOUS SOLID AND BROKEN	3.0 6.0 3.0; 0.10 0.10 0.10	DIRECTIONAL DIVIDING LINES TWO-WAY LEFT-TURN LANES (YELLOW)
	CONDENSED BROKEN	1.0 1.0 1.0 1.0 1.0; 0.20	GUIDING LINES (E.G. INTERSECTION MOVEMENTS) (WHITE)
	WIDE BROKEN	3.0 3.0 3.0 3.0 3.0; 0.20 TO 0.30	CONTINUITY LINES (WHITE)
	BROKEN	3.0 6.0 3.0; 0.10	DIRECTIONAL DIVIDING LINES (YELLOW) URBAN LANE LINES, LOW SPEED (WHITE)
	BROKEN	3.0 9.0 3.0; 0.10	LANE LINES (WHITE) HIGH SPEED ROADWAY
TRANSVERSE	STOP	0.30 TO 0.60	INTERSECTION STOP LINES (WHITE)
	CROSSWALK	0.10 TO 0.20	CROSSWALKS (WHITE)

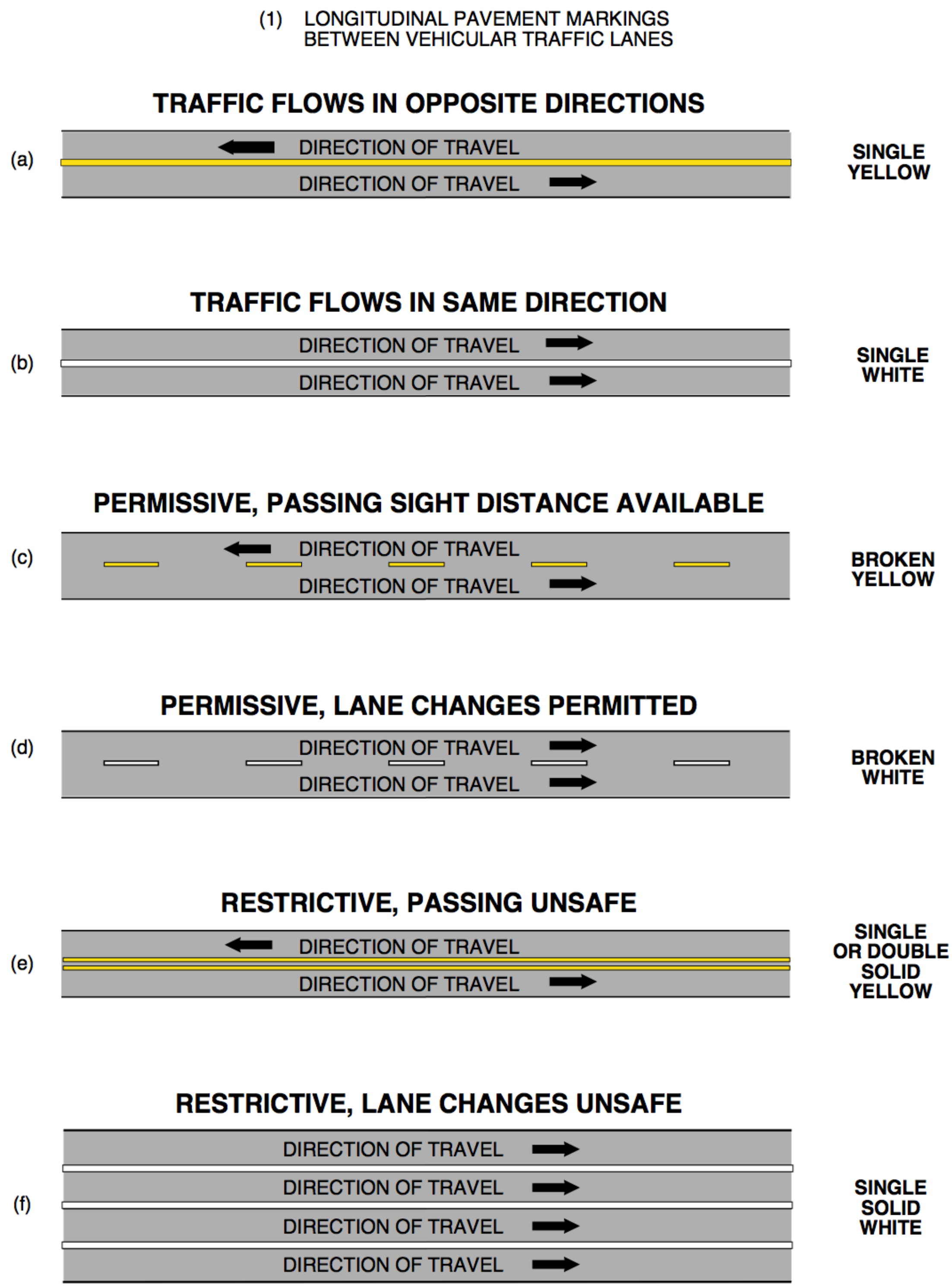


Figure 22 Road Marking Usage (Figure 4 in [OTM11])

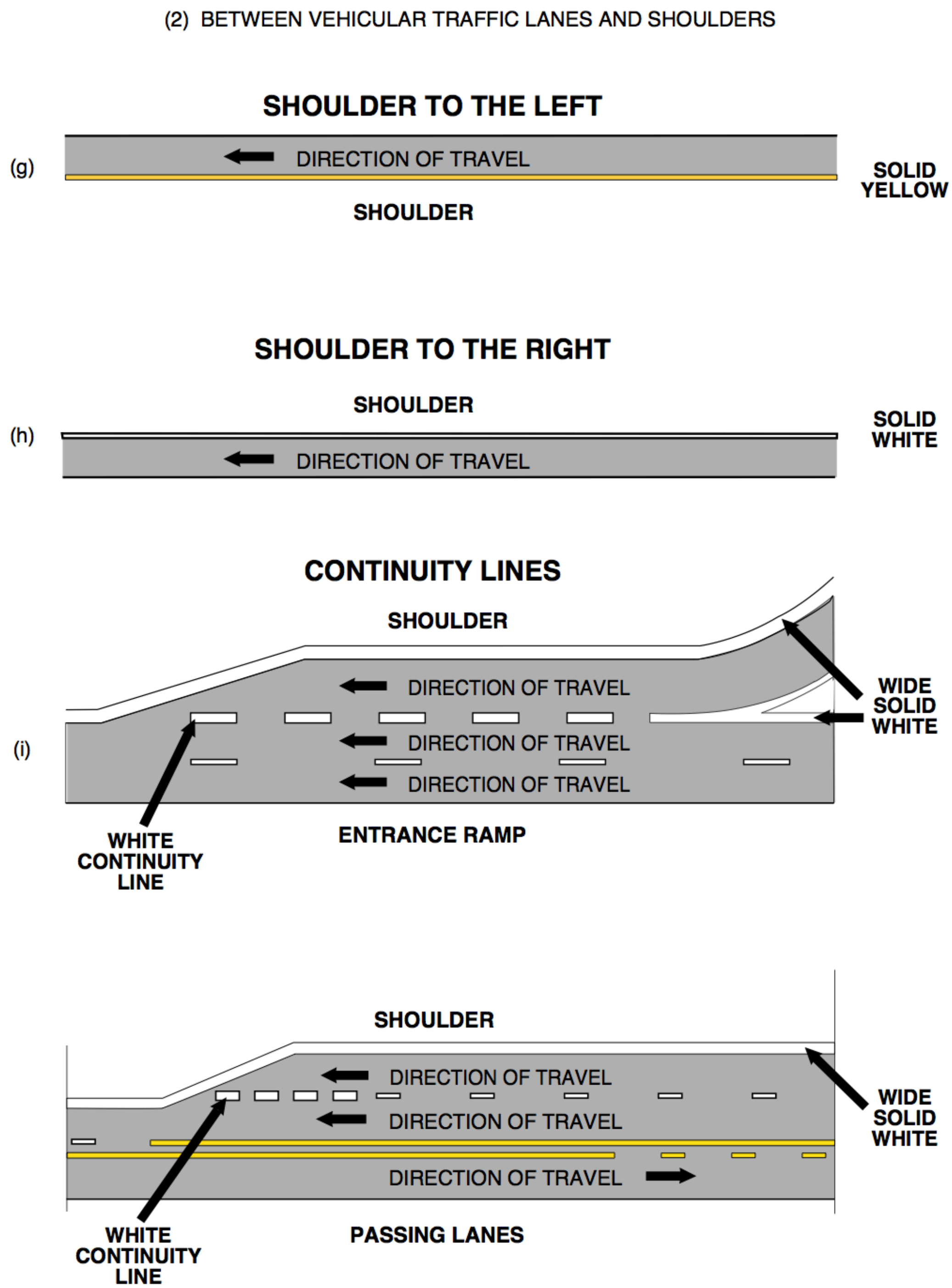


Figure 23 Road Marking Usage (Figure 4 in [OTM11])

Pavement markings may be supplemented or replaced by other devices. For example, *roadway delineators* may be implemented as pavement marking, but other types of delineation may also be used to provide audible and tactile features, such as rumble strips. Further, roadway can be delineated by reflective *chevron marking signs* at the roadside to indicate sharp turns or other hazards. *Flexible delineator marking*, which are upright, flexible bollards, may be added for increased visibility and to prevent crossing the boundary. Finally, *Roadway Pavement Markers (RPMs)*, which are crossable reflective markers on the roadway pavement that also provide audible and tactile features, may supplement or replace pavement markings [OTM11].

Pavement marking deteriorates over time due to traffic and weather. In particular, areas subjected to salt or sand anti-skid treatments in winter are prone to poor and deteriorated marking.

4.5.4 Vertical Deflections

Vertical deflections are raised areas in the roadway pavement surface extending transversely across the traveled way. They are traffic-calming devices designed to slow motor-vehicle traffic in order to improve safety conditions. Driving over a vertical deflection at speeds higher than its design speed generates a vertical acceleration that is perceived as unpleasant by the vehicle occupants.

Vertical deflections use a range of vertical profiles, with shapes including parabolic, circular, and sinusoidal curves, to enforce lower or higher speed limits, typically under 50 km/h [PSB07]:

1. *(Proper) speed bumps* are typically 0.3 to 1 m long and 50-150 mm high, and slow crossing vehicles typically down to 5 km/h.
2. *Speed humps* may be 3-5 m long and 50-120 mm high, and are used to enforce maximum speeds up to 30 km/h.
3. *Speed tables* are very long speed humps, 6-12 m long and less than 100 mm high, and with a flat vertical profile in the middle. They are used to enforce maximum speeds up to 50 km/h.

Speed cushions are a type of speed hump installation that is broken up into separate sections, or cushions, in the transverse direction. The main purpose of speed cushions is to improve emergency vehicle response times. Trucks with wider wheelbase can pass them through the open sections without being slowed down.

4.6 Pedestrian Crossing Facilities

Pedestrian crossings are facilities provided for pedestrians to safely cross a roadway. The Ontario Traffic Manual Book 15 provides rules and guidelines for the design of pedestrian crossings in Ontario [OTM15]. The manual distinguishes between

1. *Uncontrolled pedestrian crossings* are crossings that do not have any control measure to provide a dedicated pedestrian right-of-way. Pedestrians must wait a sufficient gap to fully cross the roadway or for vehicles to stop before

crossing. These crossings include mid-block crossings, designated school crossings, marked crossings, and crossings at roundabouts, provided that they have no control device such as STOP or YIELD sign, pedestrian signals, or pedestrian crossover signs, and in the absence of a school crossing guard.

2. *Controlled pedestrian crossings* are crossings that are controlled by a device, such as intersection pedestrian signals, mid-block pedestrian signals, pedestrian crossovers, and STOP or YIELD signs, or a school crossing guard. Each of these traffic control measures have traffic rules regulating the pedestrian right-of-way and the expected behavior of vehicles approaching and crossing the facility.

The OMT Book 15 defines a hierarchy of pedestrian crossings in relation to the complexity of the road environmental conditions [OTM15]:

- *Supervised School Crossing*: School crossings are supervised by school crossing guards during specified hours and during regular school periods.
- *Stop Controlled or Yield Controlled Intersections*: Vehicles approaching a STOP in advance of a crosswalk are required to stop at the stop bar, thereby, yielding to vehicular traffic and pedestrians whose arrival preceded theirs before proceeding.
- *Pedestrian Crossovers (PXO)* are distinctly defined by regulatory and warning signs and prescribed pavement marking.
    - *Level 1 Type A*: This treatment system uses internally illuminated overhead warning signs and flashing amber beacons.
    - *Level 2 Type B*: The system uses both the side mounted and over-head regulatory signs and rapid rectangular flashing beacons (RRFB).
    - *Level 2 Type C*: The system uses only side mounted regulatory signs and RRFB.
    - *Level 2 Type D*: The system uses only side mounted regulatory and warning signs.
- *Traffic Signals*:
    - *Full Traffic Signal*: These signals alternate the right-of-way between conflicting streams of vehicular traffic, or conflicting movements between vehicular traffic and pedestrians crossing a road for all approaches of an intersection by displaying instructions through light-emitted indications using regulated color and signal.
    - *Intersection Pedestrian Signal (IPS)*: IPS are traffic control signal systems that are dedicated primarily to providing traffic gaps for pedestrian right-of-way installed as pedestrian signals at intersections.
    - *Mid-block Pedestrian Signal (MPS)*: MPS are traffic control signal systems that are dedicated primarily to providing traffic gaps for pedestrian right-of-way installed as pedestrian signals at mid-block pedestrian crossings.

Any of the pedestrian crossings that are not designated as a pedestrian crossover are referred to as *pedestrian crosswalks* [OTM15]. In Ontario, a vehicle must yield the whole roadway at pedestrian crossovers, school crossings and other locations where there is a crossing guard. Only when pedestrians and school crossing guards have crossed and are safely on the sidewalk can drivers and cyclists proceed. Thus, this rule does not apply to pedestrian crosswalks, unless a school crossing guard is present.

The OMT Book 15 further notes that "in the absence of statutory provisions or bylaw, a pedestrian is not confined to a street crossing or intersection and is entitled to cross at any point, although greater care may then be required of him or her in crossing. Where portions of a roadway are marked for pedestrian use, no pedestrian shall cross the roadway except within a portion so marked." [OTM15]

4.7 Cycling Facilities

Cycling facilities provide spaces for the safe travel of pedalcyclists. The Ontario Traffic Manual Book 18 provides guidelines and rules for the design and operation of cycling facilities [OMT18], which include

1. Shared curb lanes,
2. Signed bicycle routes with paved shoulder,
3. Bicycle lanes,
4. Raised cycle tracks, and
5. In-boulevard bicycle facilities.

4.8 Junctions

Junctions are where two or more (public) roads meet. Depending whether roads meet at the same elevation or not, junctions are classified into

1. intersections, and
2. interchanges.

4.8.1 Intersections

Intersections are junctions where two or more roads meet at grade. Each adjacent road segment is referred to as an *intersection leg*. Typically, intersections have three or four legs. Multi-leg intersections, which have more than four legs, are uncommon and not recommended in road design [AA11].

4.8.1.1 Intersection Forms

Intersections occur in several *basic forms* shown in Figure 24. Any of the basic form can vary greatly scope and shape. The legs of an offset four-leg intersection are normally apart up to 10 meters, measured between the edge of the roadway of one leg that is closest to the other leg and the closest edge of the roadway of the other leg; if that distance is more than 10 meters, the intersection is classified as two adjacent three-leg intersections [GES].

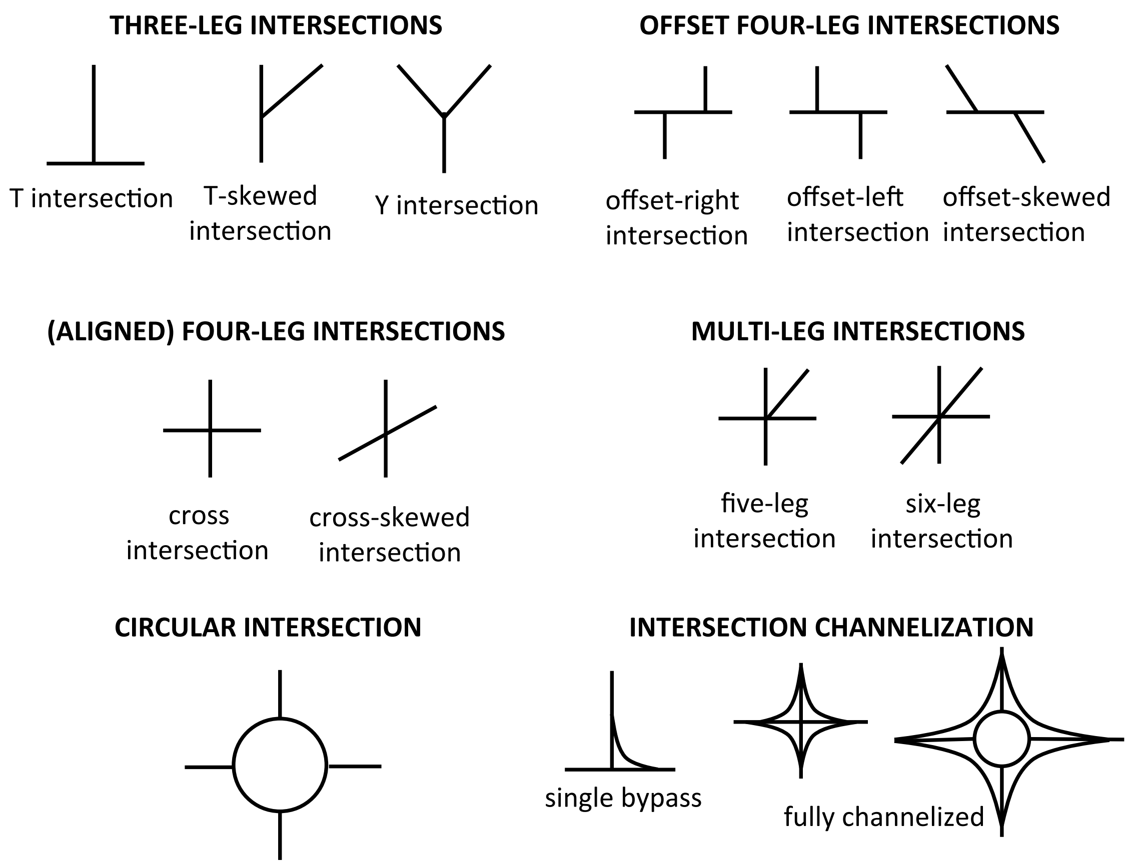


Figure 24 Basic intersection forms (Figure E2-2 adapted from [GDS85])

4.8.1.2 Intersection Maneuvers and Traffic Conflicts

At intersections, drivers are faced with the possibilities of four types of maneuvers (Figure 25):

1. diverging,
2. merging,
3. weaving, and
4. crossing.

A *traffic conflict* is a traffic event involving the interaction of two or more road users, where one or both users take evasive action such as stopping or swerving to avoid a collision [PZ89]. Figure 25 orders the maneuvers in the increasing order of relative severity of the potential conflict. Diverging maneuvers create potential conflicts for the following vehicles because turning vehicles typically slow down. For completeness, the least severe conflict, which occurs when driving in a single lane in traffic, is *sequential conflict*, and the most severe one is *head-on conflict* (Figure 16). Head-on conflicts can occur in constrictions, during passing maneuvers, or when drivers travel in the wrong lane by mistake.

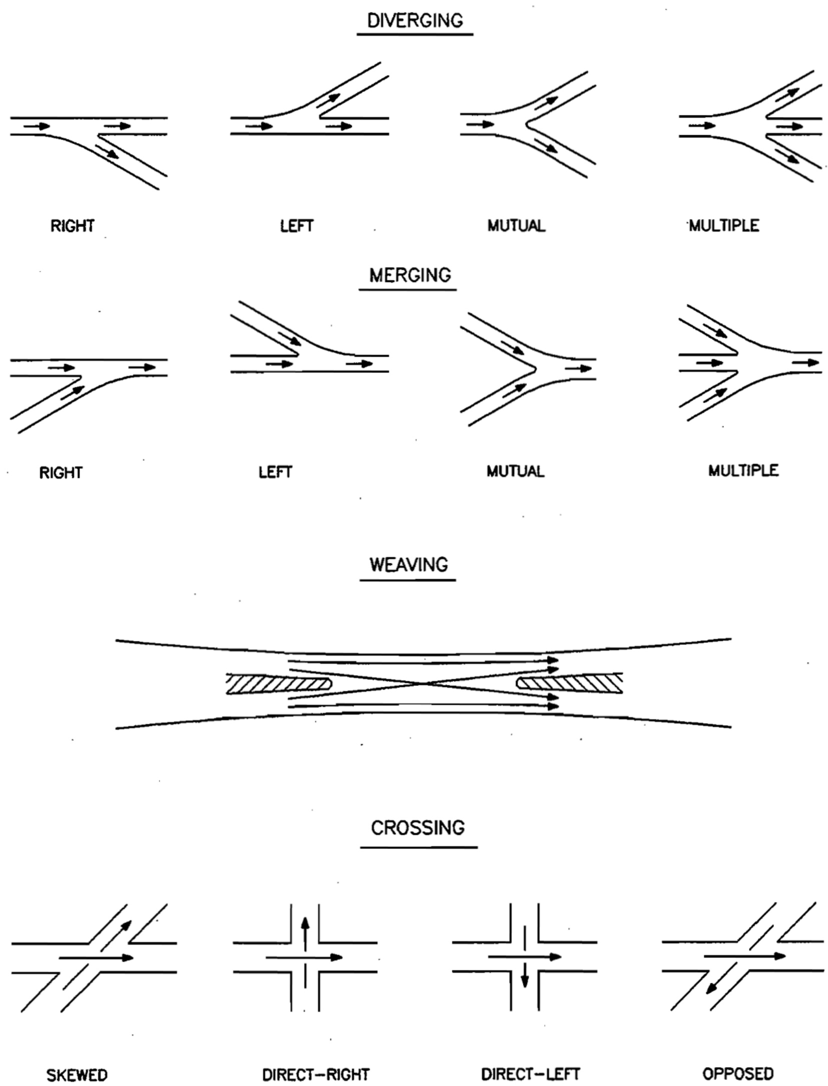


Figure 25 Types of maneuvers and potential conflicts at intersections (Figure E2-1 from [GDS85])

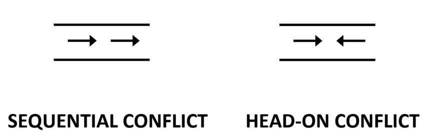


Figure 26 Potential conflicts for vehicles travelling in the same lane

Traffic conflict areas are areas at which a road user crossing, merging with, or diverging from a lane of traffic conflicts with another road user using the same lane. Figure 27 shows conflict areas at intersections. The conflict areas are divided into two categories [GDS85]:

1. *Major conflict areas* are those where head-on or near head-on collisions can occur, and
2. *Minor conflict areas* are those where merging type collisions may take place.

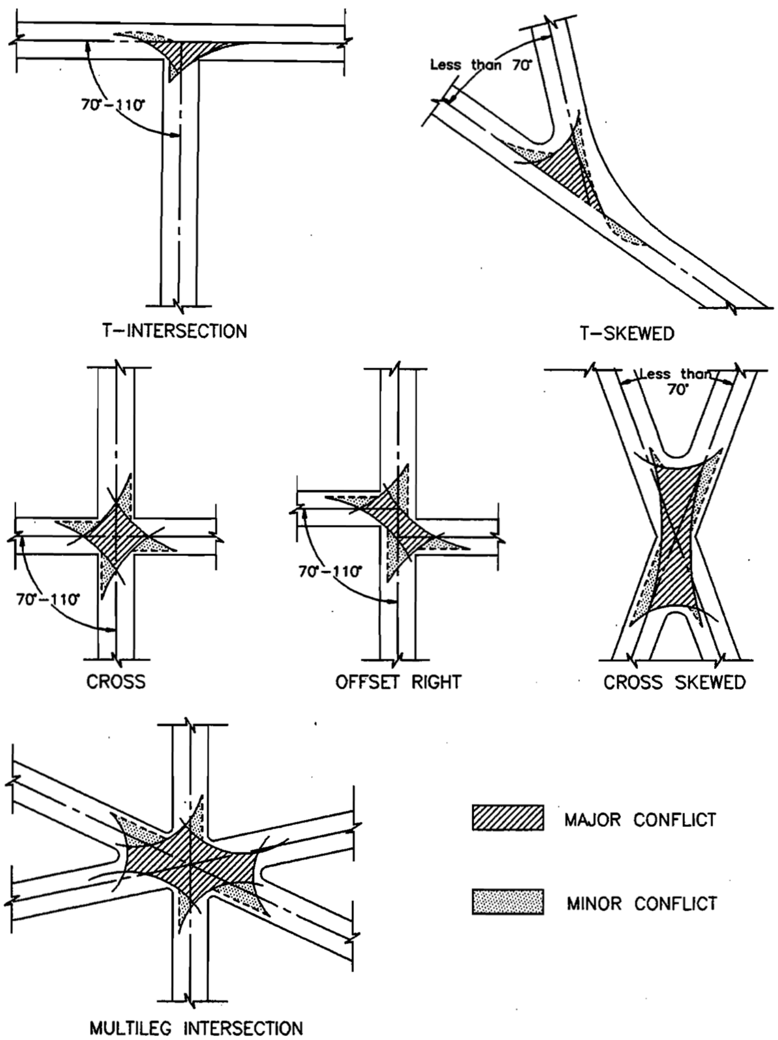


Figure 27 Conflict areas at intersections (Figure E2-3 from [GDS85)

Traffic conflict areas are often abstracted as *traffic conflict points* or *lines* by considering the intersection points of lane centerlines or their sections where may conflicts occur, respectively. Figures 28 and 29 show the conflict points for T and cross intersections, respectively.

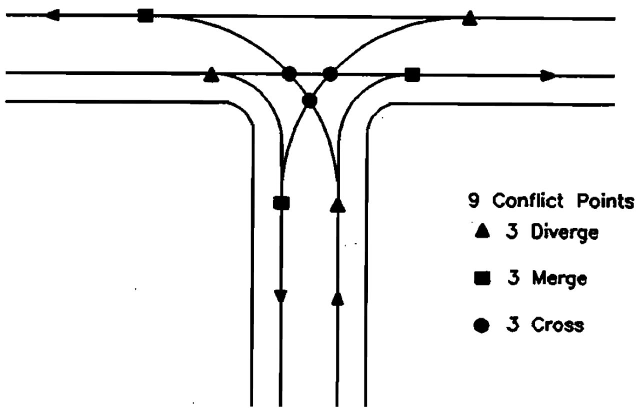


Figure 28 Conflict points at a T intersection (Figure 2-4 from [GDS85])

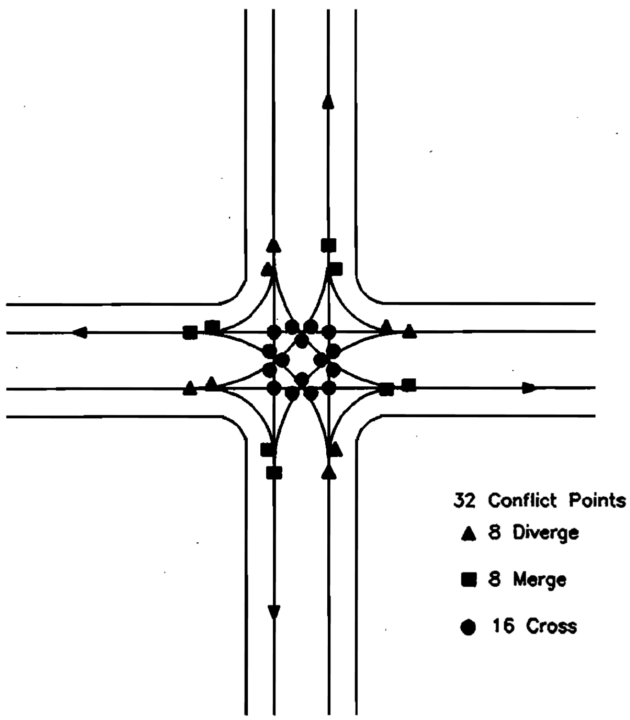


Figure 28 Conflict points at a cross intersection (Figure 2-4 from [GDS85])

Roundabouts greatly reduce the number and severity of conflict points compared to cross intersections (Figure 29).

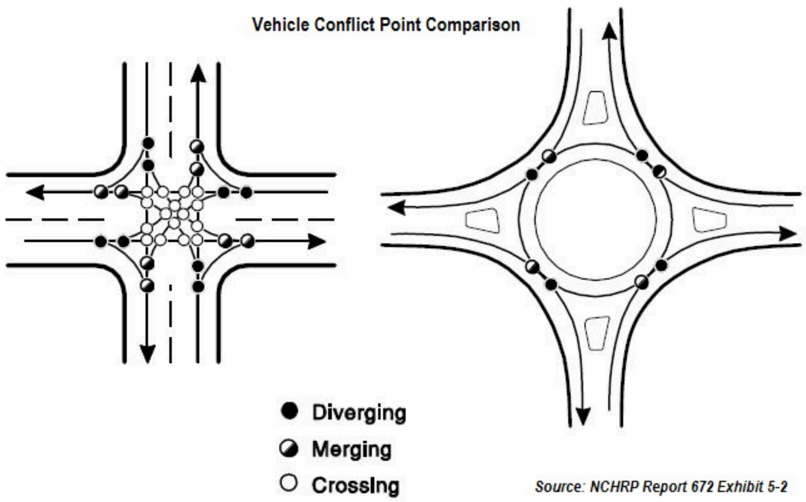
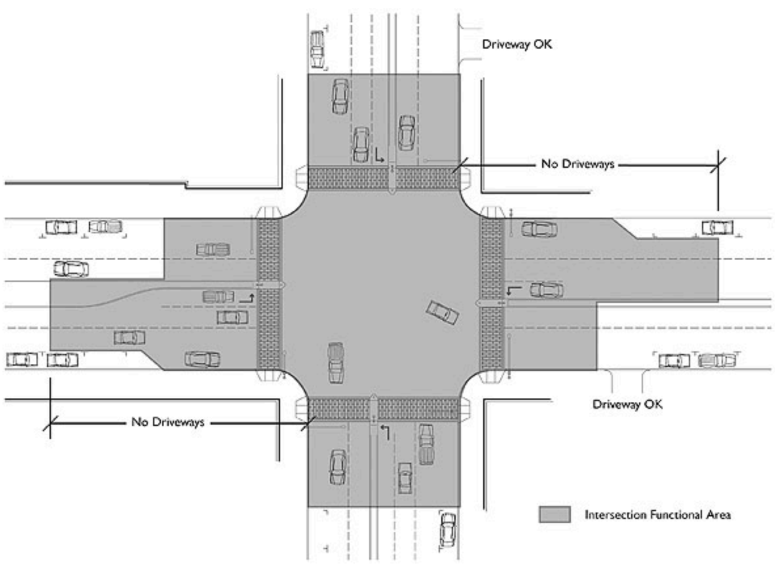


Figure 29 Comparison of vehicular conflict points on a open-throat cross intersection of two-lane roads versus a four-leg roundabout ([RG10])

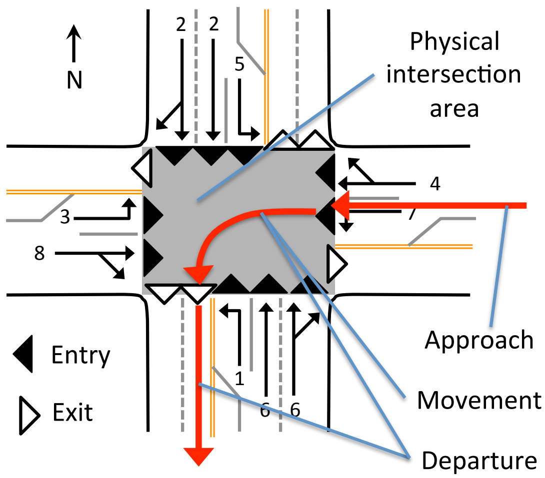
4.8.1.3 Intersection Designs

The functional area of an intersection (Figure 30 A) consists of:

1) *intersection physical area*, which the area where roads intersect (Figure 30 B); the area has *entries* and *exists*; and
2) *approach lanes*, which are the sections of lanes that connect and lead into the physical intersection area and are under the influence of the intersection.
3) *departure lanes,* which are the sections of lanes that connect and lead out of the physical intersection area and are under the influence of the intersection.



A) Intersection functional area [DWU10]



B) Intersection physical area with entries and exists and vehicle traversal

Figure 30 Functional elements of an intersection

The approach lanes are divided into three functional sections (Figure 31):

1) *decision section*, where drivers decide on the approach maneuver; this includes first deciding whether to slow down, maintain speed, or stop for the approach; and potentially whether to change lane;
2) *maneuver section*, where drivers decelerate and change to the desired lane; and
3) *storage section*, where vehicles queue up before entering the intersection.

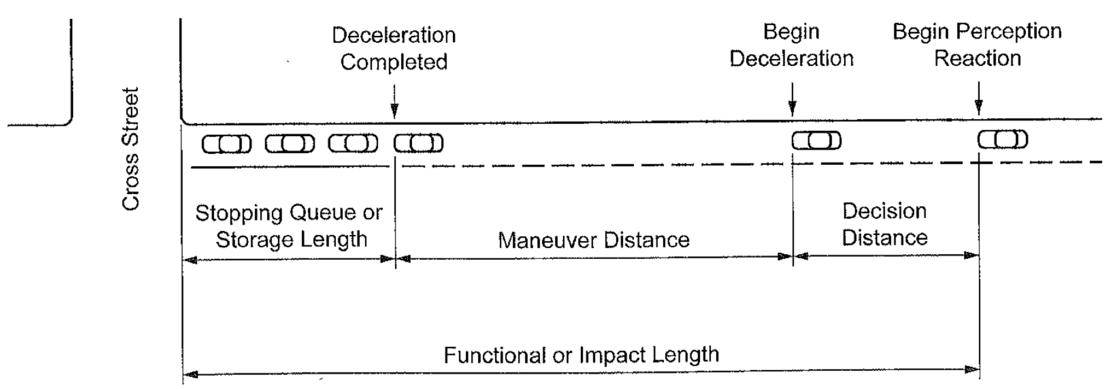


Figure 31 Functional areas of an intersection approach lane (Figure 9-2 from [AA11])

A vehicle travelling through an intersection, shown as red arrows in Figure 30 executes the following actions:

1. it *approaches* the intersection on the approach lane,

2. potentially *stops* in the queue area,
3. *departs* from the queue area and *enters* the intersection,
4. *moves* to the desired exist, and
5. continues *departure* on the departure lane.

Depending on the number of lanes and the channelization treatment, a wide variety of intersection designs are possible for each of the basic intersection forms. The simplest are so-called *open-throat designs*, which account for minimum turning radius at the approach ends. Figures 32 and 35 show open-throat designs of three- and four-leg intersections. Additional treatments such as channelization islands and allow reducing the conflict areas and simplify driver decision making at intersections (Figures 33-34 and 36-38).

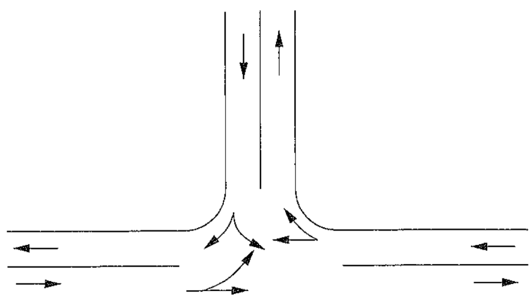


Figure 32 An open-throat T intersection with single-lane approaches (Figure 9-4 from [AA11])

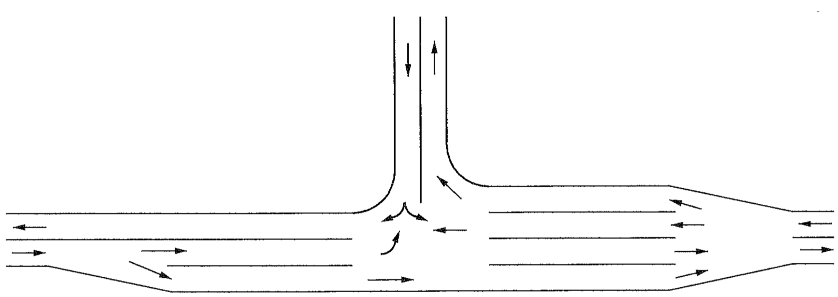


Figure 33 Flared T intersection with right-turn lane and bypass lane (Figure 9-4 from [AA11])

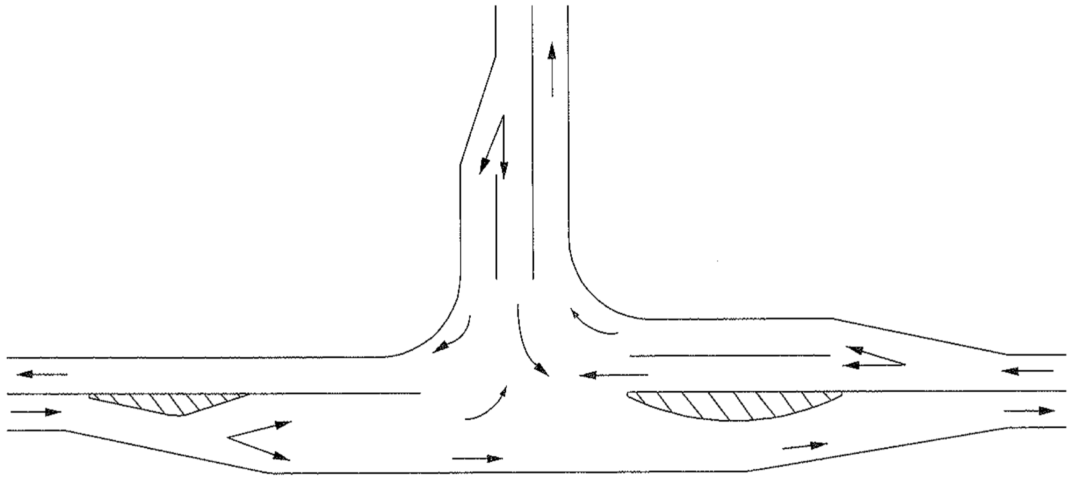


Figure 34 Channelized T intersection with designated lanes for each movement (Figure 9-4 from [AA11])

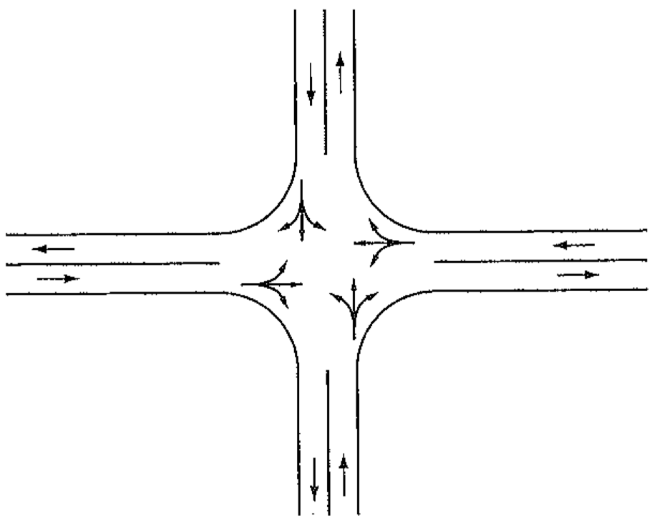


Figure 35 An open-throat four-leg cross intersection with single-lane approaches (Figure 9-3 from [AA11])

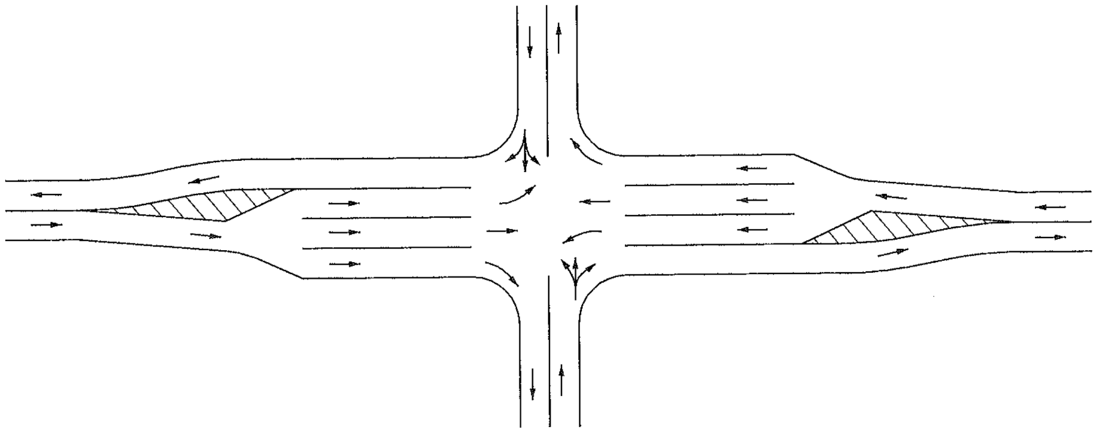


Figure 36 A flared four-leg cross intersection with marked left-turn lanes (Figure 9-3 from [AA11])

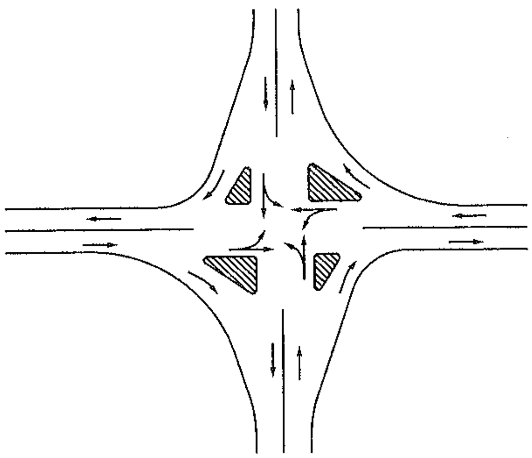


Figure 37 Channelized four-leg cross intersections with right-turn islands (Figure 9-3 from [AA11])

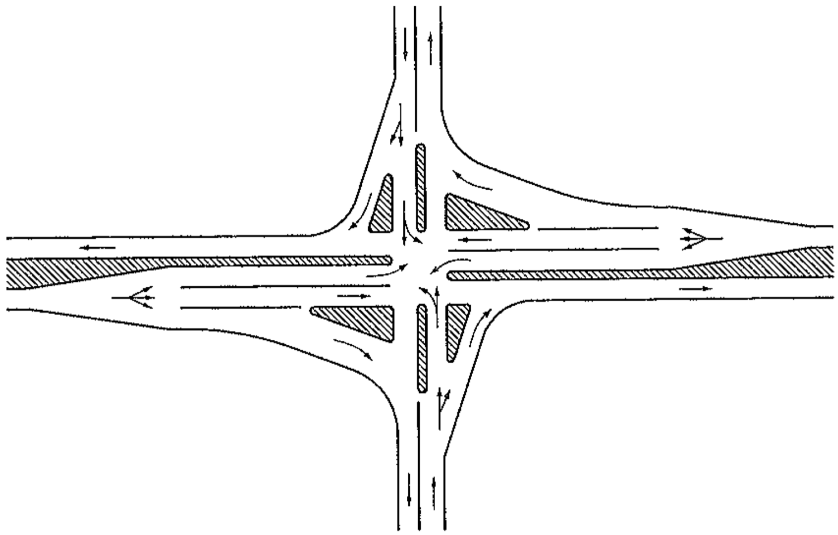


Figure 38 Channelized four-leg cross intersections with right-turn and divisional islands (Figure 9-3 from [AA11])

Another intersection design concern is the accommodation of U-turns. Ideally, U-turns are accommodated with minimal conflict, for example, by allowing the maneuver outside the physical intersection area. Figure 39 shows how U-turns could be accommodated before an intersection, subject to minimum turning radius. A safer design is to use channelization and median openings dedicated to U-turns that are offset from the intersection. For example, the median U-turn intersection (Figure 40) has dedicated U-turn median openings and eliminates unprotected left-turns.

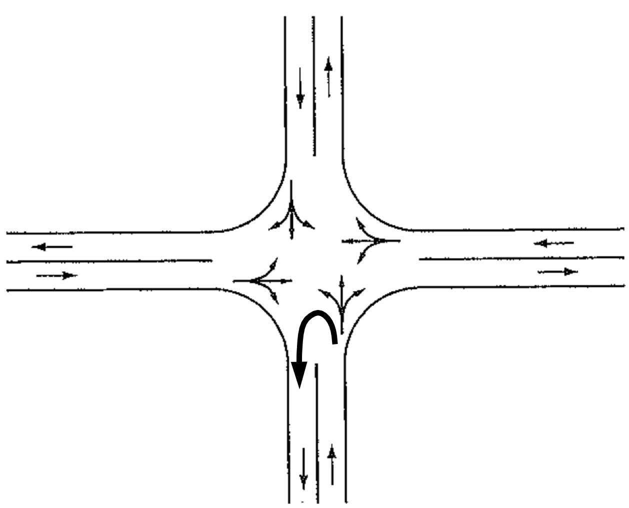


Figure 39 Accommodation of U-turns at four-leg cross intersection

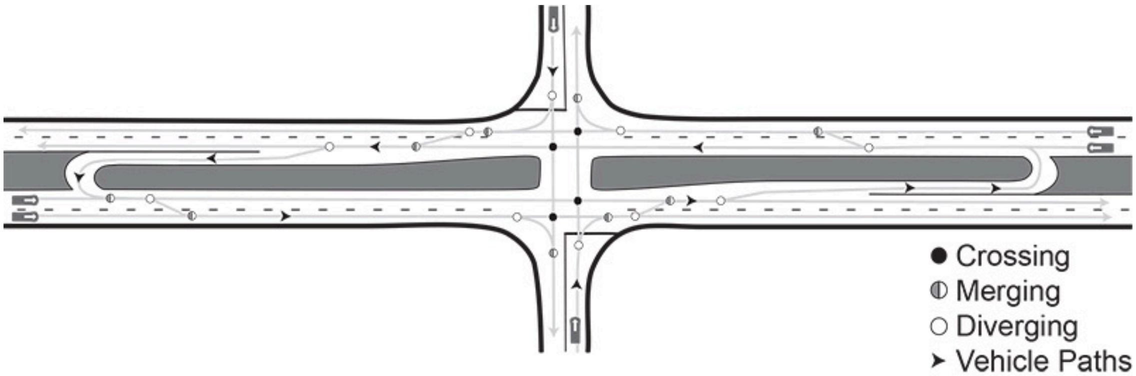


Figure 40 Median U-turn intersection (Figure 38 from [AII10])

Circular intersections include

1. *roundabouts*,
2. *mini-roundabouts*, and
3. *residential traffic circles*.

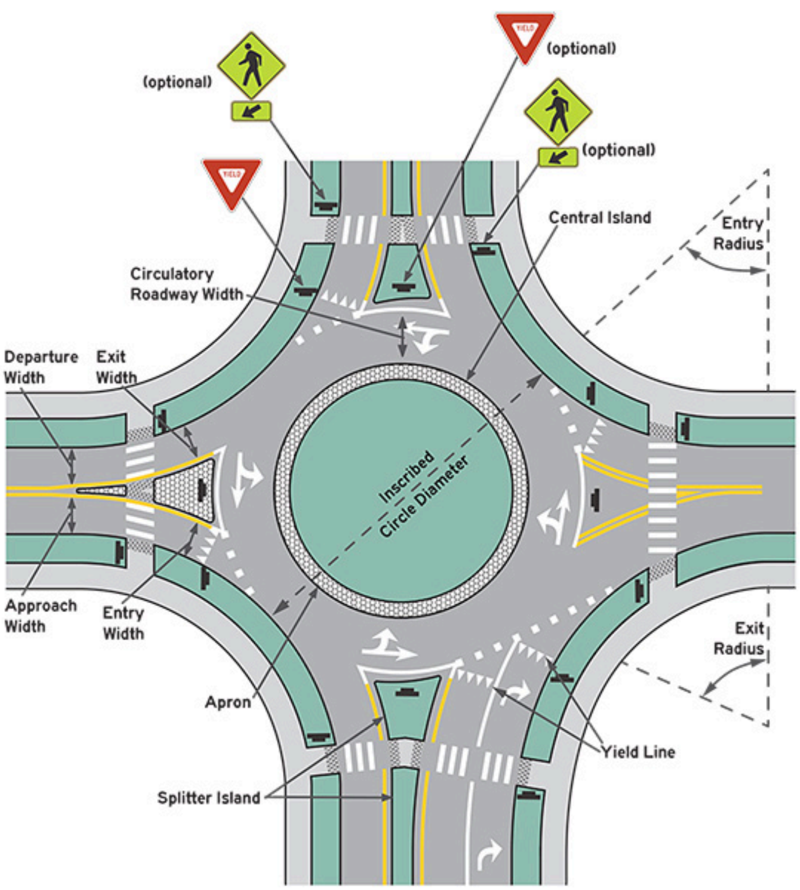


Figure 41 Key geometric design elements and traffic control devices for roundabouts (Figure 29 from [RG10])

Single-lane roundabouts have single-lane entries at all approaches. *Multi-lane roundabouts* have at least one entry with on or more lanes. Figure 41 shows a typical modern multi-lane roundabout. The design illustrates both single-lane entries and a two-lane entry (northbound approach).

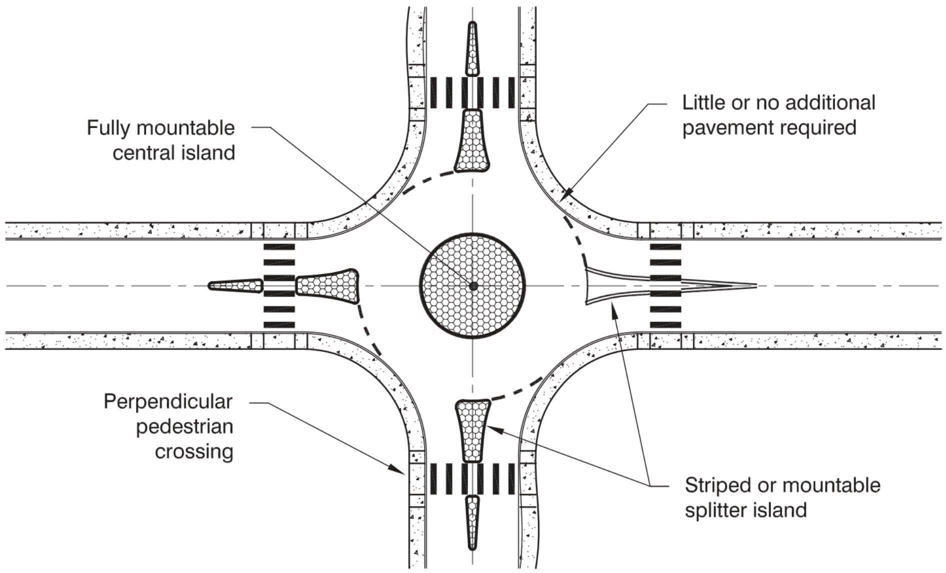


Figure 42 Mini-roundabout (Figure 1-10 from [AA11])

Mini-roundabouts are small roundabouts used in low-speed urban environments (Figure 42). They use little extra pavement at the throats of the approach legs compared to a conventional roundabout. The throats and the circular road are sufficiently large for passenger cars, but not for trucks or busses, which can drive over the fully traversable center island. However, no vehicles are allowed to turn left in front of the island.

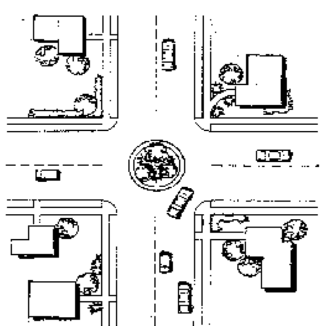


Figure 43 Residential traffic circle (Figure 29 from [NTC])

Residential traffic circle is a type of circular intersection of two local roads with a center island. It is used in residential areas for traffic calming (Figure 43). The center island may or may not be traversable. The approaches may be uncontrolled or controlled by YIELD signs. Large vehicles are allowed to turn left in front of the island.

4.8.1.4 Intersection Traffic Control

As illustrated in the previous sections, geometric design can eliminate or reduce the severity of some potential conflicts at intersections. The remaining conflicts are resolved using traffic rules and, optionally, traffic control devices.

Based on the traffic control treatment, intersections can be classified as [UII]

1. An *uncontrolled intersection* is one in which the entrance into the intersection from any one of the approaches is not controlled by regulatory sign, that is, STOP or YIELD sign, or a traffic signal. A vehicle approaching the intersection must yield to any vehicle that is already lawfully in the intersection and any pedestrian in a marked or unmarked crosswalk. When two vehicles approach the intersection at approximately same time, the vehicle on the left should yield to the vehicle on the right. Uncontrolled intersections are usually limited to very low-volume roads in rural or residential areas and require sufficient sight distance.
2. A *controlled intersection* is one of
    a. A *YIELD-sign controlled intersection* is one for which entrances from one or more of the approaches are controlled by a YIELD sign. "Under this control, drivers on each approach controlled by a YIELD sign are required to reduce their speed to concede the right-of-way to vehicles and non-motorists in the intersection; therefore, adequate sight distance must be present so the driver approaching the YIELD sign can stop if necessary. YIELD signs are usually placed to control the minor road, and they are often installed at ramp intersections or Y-intersections. Circular intersections—specifically, roundabouts and mini-roundabouts—represent the only intersections at which YIELD signs are installed on all approaches, as vehicles within the circular roadway always have the right-of-way." [UII]
    b. A *STOP-sign controlled intersection* is one for which entrances from one or more of the approaches are controlled by a STOP sign. "Under this control, drivers are required to come to a full stop at the intersection and proceed only if there are no vehicles approaching from any of the uncontrolled approaches and there are no pedestrians in the intersection. Within this category are two basic types:
        i. *Minor-road-only stop control*—at intersections having at least one approach (typically, the lower-volume, minor road) under the control of a STOP sign and at least one approach not controlled by a STOP sign; and

ii. *Multi-way stop control*—at intersections where all approaches are controlled by a STOP sign and an ALL WAY tab sign is used. For this application, the right-of-way is determined by the order in which users reach the intersection; if two vehicles arrive at the intersection at nearly the same time, then the vehicle on the right has the right-of-way.”[UII]

c. *Signalized intersection* is one for which entrances from one or more of the approaches are controlled by an intersection traffic control signal (see Section 4.5.2).

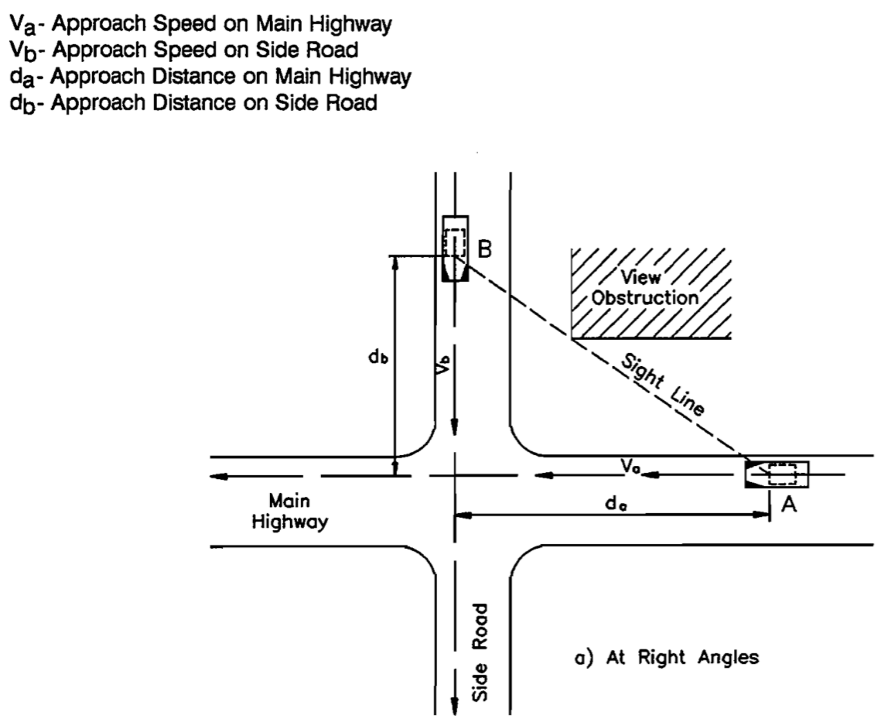


Figure 44 Approach sight triangle at a right-angle intersection (Figure E3-1 from [GDS85])

The option and choice of traffic control devices depends on the physical design, design speed, and expected traffic volumes. An important geometric aspect is the *approach sight triangle* (Figure 44). The minimum required sight triangle for an uncontrolled intersection depends on the approach speeds of the vehicles and the required action in the decision section of the approach. On approach, a driver may decide to accelerate, continue at present speed, slow down, or stop. The minimum sight triangle must be such that both drivers can see potential conflict and be able to slow down or stop before colliding at the conflict point. For this purpose, each driver needs a minimum of three seconds to execute the remedial action. This time includes 1.5 second *perception time*, which is time elapsed from the instant that a driver observes an object for which it is necessary to stop until the instant that he or she decides to take a remedial action, such as braking, 1 second of *reaction time*, which is the time elapsed from the instant the driver decides to take a remedial action until the action begins, such as application of the brake [GDS85], and minimum of 0.5 second of braking to modify the speed to avoid the conflict. Table 14 lists distance required to allow 3 seconds for various approach speeds.

Table 14 Distances traveled in 3 seconds (Table E3-1 from [GDS85)

Design speed (km/h)	30	40	50	60	70	80	90	100	110
Distance (m)	25	30	40	50	60	65	75	85	95

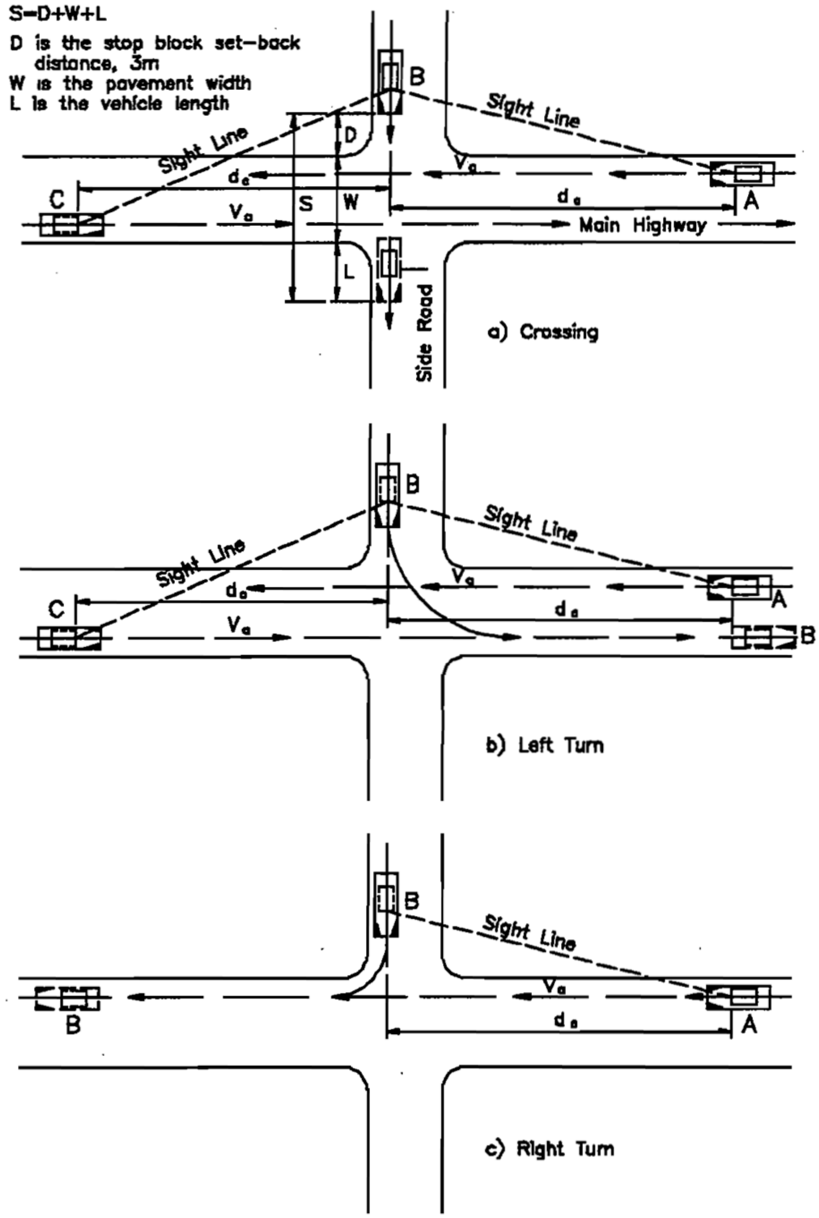


Figure 45 Departure sight triangles at a right-angle intersection (Figure E3-2 from [GDS85])

After a vehicle has stopped at an intersection, the driver must have sufficient sight distance to make safe departure and traversing the physical intersection area while avoiding conflicts. *Departure sight triangles* model the required sight distance for departures. Figure 45 shows the departure triangles for a vehicle making through, left-turn, and right-turn maneuvers. Distances d_a are the lengths travelled by vehicles at the design speed V_a of the main highway during the time it takes for the stopped vehicle to leave its stopped position and clear the intersection over the distance S = D + W + L or make a turn to the left or to the right. This time includes the perception-reaction time to start accelerating and the acceleration time to leave and clear the intersection. [GDS85]

4.8.2 Interchanges

Interchanges are not in the scope of the current version of this document.

Future versions will cover, among others, the following topics:

- Freeway components [GDS85, Part 1, B.5 p. 93]
- Ramp and junction types [GDS85, Part 1, B.5, p. 112]
- Ramp configurations: [GDS85, Part 1, B.5, p. 106]
- Transfer lanes
- Weaving areas and weaving configurations [GDS85, Part 1, B.5, p. 96, 98, 100]

4.9 Railroad Level Crossings

Interchanges are not in the scope of the current version of this document.

4.10 Bridges

Interchanges are not in the scope of the current version of this document.

4.11 Tunnels

Interchanges are not in the scope of the current version of this document.

4.12 Driveways and Driveway Access Points

A *driveway* is the physical connection for vehicular traffic between a roadway and abutting land [AMG05]. Driveways are private *access roads* that connect private and commercial developments to mainly local roads or collectors, and less frequently to arterials. The design and relative spacing of driveways reflects the type of developments they serve. Driveways classified by development type include *commercial*, *industrial*, *residential*, *field*, *rural recreational*, or a *temporary access driveways* [TAC17]. Some taxonomies distinguish between driveways, which are access roads that are private and closed to public traffic, and business entrances or parking lot entrances that are open to public traffic [ANSI]. Depending on the type of development, a driveway may be a low traffic generator, such as private residence, or a major traffic generator, such as a busy shopping plaza. Major traffic generators usually require establishing an intersection for safe access.

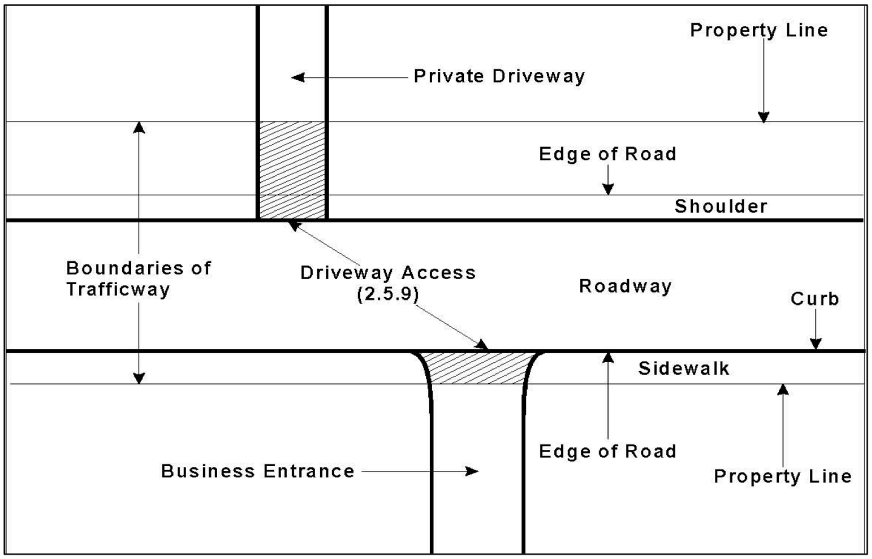


Figure 46 Driveway access [ANSI]

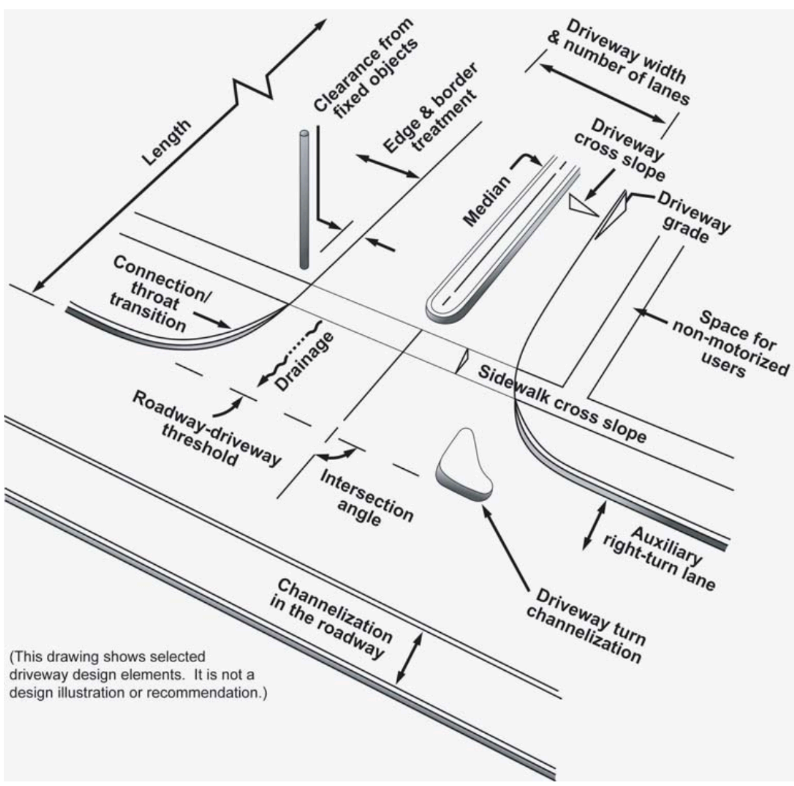


Figure 47 Elements of driveway access point design [GDD10]

The point where a driveway connects to a public road is called a *driveway connection* or a *driveway access point* (Figures 46 and 47). The pavement at the access point typically widens towards the main road. This widening, referred to as a *driveway throat* or *flare*, facilitates turning movements and is used to replicate turning radius in areas with curb and gutter construction. A *shared access point* is a single connection serving two or more adjoining lots or parcels [AMG05].

Technically, driveway access points can be seen as low-volume intersections; however, they are legally *not* intersections, and they have their own design and traffic rules [GDD10]. For example, barrier lines on a public road must not be broken at private or commercial entrances, but must be discontinued where public roads intersect or where left channelization is present [OTM11]. Driveways create potential traffic merge, diverge, and cross points and lines similar to intersections. In contrast to intersections, a potentially large number of driveways can be spaced very closely to each other, such as in residential areas, leading to a high density of conflict points and lines in such areas. The close spacing of driveways, possible on both sides of a road, effectively creates configurations similar to three-leg T intersections and four-leg cross and offset intersections. Driveways, when they are attached to an approach leg or the physical area of an intersection, complicate the intersection. For example, a driveway opposite to a side leg of a T intersection converts this intersection, effectively, into a four-leg one. Therefore, it is desirable to space intersections and driveways apart.

Access management is a discipline of road design that deals with "systematic control of the location, spacing, design, and operation of driveways, median openings, interchanges, and street connections to a roadway, as well as roadway design applications that affect access, such as median treatments and auxiliary lanes, and the appropriate separation of traffic signals." Several manuals [AMM03, AMG05, GDD10, TAC17] provide guidance on driveway design and access management.

4.13 Temporary Road Structure

Temporary road structure refers to temporary redesign of the road structure to accommodate temporary conditions, such as

1. *construction zones*;
2. *special events*, such as festivals and concerts; and
3. *unplanned events*, such traffic crashes and road and infrastructure damage, such as watermain breaks, fallen trees, road washout, etc.

Temporary structure includes

1. Detours;
2. Temporary roads and pavement widening;
3. Temporary road and lane closures; and
4. Temporary lane reassignment.

Ontario Traffic Manual Book 7 provides a set of design guidelines for temporary road structure in Ontario.

Construction zones are structured using a well-developed set guidelines, which include both road and lane configuration and traffic control measures. The specific structure varies depending whether the construction occurs on basic road sections, intersections, driveways, ramps, freeways, etc. Figure 48 shows the overall structure of a construction zone on a major road or freeway.

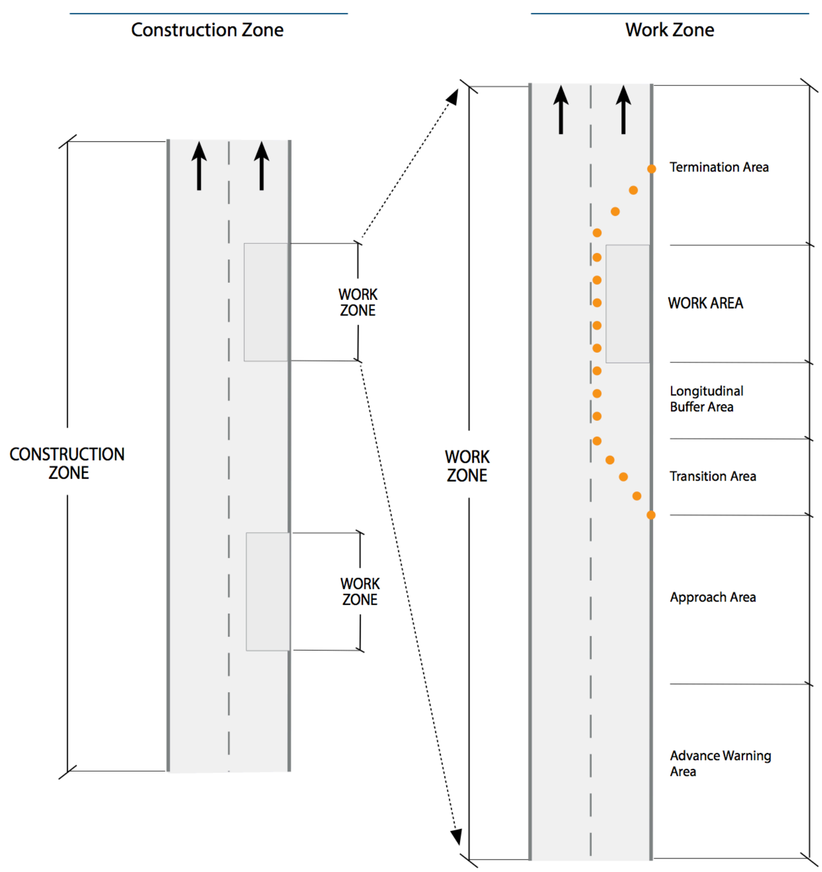


Figure 48 Design of a typical construction zone (Figure 1 from [OTM7])

Temporary road structure may use a wide range of traffic control measures, which include

1. orange traffic signs and markers dedicated to temporary road conditions,
2. *portable lane control signals (PLCS)*,
3. temporary pavement marking, and
4. traffic control persons ("flaggers", police, etc.).

The following orange traffic signs and markers dedicated to temporary road conditions are used in Ontario [OMT7]:

1. Traffic cones
2. Construction marker
3. Flexible drum (Barrel)

4. Barricades
5. Construction ahead signs
6. Road work signs
7. Lane closed ahead signs
8. Lane closed tab signs
9. Lane closure arrow signs
10. Detour ahead signs
11. Detour-Turn Off / Diversion signs
12. Roadside diversion warning signs
13. Detour designation signs
14. Narrow lane signs
15. Trucks use center lane tab sign
16. Pavement ends sign
17. Bump ahead sign
18. Turn and curve signs
19. Advisory speed signs
20. Chevron alignment signs
21. Grooved pavement sign
22. Prepare to stop sign
23. Traffic control person (TCP) ahead sign
24. Traffic control sign (Stop/Slow) Paddle
25. Signals ahead sign
26. Remote control device ahead signs
27. Uneven lanes sign
28. Do not pass when flashing sign
29. Truck entrance signs
30. Temporary bridge sign
31. Low bridge ahead signs
32. Two-way traffic sign
33. Ramp closed ahead sign
34. Maximum speed advisory sign
35. Soft shoulder sign
36. No exit sign
37. Pedestrian direction sign
38. Lane direction designation sign
39. Construction zone sign
40. Yield to oncoming traffic sign
41. Road closed sign
42. Flashing arrow board sign

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