WISE Requirements Analysis Framework for Automated Driving Systems

Operational World Model Ontology for Automated Driving Systems

Part 2: Road Users, Animals, Other Obstacles, and Environmental Conditions

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July 21, 2018

For updates and related documents, see
https://uwaterloo.ca/waterloo-intelligent-systems-engineering-lab/projects/wise-requirements-analysis-framework-automated-driving

Document history

Updates	*Date*	*Contributor(s)*
Version 1.0 created	November 30, 2017	Krzysztof Czarnecki[1]
Version 1.1 improved with editorial changes and published online	July 21, 2018	Krzysztof Czarnecki[1]

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Abstract

This document is Part 2 of an ontology definition for specifying operational world models for an Automated Driving System (ADS). Part 2 covers road users, including vehicles and pedestrians and their behavior models; animals; other obstacles, including objects placed by forces of nature, lost cargo, and construction equipment; and environmental conditions, including atmospheric, lighting, and road surface conditions. 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, labeling and indexing of datasets, and development of environment models as part of an ADS.

Table of Contents

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.**

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 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 different jurisdictions in North America, the bulk of the rules and structures are very similar.

This document (Part 2) covers road users, animals other obstacles, and environmental conditions (Sections 4, 5, 6, and 7); the companion document (Part 1) covers road structure (Section 4). 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.

3. Object Types[1]

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

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 behavioral scenarios. Also note that fixed objects may have moving parts relevant to driving, such as railway crossing gates.

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 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.

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[1] This section is repeated from Part 1.

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 inertia; 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 Users

Road users are vehicles and persons present on a road. This definition also includes road workers, school guards, and police.

4.1 Road User Classification

This section provides a uniform classification of road users for the purpose of modeling operational environments for ADS, with focus on North America and Ontario. The classification incorporates and unifies vocabulary from many other existing classifications. These existing classifications are often inconsistent, which is not surprising since they were created in different jurisdictions for different purposes, such different application, engineering, and legal (licensing, registration, and taxation) needs.

The overall structure of the classification is largely consistent with the vocabulary used in the Ontario Highway Traffic Act (HTA) [HTA]. The corresponding definitions from the Act, where available, are quoted. Additional vocabulary is borrowed from the Canada Motor Vehicle Safety Act [MVS], the U.S. Federal Highway Administration's 13 Class vehicle classification scheme [FHW], ISO 3833-1977 [RVT], the Australian AUSTROADS Vehicle Classification System [AUS], and several Wikipedia articles, which include a wide range of detailed terms and concepts.

Road users are classified into

1. ground vehicles, including their occupants;
    a. road vehicles;
        i. motor vehicles;
            1. passenger cars;
            2. trucks;
            3. buses;
            4. motorcycles;
            5. small and low-speed vehicles;
            6. emergency vehicles;
        ii. pedalcycles;
        iii. trailers;
    b. off-road vehicles;
        i. motorized off-road vehicles;
        ii. animal-drawn vehicles;
    c. railed vehicles;
    d. rail-road vehicles;
2. animal riders;
3. pedestrians; and
4. traffic control persons.

Human road users are pedestrians, traffic control persons, animal riders, and ground vehicles occupants.

Ground vehicles can be *unmanned*, that is, have no occupants. Such vehicles can be operated by an ADS or a remote driver.

Vulnerable road users are human road users who are at particular risk in traffic. They can be identified either by the amount of protection in traffic or by the amount of capability in traffic. Pedestrians and cyclists are vulnerable road users by the amount of protection in traffic. Young children, elderly, and disabled persons are vulnerable road users by the amount of capability in traffic. [SWO]

4.1.1 Ground Vehicles

Ground vehicles, also known as *land vehicles*, are vehicles designed to travel on paved or gravel roads, railway, or on rough terrain.

Ground vehicles are classified into
1. road vehicles;
2. off-road vehicles;
3. railed vehicles; and
4. rail-road vehicles.

The classification includes off-road and railed vehicles since off-road vehicles can travel on roads and railed vehicles may travel on rail tracks that are placed on roads next to travelled lanes, such as streetcar tracks, or cross roads at level, and thus potentially interact with other road users. Rail-road vehicles can travel both on roads and rail tracks.

In the HTA, the term “vehicle” includes “a motor vehicle, trailer, traction engine, farm tractor, road-building machine, bicycle and any vehicle drawn, propelled or driven by any kind of power, including muscular power, but does not include a motorized snow vehicle or a street car.” [HTA] In other words, the HTA refers to road and off-road vehicles that travel on roads simply as “vehicles”. Off-road vehicles are allowed to travel directly across some highways.

4.1.1.1 Road Vehicles

Road vehicles are ground vehicles designed to operate on paved or gravel roads.

Road vehicles are classified into
1. motor vehicles;
2. pedalcycles; and
3. trailers.

4.1.1.1.1 Motor Vehicles

A *motor vehicle* is a self-propelled road vehicle.

Motor vehicles are classified into
1. passenger cars;
2. trucks;
3. buses;
4. motorcycles;
5. small and low-speed vehicles; and
6. emergency vehicles.

Motor vehicles can be classified by many criteria, including unloaded weight, number of axles, purpose, where they can be operated, design, and appearance. Different jurisdictions have different, often multiple and inconsistent classifications. For example, there is no accepted national standard specifying a vehicle classification system in Canada [CMM00]. Even though Transport Canada and the provincial and territorial transport ministers came up with the so-called Canada Scheme "A" [LeM97], which has 22 classes and is a refinement of the Federal Highway Administration's 13 Class scheme [FHW], different classification systems are continued to be used across the provinces and territories for different purposes. For example, Ontario and several other provinces use the U.S. Federal Highway Administration's 13 Class scheme for traffic monitoring; yet other provinces use their own [CMM00]. At the federal level, the Motor Vehicle Safety Act [MVS] provides another classification. The International Organization for Standardization (ISO) published a classification of road type vehicles as ISO 3833-1977. Unfortunately, many countries, including Canada, have not participated in this standard. The U.S. has expressed disapproval on technical grounds, and the standard is fairly outdated.

The classification in this document combines information from the Motor Vehicle Safety Act, FHWA 13 Class scheme, ISO 3833-1977, and the Australian AUSTROADS Vehicle Classification System (12 classes). Additional level of detail, such as types of cars based on market segments, types of trucks, and types of heavy equipment, came from the following Wikipedia pages:
- https://en.wikipedia.org/wiki/Car_classification
- https://en.wikipedia.org/wiki/Truck_classification

In the HTA, the term "motor vehicle" includes an automobile [personal car], a motorcycle, a motor-assisted bicycle unless otherwise indicated in this Act, and any other vehicle propelled or driven otherwise than by muscular power, but does not include a street car or other motor vehicle running only upon rails, a power-assisted bicycle, a motorized snow vehicle, a traction engine, a farm tractor, a self-propelled implement of husbandry or a road-building machine." [HTA]

Some self-propelled vehicles that are designed for both on-road and off-road operation, such as some military transport vehicles, may also be classified as motor vehicles.

Motor vehicle exterior lighting is prominently visible and standardized aspect of motor vehicles. It includes the following types of lamps and illumination devices (applicable SAE guidance cited in parentheses):

1. *Headlamps* (SAE J1606 OCT1997, SAE J1735 DEC2006, SAE J2584 SEP2002);
2. *Headlamp Cleaners* (SAE J2111);
3. *Adaptive Forward Lighting Systems* (SAE J2591 NOV2008);
4. *Auxiliary Upper Beam Lamps* (SAE J581 JUL2004);
5. *Front Fog Lamp* (SAE J583 SEP2005);
6. *Parking Lamps*, also known as *Front Position Lamps* (SAE J222 DEC2006);
7. *Tail Lamps*, also known as *Rear Position Lamps* (SAE J585 FEB2008, SAE J586 JUL2007);
8. *License Plate Illumination Devices*, also known as *Rear Registration Plate Illumination Devices* (SAE J587 SEP2003);
9. *Turn Signal Lamps* (SAE J588 JUL2008);
10. *Spot Lamps* (SAE J591 SEP2003);
11. *Sidemarker Lamps* (SAE J592 AUG2005);
12. *Backup Lamp*, also known as *Reversing Lamp* (SAE J593 SEP2005);
13. *Reflex Reflectors* (SAE J594 DEC2003);
14. *Front Cornering Lamps* (SAE J852 APR2001);
15. *Side Turn Signal Lamps* (SAE J914 JUL2003);
16. *Fog Tail Lamp Systems*, also known as *Rear Fog Light Systems* (SAE J1319 MAY2005);
17. *Rear Cornering Lamps* (SAE J1373 MAY2006);
18. *Cargo Lamps* (SAE J1424 NOV2008);
19. *L.E.D. Signal and Marking Lighting Devices* (SAE J1889 JUL2005);
20. *Center High Mounted Stop Lamp* (SAE J1957 MAR2000);
21. *Daytime Running Light* (SAE J2087 MAR2006); and
22. *Discharge Signal Lighting System* (SAE J2320 SEP2008).

SAE J1100 *"Motor Vehicle Dimensions"* defines a standard for reporting vehicle dimensions in North America. LeMoal [LeM97] provides an extensive statistical analysis of external dimensions of motor vehicles on Canadian roads.

4.1.1.1.1.1 Passenger Cars

A *passenger car* is a motor vehicle designed and constructed primarily for the carriage of persons and their luggage, their goods, or both, having not more than a seating capacity of eight, in addition to the driver, and without space for standing passengers [FUS]. A passenger car may also tow a trailer.

Subclasses of passenger cars include:

1. *Microcar*;
2. *Sedan*;
3. *Hatchback*;
4. *Station wagon*;
5. *Stretch limousine*;
6. *Coupe*;
7. *Convertible (a.k.a. roadster)*;
8. *Van*;
    a. *Microvan*;
    b. *Minivan*;
    c. *Multi-purpose passenger vehicle (MPV)*;
    d. *Cargo van*; and
9. *Sport utility vehicle (SUV)*.

Motorized three-wheeled vehicle are motor vehicles moving on three wheels, in delta or tadpole configuration.

Motorized three-wheeled vehicle may be classified as passenger cars, motorcycles, or personal-mobility scooters (persons riding them are considered pedestrains) depending on their purpose, weight, and engine power.

4.1.1.1.1.2 Trucks

A *truck*, also known as a *commercial vehicle*, is a motor vehicle designed and constructed primarily for the carriage of goods [RVT]. A truck may also tow a trailer.

Based on their weight, trucks are classified into

1. *Light duty trucks* (mostly pickup trucks);
2. *Medium trucks*;
3. *Heavy trucks*; and
4. *Super-heavy trucks*.

The following classes are based on purpose or appearance:

1. *Pick-up truck*;
2. *Motor home*;
3. *Box truck*;
4. *Flatbed truck*;
5. *Logging truck*;
6. *Log carrier truck*;
7. *Platform truck*;
8. *Dump truck*;

9. *Tank truck*;
10. *Heavy hauler* (possibly with heavy hauler trailer);
11. *Waste collection truck*;
12. *Armored vehicle* (for carrying valuables);
13. *Snow plow truck*;
14. *Tow truck*;
15. *A crane-equipped breakdown vehicle*;
16. *Cement mixer*;
17. *Mobile crane*;
18. *Truck tractor unit*;
19. *Three, four, five, or six-axle articulated truck*;
20. *Double road train*; and
21. *Triple road train*.

ISO 3833-1977 refers to articulated trucks (19) and road trains (20 and 21) as *combination of vehicles*.

In the HTA, the term "commercial motor vehicle" means "a motor vehicle having attached to it a truck or delivery body and includes an ambulance, a hearse, a casket wagon, a fire apparatus, a bus and a tractor used for hauling purposes on a highway." [HTA] The HTA classifies buses as commercial vehicles, which is unusual and not followed in this taxonomy.

4.1.1.1.1.3 Buses

A *bus* is a motor vehicle designed and constructed primarily for the carriage of persons and their luggage, having more than a seating capacity of eight, in addition to the driver, or with space for standing passengers, or both.

Subclasses of buses include:

1. *Coach bus*;
2. *Transit bus*;
3. *School bus*;
    a. *Standard large*;
    b. *Van-type*;
4. *Double-decker bus*;
5. *Single articulated bus*;
6. *Bi-articulated bus*;
7. *Open-top bus*; and
8. *Trolley bus*.

Trolley buses are electrically propelled buses that draw power from overhead trolley lines.

In the HTA, the term “bus” means “a motor vehicle designed for carrying ten or more passengers and used for the transportation of persons.” The definition adopted in this taxonomy is slightly different to be consistent with ISO 3833-1977 and complement the definition of passenger vehicles.

4.1.1.1.1.4 Motorcycles

A *motorcycle* is a two-wheeled or three-wheeled motor vehicle, whose unloaded weight does not exceed 400 kg [RVT].

The following classification organizes motorcycle subclasses by the number of wheels and appearance:

1. *Two-wheeled motorcycles*;
    a. *Open motorcycle*;
    b. *Standard motorcycle*;
    c. *Cruiser motorcycle*;
    d. *Touring motorcycle*;
    e. *Sport motorcycle*;
    f. *Off-road motorcycle*;
    g. *Moped,* also known as *motorized bicycle* or *motor assisted bicycle*;
    h. *Underbone*;
    i. *Scooter*;
    j. *Enclosed motorcycle* (often feetforward configuration);
2. *Motorized tricycle*;
    a. *Open / enclosed motorized tricycle*; and
    b. *Freight tricycle*.

In the HTA, the term “motorcycle” means “a self-propelled vehicle having a seat or saddle for the use of the driver and designed to travel on not more than three wheels in contact with the ground, and includes a motor scooter, but does not include a motor assisted bicycle.” [HTA] In other words, mopeds are not considered motorcycles under the Act; however, the act requires moped operators to have the same types of riding skills as required for motorcycles and to hold a valid motorcycle class license.

In the HTA, the term “motor assisted bicycle” means “a bicycle,

(a) that is fitted with pedals that are operable at all times to propel the bicycle,
(b) that weighs not more than fifty-five kilograms,
(c) that has no hand or foot operated clutch or gearbox driven by the motor and transferring power to the driven wheel,
(d) that has an attached motor driven by electricity or having a piston displacement of not more than fifty cubic centimetres, and
(e) that does not have sufficient power to enable the bicycle to attain a speed greater than 50 kilometres per hour on level ground within a distance of 2 kilometres from a standing start.”

4.1.1.1.1.5 Small and Low-Speed Vehicles

Small and low-speed vehicles are self-propelled road vehicles that operate at low speeds, typically slower than 40 km/h. Examples include:

1. *Golf cart*; and
2. *Low-speed electric trolley*; and
3. *Forklift*.

These vehicles are not allowed on public roads. For example, golf carts may be operated on private roads and courses. However, some of these vehicles may have special permits to operate on certain roads, such as sightseeing trolleys.

4.1.1.1.1.6 Emergency Vehicles

An *emergency vehicle* is any vehicle that is designated and authorized to respond to an emergency in a life-threatening situation.

Emergency vehicles include

1. *Ambulance*;
2. *Fire truck*;
3. *Police car*;
4. *Police motorcycle*; and
5. *Public utility vehicle*.

The following Wikipedia article provides additional examples:

- https://en.wikipedia.org/wiki/Emergency_vehicle

In the HTA, the term "emergency vehicle" means, "

(a) an ambulance, fire department vehicle, police department vehicle or public utility emergency vehicle,

(b) a ministry vehicle operated by an officer appointed for carrying out the provisions of this Act or the Public Vehicles Act, while the officer is in the course of his or her employment,

(c) a vehicle while operated by a conservation officer, fishery officer, provincial park officer or mine rescue training officer, while the officer is in the course of his or her employment,

(d) a vehicle while operated by a provincial officer designated under the Environmental Protection Act, the Nutrient Management Act, 2002, the Ontario Water Resources Act, the Pesticides Act, the Safe Drinking Water Act, 2002 or the Toxics Reduction Act, 2009, while the officer is in the course of his or her employment, or

(e) a prescribed class or type of vehicle, driven by a prescribed class of persons or engaged in a prescribed activity or in prescribed conditions or circumstances."

Under the HTA, vehicles responding to emergencies use designated lights and sirens and have special treatment in traffic: "

(f) a vehicle while used by a person in the lawful performance of his or her duties as a police officer, on which a siren is continuously sounding and from which intermittent flashes of red light or red and blue light are visible in all directions, or

(g) either of the following vehicles, on which a siren is continuously sounding and from which intermittent flashes of red light are visible in all directions:
   i. a fire department vehicle while proceeding to a fire or responding to, but not while returning from, a fire alarm or other emergency call, or
   ii. an ambulance while responding to an emergency call or being used to transport a patient or injured person in an emergency situation."

4.1.1.1.2 Pedalcycles

A *pedalcycle* is a road vehicle that is normally propelled by human muscular power. A pedalcycle may be a unicycle, a single-track, two-wheeled vehicle, or a multi-wheeled vehicle. A pedalcycle may be solely human-powered or it may be power-assisted.

The following Wikipedia article provides a general classification of pedalcycles:

- https://en.wikipedia.org/wiki/List_of_bicycle_types

The classification classifies pedalcycles using the following characteristics:

1. *Number of wheels*:
   a. Unicycles;
   b. Bicycles;
   c. Tricycle;
      i. Delta configuration;
      ii. Tadpole configuration;
   d. Quadricycle;
2. *Rider position*:
   a. Upright;
   b. Recumbent;
   c. Prone;
3. *Number of riders*:
   a. Single rider;
   b. Tandem;
   c. Triplet;
   d. Quadruplet;
   e. Party bike (typically quadricycle);

4. *Propulsion*:
    a. Human muscular power (legs or hands);
    b. Electric propulsion.

Different classes of pedalcycles can be obtained by combining these characteristics. For example, *cycle rickshaws* are typically human-propelled triplet upright delta tricycles.

In the HTA, the term “bicycle” includes “a tricycle, a unicycle and a power-assisted bicycle but does not include a motor-assisted bicycle.” Thus, the HTA refers to a pedalcycles as bicycles, independently of how many wheels they have.

Further, the HTA defines a “power-assisted bicycle” as “a bicycle that
(a) is a power-assisted bicycle as defined in subsection 2 (1) of the Motor Vehicle Safety Regulations made under the Motor Vehicle Safety Act (Canada),
(b) bears a label affixed by the manufacturer in compliance with the definition referred to in clause (a),
(c) has affixed to it pedals that are operable, and
(d) is capable of being propelled solely by muscular power.

4.1.1.1.3 Trailers

A *trailer* is road vehicle that is not self-propelled and is designed to be towed by a motor vehicle, a horse-drawn vehicle, or a pedalcycle for the transport of persons or goods.

Trailers designed to be drawn by motor vehicles include
1. *Semi-trailer*;
2. *Full trailer*;
3. *Livestock trailer*;
4. *Boat trailer*;
5. *Motorcycle trailer*;
6. *Dolly*;
7. *Bus trailer*; and
8. *Caravan*.

The following non-motorized road vehicles being towed are typically not considered trailers:
1. *Construction trailer*; and
2. *Farm equipment*.

The following are classes of trailers designed to be drawn by pedalcycles:
1. *Cargo trailer*;
2. *Human passenger trailer*;
3. *Child passenger trailer*; and

4. *Pets as cargo trailer*.

ISO 3833-1977 refers to trailers as “towed vehicles”.

In the HTA, the term “trailer” means “a vehicle that is at any time drawn upon a highway by a motor vehicle, except an implement of husbandry, a mobile home, another motor vehicle or any device or apparatus not designed to transport persons or property, temporarily drawn, propelled or moved upon such highway, and except a side car attached to a motorcycle, and shall be considered a separate vehicle and not part of the motor vehicle by which it is drawn.” Thus, the act does not include farm equipment.

In the HTA, the term “mobile home” means “a vehicle, other than a motor vehicle, that is designed and used as a residence or working accommodation unit and exceeds 2.6 meters in width or eleven meters in length.”

In the HTA, the term “trailer converter dolly” means “a device consisting of one or more axles, a fifth wheel lower-half and a tow bar.”

4.1.1.2 Off Road Vehicles

Off-road vehicles are ground vehicles that can normally operate both on and off paved or gravel roads.

Off-road vehicles include:
1. motorized off-road vehicles; and
2. animal-drawn vehicles.

4.1.1.2.1 Motorized Off-Road Vehicles

Motorized off-road vehicles are self-propelled off-road vehicles.

Motorized off-road vehicles include:
1. *All-terrain vehicles (ATV)*;
2. *Motorized Snow Vehicles*;
3. *Motorized equipment*:
    a. *Construction equipment*:
        i. *Wheeled bulldozer*;
        ii. *Backhoe loader*;
        iii. *Excavator*;
        iv. *Grader*;
        v. *Other*;
    b. *Agricultural equipment*:
        i. *Farm tractor*;

ii. *Harvester*;
iii. *Other*.

All terrain vehicle (ATVs) are motorized quadricycles. These vehicles are intended normally for off-road use; however, they may be driven on selected public roads in Ontario. Ontario Regulation 316/03 “Operation of off-road vehicles on highways,” which was established under the HTA, governs the use of these vehicles on public roads in Ontario.

Motorized Snow Vehicles are self-propelled ground vehicles designed to travel primarily on snow. In Ontario, *motorized snow vehicles* are normally not permitted on public roads except for some designated highways and for crossing. The Motorized Snow Vehicles Act regulates the use of these vehicles in Ontario [MSV].

Motorized equipment are self-propelled vehicles whose primary purpose is not the transport of people and goods, but mobility of specialized equipment, such as agriculture and construction. The following Wikipedia article provides an extensive list of motorized equipment:

- https://en.wikipedia.org/wiki/Heavy_equipment

Off-road vehicles may be further classified as

1. *Large-wheeled vehicles*;
2. *Tracked vehicles*; and
3. *Amphibious vehicles*.

Motorized equipment often uses large wheels or tracks. Tracked vehicles may be equipped with rubber pads to travel on paved roads. Motorized equipment may be restricted to low speeds operation, in which case it must be marked as a *slow moving vehicle*.

In the HTA, the term “self-propelled implement of husbandry,” also known as *motorized agricultural equipment*, means “a self-propelled vehicle manufactured, designed, redesigned, converted or reconstructed for a specific use in farming.”

In the HTA, the term “farm tractor” means “a self-propelled vehicle designed and used primarily as a farm implement for drawing ploughs, mowing-machines and other implements of husbandry and not designed or used for carrying a load.”

4.1.1.2.2 Animal-Drawn Vehicles

An *animal-drawn vehicle* is an off-road vehicle pulled by one animal or by a team of animals. These vehicles may have two, three, four, or more wheels.

The most common type of animal-drawn vehicles are *horse-drawn vehicles*. There is a large variety of horse-drawn road vehicles; the following Wikipedia article list over 80 different types:

- https://en.wikipedia.org/wiki/Horse-drawn_vehicle

Examples of horse-drawn wheeled vehicles that may be encountered on public roads in different regions or towns in Ontario today include:

1. *Buggy*;
2. *Carriage*;
3. *Landau*;
4. *Wagonette*; and
5. *Omnibus*.

In winter, *horse-drawn sleighs* may also be encountered.

4.1.1.3 Railed Vehicles

Railed vehicles are ground vehicles that operate on rails.

Railed vehicles include:

1. *Street cars*, also known as *tram*;
2. *Light rail transit trains*, also know as *fast tram*; and
3. *Railway trains*.

4.1.1.4 Rail-Road Vehicles

Rail-road vehicles are ground vehicles that can operate both on rails and roads.

4.1.2 Animal Riders

An *animal rider* is a person riding an animal.

A *horse rider* is a person mounted on a horse. The HTA allows horse riders on public roads, provided they are 18 years old or older and use appropriate helmet and footwear; however, horse-riding associations generally discourage the use of horses on public roads [OEF].

4.1.3 Pedestrians

A *pedestrian* is "any person who is not in or upon a vehicle, motorized or otherwise propelled, or a person in a non-motorized wheelchair, or person in a motorized wheelchair that cannot travel at over 10 km/h or a person pushing a bicycle or motorized or non-motorized wheelchair." [OMT15] Thus, a *person pushing or pulling a vehicle*, such as a bicycle or a food stand trailer, is classified as a pedestrian. A person riding a *personal-mobility scooter*, that is, a scooter intended for medical purposes that is used for outside transportation by disabled persons, is classified as a pedestrian.

Pedestrians normally use sidewalks and pedestrian crossings, but may enter the roadway for a wide range of reasons, including

1. *crossing* the roadway mid-block;
2. *walking along* the curb on the roadway, especially where no sidewalk is available;
3. *accessing vehicles* parked at the curb;
4. *performing work*, such as cleaning or repair; and
5. *playing* on the roadway; for example, some city bylaws allow and regulate playing road hockey on public roads; Kingston, Ontario, allows road hockey on residential streets where the posted speed limit is 50 km/h or less and provides additional guidelines in its Street Hockey Policy and Code of Conduct;
6. *retrieving an object,* such as a soccer ball;
7. *riding skateboard, roller skates,* and *in-line skates* and similar devices on the roadway; and
8. *lying on the pavement*, such as fainted or struck by another vehicle.

There may also be pedestrians in unusual poses, such as.

The City of Toronto clarifies the rules on using skateboard, roller skates, and in-line skates and similar devices on public roads in Ontario [CTK]: "The HTA prohibits the use of skateboard, roller skates, and in-line skates and similar devices on the roadway on public roads where there are sidewalks, except for the purpose of crossing the road. When so crossing, people using these devices are subject to the same rights and obligations as a pedestrian. On roads where sidewalks are not provided, a person wearing in-line skates, as a pedestrian, is required to be on the left side of the roadway, facing oncoming traffic, as close to the left edge of the roadway as possible. On-street bicycle lanes are designated for bicycles only, so in-line skating is not permitted in these designated lanes. Devices powered by any means other than muscular power, such as hoverboards or motorized skateboards, are not allowed on public roadways or the sidewalk; they may only be used off public roads."

A person riding a pedalcycle is not a pedestrian; a pedalcycle is classified as a road vehicle. Thus, cyclists must get off a pedalcycle and push it when using a cross walk. The HTA does not prohibit the use of sidewalks by cyclists; however, many municipal bylaws do. For example, the City of Toronto does not allow riding a pedalcycle on sidewalks by anyone of age 14 or older.

Pedestrian areas are classified by *pedestrian conflict*, defined as the total number of people on both sides of the road within a given section (200 meters):

1. *Low pedestrian conflict* = 10 or fewer pedestrians; e.g., residential areas;
2. *Medium pedestrian conflict* = 11 to 100; e.g., schools and recreation centers areas;
3. *High pedestrian conflict* => 100; e.g., restaurants and shopping, theaters.

4.1.4 Traffic Control Persons

Traffic control persons (TCP) are persons legally performing traffic control tasks.

Examples of TCPs include:

1. School crossing guard;
2. Construction zone flagger; and
3. Police officer directing traffic.

The term "TCP" is often used specifically to refer to a construction zone flagger. This ontology defines this term in a more general sense.

As a special case, a police officer directing traffic may also be mounted on a horse.

4.2 Road User Behavior

Road user behavior is the change of state of a road user over time in response to factors that are external or internal to the road user. Road user state includes both *externally observable state* and *externally unobservable, internal state*.

Externally observable state of a road user can be perceived directly through senses or sensors of other road users. This type of state typically includes

1. *basic motion state*, including position and orientation, velocity, and acceleration;
2. *physical form*, such as, for a vehicle, doors being open or closed and bending state of an articulated body; and for a human road user, different postures and gestures due to body part movements;
3. *relationship between the road user and other objects*, such as a vehicle being occupied or unoccupied and a pedestrian carrying an object or pushing a vehicle;
4. *activity performed by a road user*, such as a vehicle being temporarily stopped at a stop sign or parked at a curb side or a pedestrian gardening on a boulevard strip or looking to cross the roadway; and
5. *signal state communicated in visible light or radio waves*, such as turn indicator lights, brake lights, hazards lights, emergency vehicle lights, radio messages sent and received by a vehicle, such as in vehicle-to-vehicle communication.

Externally unobservable, internal state of a road user is state that is not directly observable, but may be inferred or communicated. This type of state includes

1. *intention* of the user, such as short-term and long-term objectives;
2. *strategy and tactics* the user is currently committed to; and
3. *physical and cognitive capabilities and state*; examples for a vehicle are system capabilities and system health, including potential internal faults or failures; examples for a human road user include general physical and mental capacity, skills, experience, personality factors, attitudes, emotions, and alertness.

The distinction between externally observable and internal state depends on the specifics of the road user and the sensing capabilities of the observer. For example, an observer may be able to confirm whether a vehicle is occupied using vision provided the vehicle windows are not shaded.

External factors influencing the behavior a road user are factors stemming from the environment of the user. These factors include

1. *situation and context*, including road structure, presence and location of other road users, environmental factors such as weather, etc.
2. *changes of the environment state and actions of dynamic objects*, including other road users, animals, traffic signals, etc.; and
3. *traffic rules and social norms*.

Internal factors influencing the behavior a road user are the internal state of the user and changes of the internal state. Some changes of the internal state, which may occur spontaneously, can trigger other changes of the internal state. For example, for a human road user, change of an objective, such as remembering a forgotten errand, may change the strategy, emotions, alertness, and other parts of the user's internal state.

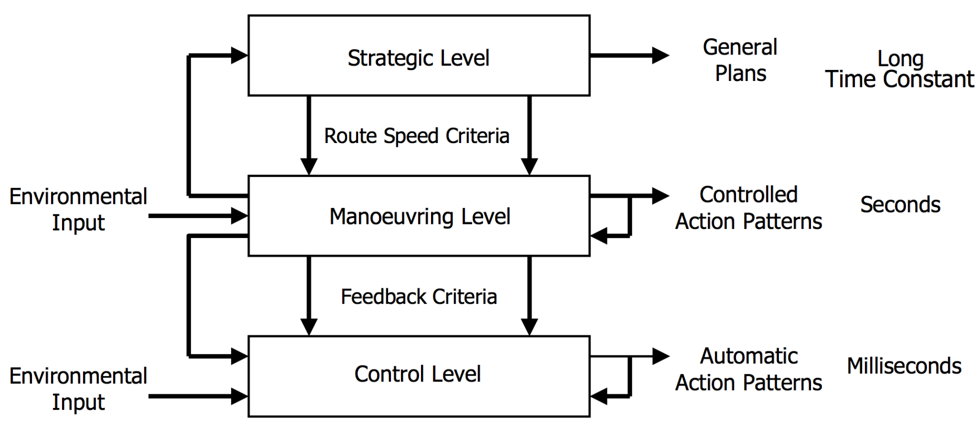

Figure 1 The hierarchical structure of road user task (Figure 2 from [Mic85])

Behavior unfolds and is interpreted at different levels of abstraction, both specially and temporally. For example, driver behavior can be interpreted relative to the levels of the driving task (Figure 1), as defined by Michon [Mic85] (note that the original figure targets driver behavior, but is applicable to road user behavior in general):

1. *Strategic level* comprises "trip planning, including determination of trip goals, route, modal choice, and evaluation of the costs and risks involved; further aspects are general transport and mobility considerations and concomitant factors such as aesthetic satisfaction and comfort." [Mic85] For drivers and pedestrians using the road for mobility, this level involves high-level planning behaviors that span the entire trip or portions of a trip whenever strategy needs to be adjusted with respect to the trip objectives, such as the level of risk, comfort, progress, and energy efficiency. For road users performing work on the road, such as road or infrastructure repairs of maintenance, the strategy components are specific to their overall task.
2. *Tactical level*, also known as *maneuvering level* is "where drivers exercise maneuver control to negotiate the directly prevailing circumstances. Although largely constrained by the exigencies of actual situation, maneuvers such as obstacle avoidance, gap acceptance, turning, and overtaking, must meet the criteria derived from the general goals set at the strategic level. Conversely, these goals may need to be adapted to fit the outcome of certain maneuvers." [Mic85] This level comprises maneuver decision-making behaviors that span seconds.
3. *Operational level*, also known as *control level*, is where drivers exercise longitudinal (acceleration, braking) and lateral (steering) control. This level implements the maneuvers decided in at the tactical level and involves continuous behavior in the scale of milliseconds.

At higher abstraction level, road user movements can also be interpreted as communication. For example, pedestrian movements give rise to body language, facial expressions, informal hand gesturing, and formal sign languages, such as hand signaling directions. Vehicle movements may also constitute communication, such as the nudging behavior when vehicles drive close to the lane marking to signalize their intention to make a lane change, or acceleration or deceleration to give way or take way in merge situations.

4.2.1 Behavioral Factors

Several factors influence the behaviors of road users:

1. *Traffic rules*, including *traffic laws* and *informal best practice rules* from driver's handbooks;
2. *Social norms*, which may be *law conformant* or *non-conformant*;
3. *Individual behavior factors* of road users, including physical and cognitive capacity, skills, experience, attitudes, personality factors, and emotions; and

4. *Vehicle capabilities*, such as acceleration, braking, and handling performance and ride quality.

Individual behavior factors listed under item 3. are mainly applicable to human road users, including drivers and pedestrians.

ADS-operated vehicles, when they blend with human-driven vehicles, are expected to obey traffic rules and should likely respect at least some of the law-conformant social norms of human drivers. For example, the German Road Traffic Act requires that ADS-operated vehicles obey existing traffic regulations that were originally developed for human drivers [GRT]. However, new rules specific to ADS-operated vehicles are likely to emerge over time.

4.2.1.1 Traffic Rules

Traffic rules, also known as the *rules of the road*, are both *formal rules* established by *traffic laws* and *informal best practice rules* that govern road traffic, including road user behavior, in a given geographic area.

4.2.1.1.1 Traffic Laws

Traffic laws exist at different territorial extents, including international, national, and regional laws. An example of an international traffic law is the Convention on Road Traffic [VC], commonly know as the Vienna Convention on Road Traffic. The convention includes traffic rules for road user behaviors, such as vehicle speed limits, following distance, overtaking rules, pedestrian crossing rules, etc. The convention has been ratified by 74 countries in Europe, Asia, Africa, and South America, and additional countries abide by it without having ratified it. However, neither the U.S. nor Canada has adopted the convention.

In Canada, each province is responsible for maintaining its roads and establishing traffic regulations through provincial highway traffic laws. For example, the Highway Traffic Act (HTA) sets the traffic rules for Ontario [HTA]. Provinces delegate some responsibility for maintenance and creation of additional traffic regulations to municipalities through bylaws. As the Canadian Encyclopedia states: "Federal involvement comes primarily from criminal law. The Canadian Criminal Code provides for numerous serious offences – including dangerous driving, criminal negligence in the operation of a motor vehicle, criminal negligence causing death, and impaired driving." [TLC]

4.2.1.1.2 Informal Best Practice Rules

Informal rules representing best practices are often documented in official driver handbooks. In Canada, each province, including Ontario [ODH], has its own driver's handbook. The informal rules are consistent with the traffic laws and refine and complement the legal rules. For example, the HTA requires vehicles to maintain a safe gap to a front vehicle:

> "The driver of a motor vehicle or street car shall not follow another vehicle or street car more closely than is reasonable and prudent having due regard for the speed of the vehicle and the traffic on and the conditions of the highway." R.S.O. 1990, c. H.8, s. 158 (1).

The Ontario Driver's handbook refines the general rule from the HTA and gives the "two-second" rule as a more concrete guidance:

> "Whenever you follow another vehicle, you need enough space to stop safely if the other vehicle brakes suddenly. A safe following distance is at least two seconds behind the vehicle in front of you. This lets you see around the vehicle ahead and gives you enough distance to stop suddenly. [...] Remember that the two-second rule gives a minimum following distance. It applies only to ideal driving conditions. You will need extra space in certain situations, such as bad weather, when following motorcycles or large trucks, or when carrying a heavy load." [ODH]

Additional best practices are defined in existing driver education literature. For example, the driving task analysis report by McKnight and Adams [MA70] provides an extensive collection of driving best practices.

4.2.1.2 Social Norms

Social norms are informal understandings that govern the behavior of members of society [Mar15]. Some of the informal understandings may be captured by formal rules, such as traffic laws. Social norms vary by geographic locations and even by segments of the society. Driving practices may vary across different cities even if the laws are the same. Similarly, within the same geographic area, different subgroups of road users, such as local residents versus taxicab drivers, may follow different norms.

Norms may be consistent or inconsistent with traffic rules:

1. *Law-conformant norms* refine or complement the informal rules stated in driver's handbook. For example, it is a common practice in Ontario that cars wishing to turn left that arrived after the left turn signal ended do so during the yellow phase, as long as there is enough time to make a safe turn [TL].
2. *Law non-conformant norms* run contrary to traffic laws, such as the practice to travel 10-20 km/h above the speed limit on freeways, which is common in Ontario.

Formal and informal rules and norms may blend in complex ways. For example, Björklund and Åberg [BA05] study the formal and informal rules of driver behavior at unsignalized intersections and identify both law-conformant and law non-conformant informal rules. Among others, they identify informal rules such as a driver from a narrower road yielding to a driver from a broader road, even if the two intersecting roads have equal priority and the formal rule is to yield to the driver from the right. They also identify behaviors that replace a formal traffic rule with an informal interaction. An example is when a driver, often an older one, who has the right of way at an unsignalized intersection, delays the crossing maneuver or signals using hand gestures to let the driver from the left cross the intersection first.

4.2.1.3 Individual Behavior

Many personal factors influence the behavior of a road user. These factors are studied in traffic psychology [Por11, Shi07] and traffic sociology [Rot92] and include:

1. *physical and cognitive capacity*, which depend on age, physical and mental health, and potential intoxication;
2. *skills and experience in road traffic*, which depend on education, being a local or a visitor, etc.;
3. *personality factors*, such the "big-five factors": openness to experience, conscientiousness, extraversion, agreeableness, and neuroticism;
4. *attitudes and beliefs* relative to objects, situations, and practices in road traffic; and
5. *emotions*, such as fear and anger, which may or may not be related to the road environment.

These factors influence the behaviors and performance of road users in traffic, and may lead to deviations from norms and violations of traffic rules, and potentially to crashes (e.g., see [DW06]).

Behaviors that violate safe driving practices, whether they are slips and lapses, mistakes, or deliberate violations, are referred to as *aberrant driver behaviors* [BH95].

4.2.2 Behavioral Models

The behavior of road users, particularly human users, is an extremely complex matter. Models necessarily focus on aspects and level of detail that are relevant for a given application. Michon classifies road user behavior models along two dimensions (see Figure 3):

1. *modeling depth*, which is whether the model focuses on *input-output behavior* of the road user, or whether the model also includes *internal state*; and

2. *degree of dynamism*, which is whether the model is *taxonomic*, that is, purely descriptive and non-executable, or *functional*, that is, representing elements with dynamic interaction.

	Taxonomic	Functional
Input-Output (Behavioral)	Task Analyses	Mechanistic Models Adaptive Control Models - Servo-Control - Information Flow Control
Internal State (Psychological)	Trait Models	Motivational Models Cognitive (Process) Models

Figure 2 Classification of road user behavior models (Figure 3 from [Mic85])

These two dimensions lead to four classes of behavioral models (note that the classification was developed for driver behavior models, but it is also applicable to road user behavior in general):

1. *Taxonomic input-output behavior models:* This category includes *task analysis* models, such as the driver behavior catalog by McKnight and Adams [MA70], which specifies actions human drivers should perform in different situations. This model was created for the purpose of driver's education and defines over 1,700 elementary behaviors, including basic control tasks and responding to vehicles, pedestrians, and obstacles in different road configurations and environmental conditions.
2. *Taxonomic internal-state behavior models*: Example of models in this category are *trait models*, which attempt to correlate traits of a driver with driver behavior, e.g., [CGG59, SS71]. Traits include personality traits, such as ability to control anger, and psychophysical traits, such as reaction times. But these models do not explain the mechanisms of how behaviors are generated.
3. *Functional input-output behavior models*: These models are control-oriented, but also mechanistic in nature, as they do not consider mental states and any learning aspects. Two types of models are included in this category:
    a. *Servo-control models* are mainly concerned with the operational level, addressing tasks such as steering and speed regulation in lane following and braking in response to cues such as visual perception of time-to-collision. Figure 3 shows a block diagram of a steering control model by Donges [Don78]. The model includes both compensatory control, which corrects vehicle heading and lateral position in the

lane, and anticipatory control, which considers curvature of the path ahead. MacAdam [McA03] and Plöchl and Edelmann [PE07] provide comprehensive reviews of these models.

   b. *Information flow control models* are executable algorithms covering both operational and tactical tasks, but are still mechanistic, that is, not reflecting any mental states and not including any learning aspects. An example of a model in this category is Kidd and Laughery's model for decision making when approaching an intersection (see Figure 4) [KL64].

4. *Functional internal-state behavior models:* These models consider the internal state and have two sub-categories:
   a. *Motivational models* represent the influence of mental states of the road user on behavior. A prominent class of such models gathers those relating the perception of risk by a road user and the behavior of the user. For example, Fuller's *task difficulty homeostasis* theory [Ful05] states that road users target a specific level of driving task difficulty that they are comfortable with. In this theory, the task difficulty derives from the interaction between situation demand and the road user performance or capability. Another example is the model by Kageyama and Pacejka [KP91], which models risk levels in relation to the structure of the driving environment for the purpose of path planning (Figure 5). The model uses exponential functions to represent the risk levels, for example, when approaching an obstacle. This risk level cannot be measured directly, but the authors presuppose its correlation to driver's perceived risk. The perceived risk is the driver's heartbeat rate, which also rises exponentially when approaching an obstacle or the edge of the roadway. Motivational models address either general mechanisms or specific tasks, but do not provide a comprehensive representation of the cognitive processes that generate behavior.
   b. *Cognitive process models* attempt to model the cognitive processes spanning operational, tactical, and strategic levels. A key approach in this category has been to represent executable knowledge using production rules, such as the ACT-R approach [ABB04]. An example is Salvucci's executable model of multi-lane highway driving in ACT-R [Sal06].

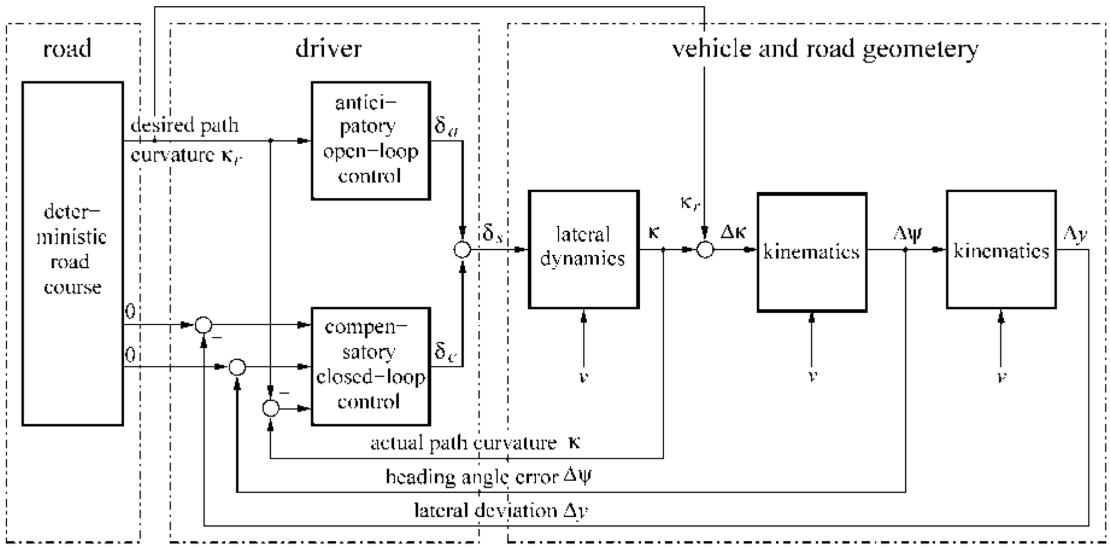

Figure 3 Two-level human driver steering model by Donges [Don78]

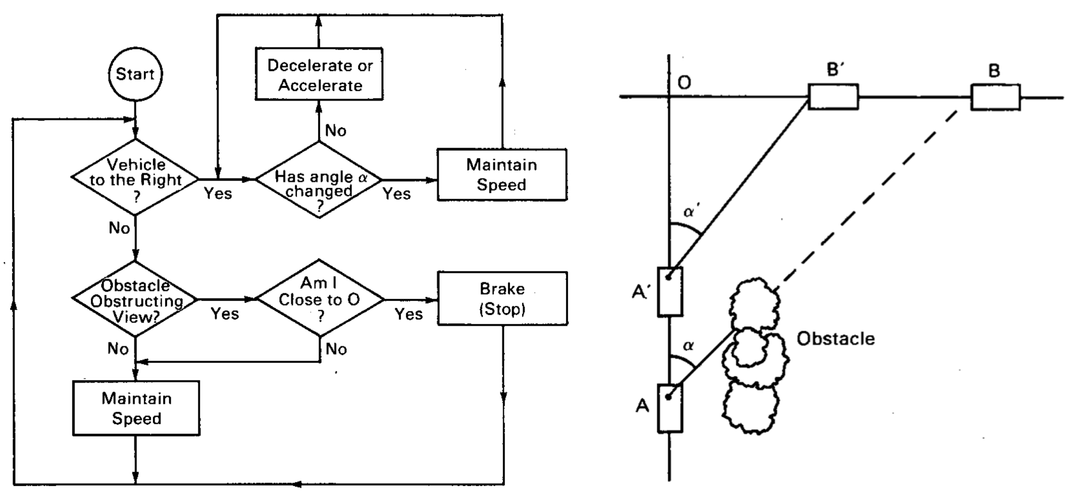

Figure 4 Approaching an intersection according to the information flow model of Kidd and Laughery [KL64] (from [Mic84])

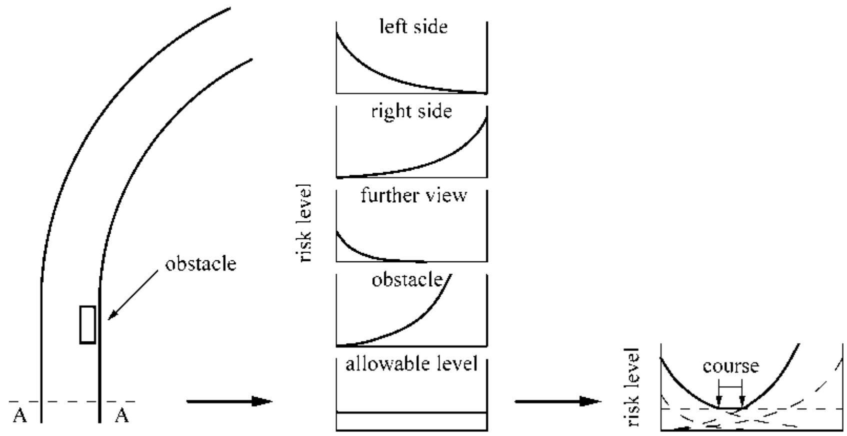

Figure 5 Driving decision based on minimum risk level [KP91]

4.2.2.1 Vehicle Behavior Models

A *vehicle behavior model* represents the behavior of the overall vehicle and driver system. The model can represent the behavior as a unit or as a composition of a *vehicle model*, which maps driver inputs to vehicle behavior, and *driver model*. A model that represents the behavior as a unit abstracts from possible compensatory and adaptive human behavior with respect to vehicle performance variations [McA03]. On the other hand, a compositional model allows explicit manipulation of vehicle dynamics and human behavior parameters.

4.2.2.1.1 Vehicle Models

A *vehicle model* maps driver control inputs, such as steering, braking, and throttle, to vehicle behavior. Models of motorized vehicles typically include

1. *vehicle dynamics model*, which covers longitudinal dynamics (acceleration, braking, and pitching), lateral dynamics (turning and rolling), and vertical dynamics (bounce); and
2. *powertrain model*, which maps throttle inputs to drive torques at the driven wheels.

For vehicles propelled by muscular power, the second component involves modeling a biological system, such as a human or animal, as a source of propulsion.

A wide range of vehicle models exist depending on the type of vehicle and the desired degree of fidelity. Single-track models, such as *bicycle models*, can be used for bicycles, motorcycles, and passenger cars. Kinematic bicycle models are adequate for normal driving at lower speeds, typically below 50 km/h. Dynamic bicycle models are needed to model extreme maneuvers and driving at higher speeds [KPS15]. Modeling of more complete behavior of passenger cars, which includes roll and pitch, requires four-wheel models with suspension, e.g., [Raj12]. Large articulated vehicles require specialized multi-body dynamics models [EP00]. Power-train models depend on type of propulsion, such as internal combustion engine, hybrid, or electric, and the specifics of the powertrain configuration [GS07].

4.2.2.1.2 Driver Behavior Models

A vehicle may be operated by a human driver or an ADS. A human driver may be a *conventional deriver* seated in the driver seat, or a *remote driver*, that is, a driver that is physically not in the vehicle. Vehicle-remote-driver system potentially includes significant communication delays that need to be modeled.

The remainder of this section focuses on motor vehicle drivers. The overall tasks for cyclists are similar to those for motor vehicle drivers, including basic control, lane following, passing, intersection maneuvers, etc.; however, the specific models are different because of the significant differences in propulsion, dynamics, traffic regulations, and the ability of cyclists to transition between cyclist and pedestrian mode.

4.2.2.1.2.1 Human Driver Behavior Models

Human driver performance is bounded by psychomotoric limitations, including limitations of multi-sensory perception, working memory capability, and motoric capability. MacAdam [McA03] and Layton and Dixon [LD12] provide a detailed discussion of these factors and associated performance metrics and ranges for basic perception and control. SAE J2944 also provides human-driver performance metrics and ranges for different maneuvers [DPM15].

The *perception-reaction time* is a fundamental human factor that needs to be respected by any driver model. The perception-reaction time is typically broken down into [LD12]:

1. *Perception time* to see or discern an object or event;
2. *Intellection time* to understand the implication of the object's presence or event;
3. *Emotion time*, also known as decision time, to decide how to react; and
4. *Volition time* to initiate the action, for example, the time to engage the brakes.

Table 1 shows values for the overall perception-reaction time for 85th and 95th percentile time observed in different traffic experiments. The perception-reaction time depends on personal characteristics, but also the mental state of the driver, the complexity of the traffic situation (Table 2), and how expected or surprising the perceived object or event was (Figure 6). The horizontal axis in Figure 6 represents the number of objects or events observed; 0 corresponds to basic control where no new objects or events are observed. Solid or dashed line corresponds to, respectively, expected or unexpected events or objects.

Table 1 Perception-reaction time in seconds observed in experiments for 85th and 95th percentile time (Table 1 from [LD12])

	85th	95th
Gazis et al.	1.48	1.75
Wortman et al.	1.80	2.35
Chang et al.	1.90	2.50
Sivak et al.	1.78	2.40

Table 2 Perception-reaction time considering complexity and driver state (Table 2 from [LD12])

	Driver's State	Complexity	Perception-Reaction Time
Low Volume Road	Alert	Low	1.5 s
Two-Lane Primary Rural Road	Fatigued	Moderate	3.0 s
Urban Arterial	Alert	High	2.5 s
Rural Freeway	Fatigued	Low	2.5 s
Urban Freeway	Fatigued	High	3.0 s

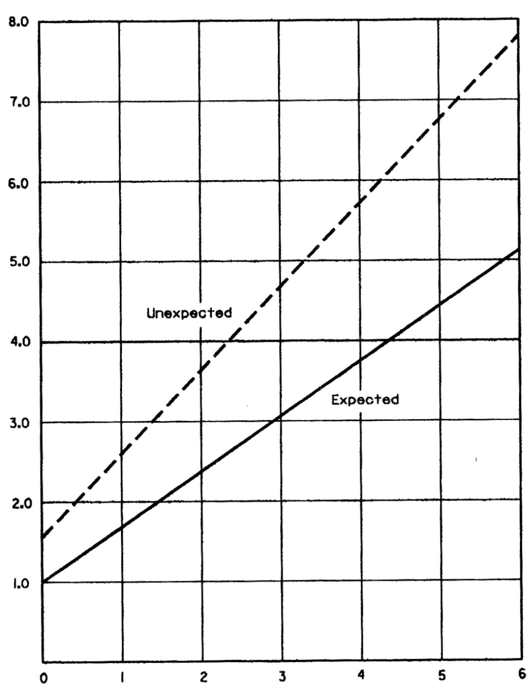

Figure 6 Perception-reaction time as a function of situation complexity (from [AA11])

The following subsections review human driver behavior models, with focus on functional models at operational and tactical levels that can be used in simulations.

4.2.2.1.2.1.1 Operational Behavior

The servo-control models represent human steering and speed regulation performance at the operational level. MacAdam [McA03] and Plöchl and Edelmann [PE07] provide comprehensive surveys of these models. These models include classic "pursuit type" models, but also more complex ones. Figure 7 shows the block diagram of the so-called GM/UMTRI driver model [McA01], which is one of the most comprehensive servo-control models of steering.

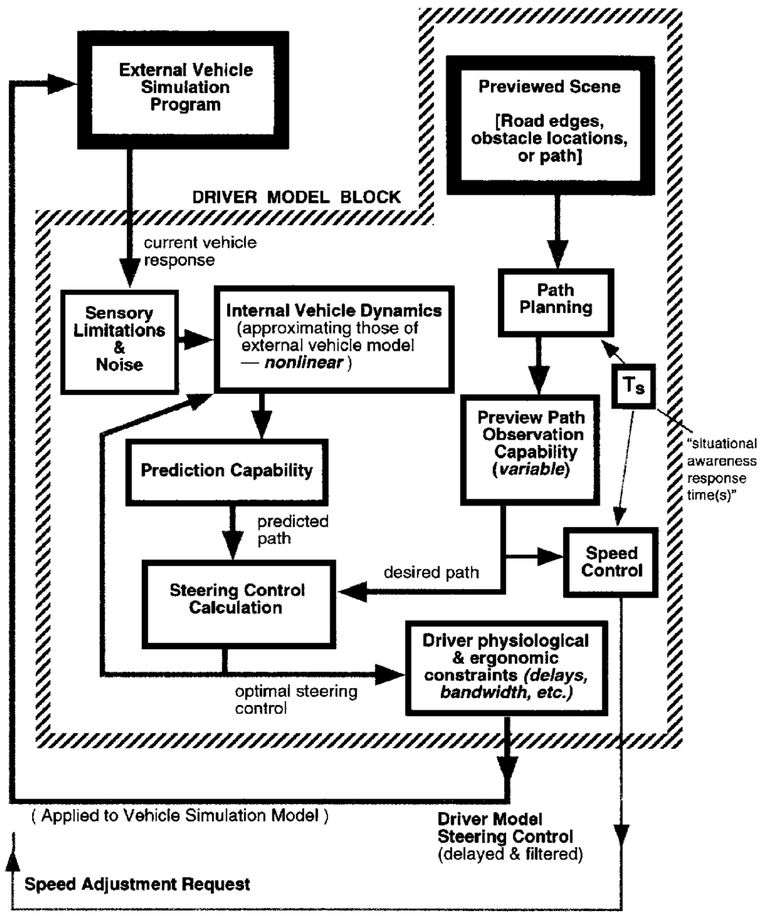

Figure 7 GM/UMTRI driver model of steering (Figure 2-1 from [McA01])

4.2.2.1.2.1.2 Tactical Behavior

Models of tactical driver behavior target different maneuvers or maneuver combinations:

1. *Speed selection* by the driver depends on many factors, including the driver's characteristics; vehicle characteristics; environmental characteristics, such as road configuration, traffic, weather, and the speed limit; time-saving benefits; and crash and ticket risks. Sadia et al. [SBP17] provide a speed selection model that was derived from experimental data.
2. *Lane following* is the task of driving within a lane. Lane following has different modes. *Free driving* is when the subject vehicle is not constrained by other vehicles or obstacles. The main objective is to trace the center of the lane and navigate curves. *Car following* is when the subject vehicle is constrained by a front vehicle, which requires maintaining an appropriate front gap. Car following can be refined into additional sub-modes based on the level of congestion. Barceló [Bar10] and Elefteriadou [Ele14] provide reviews of car following models. Prominent models include Intelligent Driver Model [KTS08, KTH10] and the so-called Wiedeman model [HAM11].
3. *Lane changing* can occur on a *mandatory*, e.g., when taking an exit, or *discretionary* bases, such as to enter a faster lane, and involves lane choice, gap acceptance, intention communication, deceleration or acceleration into a target gap, and the actual lane change. Barceló [Bar10] and Elefteriadou [Ele14] survey existing lane changing models.
4. *Passing* on two-lane roads, also known as *overtaking*, requires crossing the directional divider, which exposes the subject vehicle to oncoming traffic and potential head-on collisions. The key element of a passing maneuver is the decision to pass, which requires sufficient sight distance. Harwood and Sun [HS08] provide a comprehensive discussion of this topic. Capaldo and Risoli [CR12] model two types of passing maneuvers, flying pass and accelerative pass.
5. *Intersection behaviors* include intersection approaches and through and turn movements, which may require navigating cross-traffic and merging. There is a large number of intersection types, where different formal and informal rules apply. Examples of intersection models include [ADS12] and [LO07].
6. *Pedestrian crossing* can occur at marked or unmarked roadway locations and drivers need to respond appropriately. In the case of unsignalized crossing, a driver must first recognize pedestrian intention to cross, then to decide whether to yield or not, and then select speed accordingly [Var98]. Schroeder and Rouphail [SR10] analyze driver yielding and speed selection behavior at pedestrian crossings.
7. *Emergency maneuvers* include emergency braking [WDT09] and evasion [SK15].
8. *Integrated models* handle composite behaviors including the interactions among the individual maneuvers. For example, Yeo and Skabardonis [YS07] developed a model that integrates lane following and changing and accounts for different modes of lane following when preparing to do a lane change or responding to a lane change by another vehicle (Figure 8). Other examples of integrated models are [TKB07] and [Sal06].

9. *Aberrant behavior models* specifically include driver errors and violations [YP09, SZ14, LMK09, DEM06].

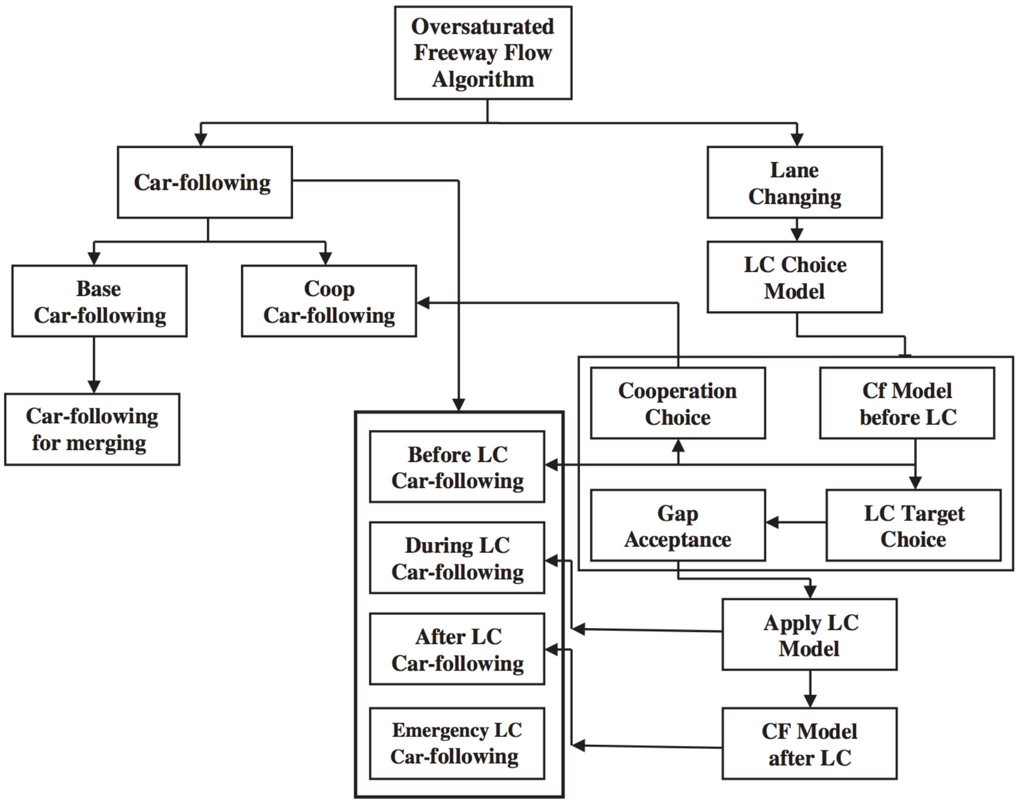

Figure 8 Components of the proposed oversaturated freeway flow algorithm [YS07]

4.2.2.1.2.2 Automated Driving System Models

In contrast to modeling human driver behavior, adequate models of automated driving system (ADS) behaviors can be developed during the design of the ADS. Manufacturers could publish ADS models of sufficient fidelity to enable simulating traffic with different ADS-operated vehicles.

4.2.2.2 Pedestrian Models

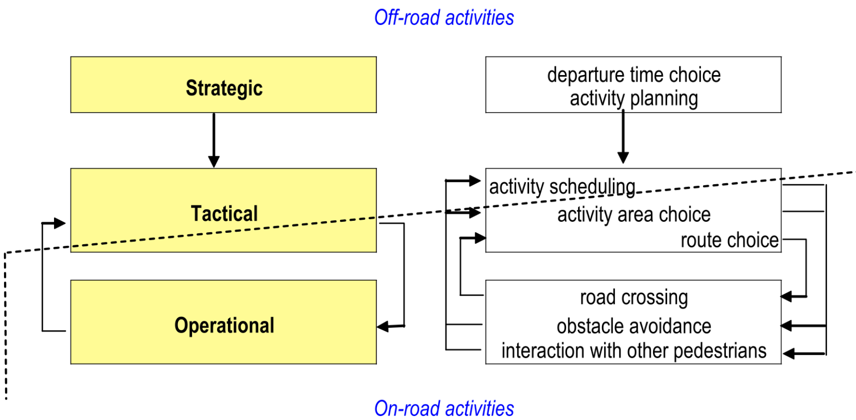

Figure 9 Levels of pedestrian behavior (Figure 1 from [PYG09])

Pedestrian behavior is far more less constrained than that of vehicles and thus much more complex. Pedestrian behavior can also be classified into strategic, tactical, and operational level (Figure 9). The tactical level includes *route choice* and *choice of activity area*, such as avoiding crowded locations. The operational level include road *crossing behavior*, *obstacle avoidance*, and *interaction with other pedestrians*, such as walking in groups and *group behavior*. Crossing behavior includes decision making where to cross the roadway; *gap acceptance* to oncoming vehicles; interaction with oncoming vehicles; mode of crossing, such as walking or running; activities when crossing, such as monitoring traffic and smartphone use. Papadimitriou et al. [PYG09] provide a comprehensive review of existing pedestrian behavior models for route choice and crossing behavior. McMahon et al. [MZD02] analyze the pedestrian behavior of *walking along the road* and its safety. Knoblauch et al. [KPN96] provide an analysis of pedestrian walking speeds and start-up times. A particular concern is the case of a human lying on the roadway, which primarily occurs as a result of a vehicle striking a pedestrian. Subsequent vehicles may drive over the pedestrian, particularly in low visibility.

5. Animals

The attributes of animals entering the roadway that are most relevant to traffic are their size and mass, and whether they are

1. *supervised* by a human, such as walked pets or herded farm animals; or
2. *unsupervised*, such as wandering domestic animals or wild animals.

The particular animals that are likely to be encountered depend on the geographic area and zone, such as pets and urban wildlife in urban zones, wild animals in conservation zones, and farm animals and wild animals in rural zones. Huijser et al. [HMF07] review the risks of *animal-vehicle crashes* in North America. Wildlife collision prevention programs provide guidance for drivers on how to react in near-crash or crash situations with animals, e.g., [WCP].

With respect to severity of a potential collision, animals are classified into *small*, *medium*, and *large size*, based on their weight and height:

1. *Small animals*: Small animals are those weighing less than 25 kg, and are typically less than 40 cm high. Bumper height for passenger cars is between 40 and 50 cm. Small animals are likely to go under the car during a collision and pose a small risk to the occupants. Animals up to 13 cm of height fit completely under the body of an average passenger car.
2. *Medium-size animals*: Medium-size animals are between 40 and 80 cm high and weight between 25 and 100 kg. The cowl height of a typical passenger car, that is the distance between ground and the lower edge of the windshield, ranges between 80 and 100 cm. Animals that approach 80 cm or are higher than 80 cm and have significant upper body mass tend to go through the windshield creating a significant risk to the occupants [LLC15]. Collisions with heavy animals that are up to 60 cm tall and primarily collide with the bumper area are less of a threat to occupants than to the animal. Collisions with these animals are still likely to cause significant vehicle damage at higher speeds and potential neck injuries to occupants due to the sudden deceleration.
3. *Large animals*: Large animals are higher than 80 cm and heavier than 25 kg. These animals pose a significant risk of crushing through the windshield. Heavy and tall animals such as a moose, cattle, or horse may completely flatten the roof a vehicle (see Figure 10).

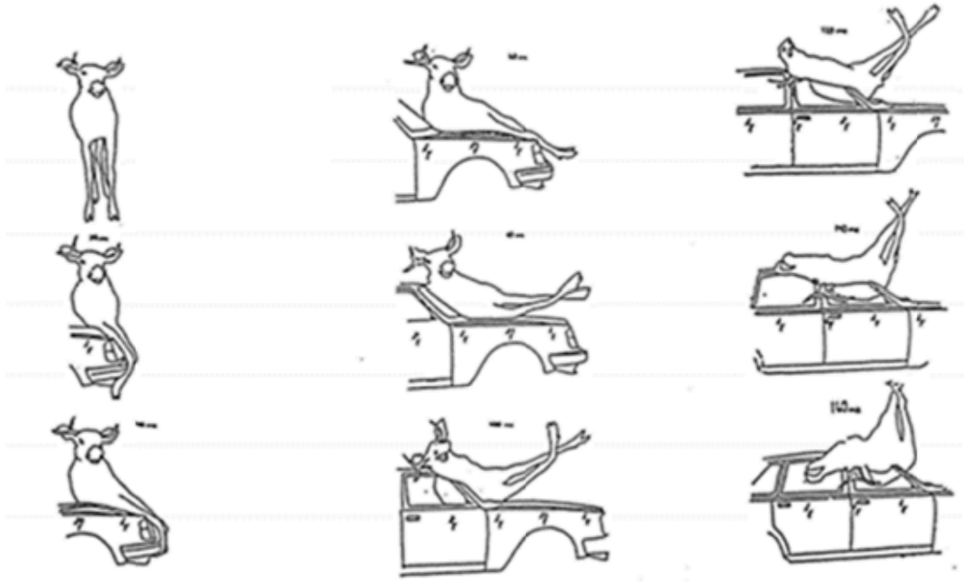

Figure 10 Vehicle-moose interaction, up to 160 ms (from [LNS89])

Table 3 classifies domestic and wild animals that are common in Ontario.

Table 3 Height and weight of small, medium, and large adult animals commonly occurring in Ontario

Size	**Domestic/Wild**	**Animal**	**Height**	**Weight**
Small	Wild	Gray squirrel	15 – 20 cm	0.4 – 0.6 kg
Small	Domestic	Cat	23 – 25 cm	3.6 – 4.5 kg
Small	Wild	Raccoon	23 – 30 cm	3.5 – 9 kg
Small	Wild	Canada goose	70 – 100 cm	2.6 – 6.5 kg
Small	Wild	Red fox	35 – 50 cm	2.2 – 14 kg
Small	Domestic	Small dog	15 – 40 cm	2 – 20 kg
Small-medium	Domestic	Mid-size dog	45 – 55 cm	20 – 30 kg
Small-medium	Wild	Roe deer	65 – 75 cm	15 – 35 kg
Small-medium	Domestic	Large dog	30 – 70 cm	30 – 60 kg
Mostly medium-large	Wild	Grey wolf	80 – 100 cm	23 – 80 kg
Mostly-large	Wild	White-tailed deer	80 – 100 cm	35 – 100 kg
Medium-large	Domestic	Sheep	65 – 127 cm	45 – 100 kg
Medium-large	Wild	Boar	55 – 120 cm	50 – 270 kg
Mostly large	Wild	Brown bear	70 – 150 cm	80 – 600 kg
Large	Wild	Elk	120 – 150 cm	200 – 330 kg
Large	Domestic	Cattle	80 – 150 cm	250 – 1000 kg
Large	Wild	Moose	140 – 210 cm	200 – 700 kg
Large	Domestic	Horse	140 – 180 cm	380 – 1000 kg

Most severe animal-vehicle crashes in North America involve large livestock, such as sheep, cattle, and horses, followed by crashes involving large wild animals such as deer, elk and moose [PD03].

In general, animal behavior is difficult to predict, and most work on the road crossing behavior of wild animals focuses on predicting locations where such crossings are likely based on geographic and environmental variables [VGB12]. Exceptions include the work by Alden et al. [AMM16], which presents a large naturalistic driving data set of recorded animal-vehicle encounters and crashes and a photogrammetric analysis of these encounters in North America, and a study by Erbsmehl et al. [ELY17], which analyzes animal crossing-behavior in Germany based on infrared camera recordings.

6. Other Obstacles

An *obstacle* is any object that is in the path of a vehicle. During normal driving, drivers are mainly concerned with objects on the roadway, but objects on the roadside are also relevant in near-crash and crash situations where a vehicle may leave the roadway. The previous sections have already covered major classes of objects found on the roadway, which are road users, including parked vehicles, and animals, and objects that are part of the roadside, including barriers, traffic signs, vegetation, etc. This section focuses on the remaining objects that may occur on the roadway.

There are a huge and unbounded variety of objects that can be found on the roadway. The following list provides some examples based on the causes for the presence of an object on the roadway:

1. *objects placed by forces of nature*: rocks falling off escarpments, trees blown over by the wind onto the roadway, snowdrifts, leaf piles, etc.;
2. *lost cargo*: any object transported by road users and lost on the roadway, such as packages, construction material, etc.
3. *vehicle parts detached from vehicles*: for example, a wheel detached from an 18-wheel truck may easily go unnoticed by the truck driver;
4. *work- or activity-related objects*: construction equipment, waste bins and their content on waste collection day, soccer balls, toys, etc.;
5. *infrastructure decay related*: debris falling from overpasses and other decaying infrastructure;
6. *road surface roughness*: road surface damage, improperly installed manholes and gutters (see section on road surface roughness); and
7. *maliciously placed or dropped objects*: rocks or other objects dropped from overpasses.

Object attributes that are most relevant to traffic are size, mass and malleability. Objects smaller than 13 cm will fit under the vehicle, assuming a vehicle ground clearance of at least 5 in. However, some small object may also be dangerous, such as power lines on the ground, for example, after a storm. Objects, even small, that may go through the windshield are also particularly dangerous.

7. Environmental Conditions

Environmental conditions include
1. *atmospheric conditions*,
2. *lighting conditions*, and
3. *weather-related road surface conditions*.

7.1 Atmospheric Conditions

Atmospheric conditions comprise the state of the atmosphere in terms of
1. *temperature*,
2. *visibility*,
3. *wind*,
4. *clouds*,
5. *precipitation*, and
6. *other atmospheric obscuration*.

7.1.1 Visibility

Visibility is a measure of the distance at which an object or light can be clearly discerned. ICAO Annex 3 Meteorological Service for International Air Navigation contains the following definitions and note [ICA07]:"

a) the greatest distance at which a black object of suitable dimensions, situated near the ground, can be seen and recognized when observed against a bright background;
b) the greatest distance at which lights of 1,000 candelas can be seen and identified against an unlit background.

Note.— The two distances have different values in air of a given extinction coefficient, and the latter b) varies with the background illumination. The former a) is represented by the *meteorological optical range (MOR)*."

Meteorological optical range captures the attenuation of light as it travels though the atmosphere. The actual visibility of a target object also depends on the size of the object.

Both the International Commission on Illumination and also Annex 3 [ICA07] assume that an object is reliably discernable to a human eye if its contrast ratio against the background is at least 5%.

Extremely clean air in Arctic or mountainous areas may have visibility up to 161 km (100 mi). Fog reduces visibility to less than 1 km (3,300 ft); visibility in extreme fog may be under 100 meters. Visibility under 100 meters is usually reported as *zero visibility* [Vis]

Meteorological Terminal Aviation Routine Weather Report (METAR) provides codes and intensity measures for various weather events.

7.1.2 Wind

Wind is normally characterized by its speed, direction, and changes in speed.

Wind speed is normally measured in km/h, as average over one- or two-minute intervals. The *Beaufort scale* also provides wind speed categories based on specifically defined wind effects:

0. *Calm*, < 1 km/h;
1. *Light air*, 1–5 km/h;
2. *Light breeze*, 6–11 km/h;
3. *Gentle breeze*, 12–19 km/h;
4. *Moderate breeze*, 20–28 km/h;
5. *Fresh breeze*, 29–38 km/h;
6. *Strong breeze*, 39–49 km/h;
7. *High wind*, 50–61 km/h;
8. *Gale*, 62–74 km/h;
9. *Strong/severe gale*, 75–88 km/h;
10. *Storm*, 89–102 km/h;
11. *Violent storm*, 103–117 km/h; and
12. *Hurricane force*, ≥ 118 km/h.

Wind direction is reported based on the direction from which it originates. Wind direction is usually reported in *cardinal directions* or in *azimuth degrees* clockwise from due north. Cardinal directions are north (N), east (E), south (S), and west (W); intermediate directions are northeast (NE), southeast (SE), southwest (SW), and northwest (NW).

Winds may have different durations and changes in speed. Long-duration winds have various names associated with their average strength, such as breeze, gale, storm, and hurricane (see above). Examples of short-duration winds include:

1. a *gust* is a short burst of high-speed wind, with maxima that exceed the lowest wind speed measured during a ten-minute time interval by 10 knots (19 km/h); and
2. a *squall* is a strong wind of intermediate duration, with doubling of the wind speed above a certain threshold and a duration of a minute or more.

Winds, especially cross winds, may affect vehicle dynamics and controllability. They also impact visibility in the presence of precipitation, such as snowfall.

7.1.3 Cloud Conditions

Clouds affect background illumination from the Sun or the Moon and may cast shadows. The basic cloud parameters include cloud type, thickness, and cover.

Cloud cover is the amount of sky covered by clouds, which is measured in octas (Figure 11). An *octa* is a unit corresponding to one eight of the sky being covered by clouds. METAR gives the following names to cloud cover levels:

1. *sky clear* (SKC) = 0 to 1 oktas;
2. *few clouds* (FEW) = 1 to 2 oktas;
3. *scattered clouds* (SCT) = 3 to 4 oktas
4. *broken clouds* (BKN) = 5 to 7 oktas; and
5. *overcast* (OVC) = 8 oktas.

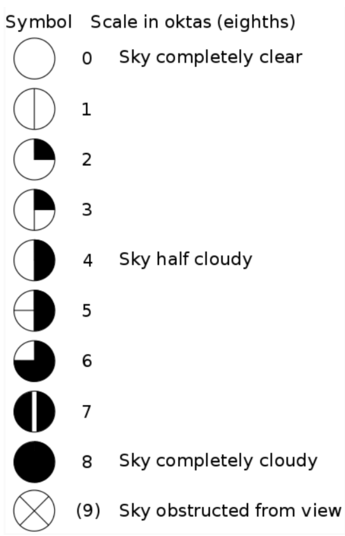

Figure 11 Cloud cover in oktas and the corresponding meteorological symbol [CC]

7.1.4 Precipitation

Precipitation is any product of the condensation of atmospheric water vapor that falls under gravity [GM]. Type of precipitation can be classified by water phase (METAR acronyms are given in parentheses):

1. Liquid precipitation:
    a. *Drizzle* (DZ)
    b. *Rain* (RA)
2. Freezing precipitation:
    a. *Freezing drizzle* (FZDZ)
    b. *Freezing rain* (FZRA)
    c. *Rain and snow mixed* (RASN)
3. Frozen precipitation:

a. *Snow* (SN)
b. *Snow grains* (SG)
c. *Ice pellets / Sleet* (PL)
d. *Hail* (GR)
e. *Snow pellets / Graupel* (GS)
f. *Ice crystals* (IC)

Rainfall intensity is classified according to the rate of precipitation [Rain]:
1. *Light rain* — when the precipitation rate is < 2.5 mm (0.098 in) per hour;
2. *Moderate rain* — when the precipitation rate is between 2.5 mm (0.098 in) per hour and 7.6 mm (0.30 in) per hour;
3. *Heavy rain* — when the precipitation rate is > 7.6 mm (0.30 in) per hour and 50 mm (2.0 in) per hour;
4. *Violent rain* — when the precipitation rate is > 50 mm (2.0 in) per hour; and
5. *Cloudburst* — when the precipitation rate is > 100 mm (3.9 in) per hour.

Rain is normally accompanied by a cloud cover. An exception is *sun shower*, which is "a meteorological phenomenon in which rain falls while the sun is shining. A sunshower is usually the result of accompanying winds associated with a rain storm sometimes miles away, blowing the airborne raindrops into an area where there are no clouds." [SS]

Freezing precipitation may result in ice cover over ground and outside objects, including vehicle windshields, lights, and sensors:
1. *Soft rime* is a white ice deposition occurring from light freezing fog or mist;
2. *Hard rime* is a white ice deposition occurring from freezing fog; and
3. *Glaze* is a smooth transparent ice sheet occurring from freezing rain and drizzle.

Snowfall events are classified into [TS]:
1. *Snow flurry*: Describes a period of light snow with occasional moderate snowfall but usually little accumulation.
2. *Snowsquall*: A brief, very intense snowstorm.
3. *Snowstorm*: Usually, a long storm of relatively heavy snow, similar to a blizzard but without the wind requirement.
4. *Blizzard*: A long-lasting snowstorm with intense snowfall reducing visibility to less than 0.4 km (0.25 mi) and a sustained wind or frequent gusts to 56 km/h (35 mph). Particularly severe storms can create whiteout conditions where visibility is severely reduced.

Snowfall intensity may be categorized by visibility and depth of accumulation. Snowfall's intensity is determined by visibility, as follows [Snow]:
1. *Light snow*: visibility greater than 1 km (0.6 mi);
2. *Moderate snow*: visibility restrictions between 0.5 and 1 km (0.3 and 0.6 mi); and
3. *Heavy snow*: visibility is less than 0.5 km (0.3 mi).

7.1.5 Atmospheric Obscuration

Atmospheric obscurations, other than precipitation, that reduce visibility include (METAR acronyms are given in parentheses):

1. *fog* (FG);
2. *mist* (BR);
3. *haze* (HZ);
4. *smoke* (FU);
5. *fog and smoke (smog)*;
6. *dust or sand whirls* (PO);
7. *widespread dust* (DU);
8. *sandstorm* (SS); and
9. *spray* (PY).

Fog consists of visible cloud water droplets or ice crystals suspended in the air at or near the Earth's surface [Gul07]. Fog can be considered a type of low-lying cloud and is heavily influenced by nearby bodies of water, topography, and wind conditions. There are many types of fogs depending on the cooling process causing the condensation and topography, including radiation fog, ground fog, advection fog, evaporation fog, ice fog, freezing fog, precipitation fog, hail fog, and unslope fog [Fog].

The international definition of fog is a visibility of less than 1 km (3,300 ft); mist is a visibility of between 1 km (0.62 mi) and 2 km (1.2 mi) and haze from 2 km (1.2 mi) to 5 km (3.1 mi) [Fog].

Shadows in fog are cast in three dimensions.

Spray consists tiny water droplets blown or driven through the air, which may occur near bodies of water in strong winds. *Tire spray* occurs when vehicle tires roll over wet roadway. Large vehicles such as tractor-trailers may produce very significant spray.

7.2 Lighting Conditions

Lighting conditions differ by night and day, season, weather, and potential obstructions, such as tall buildings and vegetation at the roadside.

Daylight is present at a particular location, to some degree, whenever the sun is above the horizon at that location [DL]. The *sun location* can be specified by its

1. *azimuth* and
2. *elevation*.

Table 4 specifies the intensity of daylight illumination in different conditions.

Table 4 Intensity of daylight illumination in different conditions [DL]

Illuminance	Example
120,000 lux	Brightest sunlight
111,000 lux	Bright sunlight
20,000 lux	Shade illuminated by entire clear blue sky, midday
1,000 - 2,000 lux	Typical overcast day, midday
<200 lux	Extreme of darkest storm clouds, midday
400 lux	Sunrise or sunset on a clear day (ambient illumination)
40 lux	Fully overcast, sunset/sunrise
<1 lux	Extreme of darkest storm clouds, sunset/rise

Table 5 specifies nighttime illumination from natural sources.

Table 5 Intensity of natural illumination at nighttime [DL]

Illuminance	Example
<1 lux	Moonlight
0.25 lux	Full Moon on a clear night
0.01 lux	Quarter Moon
0.002 lux	Starlight clear moonless night sky including airglow
0.0002 lux	Starlight clear moonless night sky excluding airglow
0.00014 lux	Venus at brightest
0.0001 lux	Starlight overcast moonless night sky

Table 6 specifies the recommended street light illumination at urban intersections.

Table 6 Recommended illuminance for the intersections of continuously lighted urban roads [TAC06]

Functional Classification	Average maintained illumination at pavement by pedestrian area classification (lux)		
	High	Medium	Low
Major/major	34	26	18
Major/collector	29	22	15
Major/local	26	20	13
Collector/collector	24	18	12
Collector/local	21	16	10
Local/local	18	14	8

Note: Pedestrian area classification by pedestrian conflict, defined as the total number of people on both sides of the street within a given section (200 meters): Low = 10 or fewer pedestrians (residential); Medium = 11 to 100 (schools, recreation centers); High => 100 (restaurants, shopping, theaters).

7.3 Road Surface Conditions

General *roads surface conditions* include accumulation of precipitation; contamination, such as oil, salt, sand, mud, and leaves; and surface texture and damage (see Section on Road Surface in Part 1).

This section focuses on weather-related road surface conditions that impact the skid factor.

An important road surface conditions parameter is *pavement temperature*.

The Transportation Association of Canada (TAC) has defined a road surface condition (RCS) classification with the following categories [TAC11]:

1. *Bare and dry*;
2. *Bare and wet*;
3. *Partly icy*;
4. *Partly snow packed*;
5. *Partly snow covered*;
6. *Snow covered*;
7. *Snow packed*; and
8. *Ice covered*.

Figure 12 defines each of these categories. The combination of partly snow packed and partly icy is sometimes referred to as “slushy”. Another snow-related feature is the presence of *drifted sections* of the road due to *blowing snow*.

In winter, road surface has *winter maintenance status*:

1. untreated;
2. plowed;
3. sanded;
4. salted;
5. salted and sanded.

Fu et al. define a *Relative Risk Index* (RRI), which captures the increased crash risk based on environmental conditions, including pavement temperature, visibility, wind, precipitation, and the road surface condition [FTK17].

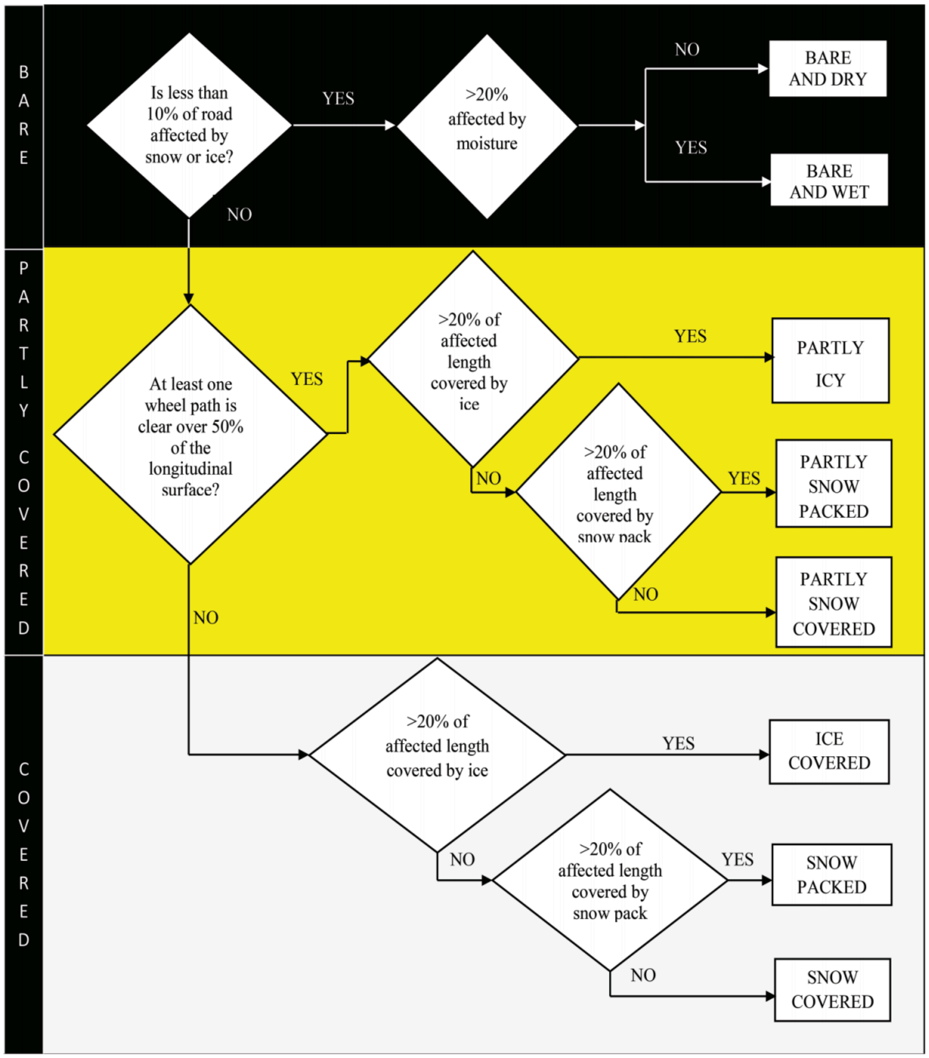

Figure 12 Road surface condition classification scheme [TAC11] (Figure 1 from [FTK17])

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