WISE Requirements Analysis Framework for Automated Driving Systems

Automated Driving System (ADS) High-Level Quality Requirements Analysis

Driving Behavior Safety

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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	*Contributor(s)*
January 5, 2018 Version 1.0 created	Krzysztof Czarnecki[1]
July 21, 2018 Version 1.1 (with minor editorial changes) published	Krzysztof Czarnecki[1]

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Abstract

This document analyzes safety requirements on driving behavior for ADS-operated vehicles, both at operational and tactical levels. The first part of the document describes motor-vehicle crash typology and pre-crash scenarios based on existing traffic safety data and literature. The second part proposes a classification of safety requirements on driving behavior into five categories: vehicle stability, assured clear distance ahead, minimum separation, traffic regulations, and best practices, and presents safety requirements on driving behavior for ADS-operated vehicles derived from human driving.

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1. Scope

This document analyzes *high-level safety requirements on driving behavior*, both at operational and tactical levels, as part of the WISE Requirements Analysis Framework for Automated Driving Systems. In particular, these requirements apply to the basic motion control tasks and maneuvers defined in companion documents [BM18, M18]. The companion documents refine the high-level safety requirements as part of the detailed analysis of the basic motion control tasks and maneuvers.

The objective of the high-level safety requirements is to ensure *driving behavior safety*, which is a key aspect of on-road safety of an Automated Driving System (ADS) [ST18]:

> *Driving behavior safety* of an ADS is the absence of unreasonable risk from transport crashes due to hazards caused by deficiencies in the specified driving behavior of the ADS-operated subject vehicle in-transport.

The high-level safety requirements on driving behavior are concerned both with the behaviors that need to be executed in a given situation and the performance level of their execution. For example, an ADS should avoid an avoidable crash by (1) applying an appropriate emergency maneuver (driving behavior), such as emergency braking or evasive steering, and (2) executing the maneuver with adequate performance that takes road friction, scene configuration, and other relevant conditions into account. Driving behavior safety is part of the more general on-road safety of ADS, which is discussed elsewhere [ST18].

The presented analysis is limited to the driving behavior of an ADS-operated *passenger vehicle*, as opposed to other types of vehicles. The analysis focuses on the safety of the vehicle behavior in traffic rather than the ADS control inputs to the vehicle. However, Object Detection, Evaluation, and Response (OEDR) functions [LA], even if they sometimes are exhibited only at the level of the ADS and do not trigger an externally visible driving behavior, are still part of the safety analysis. For example, the ADS should monitor a pedestrian close to the edge of the road even if no change to the vehicle movement may be necessary.

The document starts with a review of different types of crashes and pre-crash scenarios to define loss events in scope of this analysis and the key factors that lead to these events. This review draws on literature and standards analyzing historical crash records that involved human drivers; however, the reviewed types of crashes apply to both human- and ADS-operated vehicles. While not representing actual ADS mistakes and behaviors in the field, the pre-crash scenarios and factors do represent mistakes and behaviors of human road users that lead to crashes in the past. ADS designed to operate vehicles that interact with human road users must be cognizant of these human road user errors and behaviors. While new behaviors in the interaction between ADS-operated vehicles and human-road users will likely emerge, the pre-crash scenario analysis provides a starting point to inform the initial design. Deployments of ADS-operated vehicle fleets will provide data that is more directly applicable to ADS-operated vehicles in future.

Subsequently and as its main part, the document identifies and discusses in detail five categories of high-level safety requirements on driving behavior and performance:

1. *Vehicle stability;*
2. *Assured clear distance ahead;*
3. *Minimum separation;*
4. *Safety-relevant traffic regulations (formal traffic rules);* and
5. *Safety-relevant driving best practices (informal traffic rules).*

2. Crash Typology and Factors

A *crash* is an unstabilized situation that involves a transport vehicle in-transport and includes at least one harmful event [ANSI]. Crashes in scope of this analysis include motor vehicle crashes and railway crashes that involve a motor vehicle. The current version of this document focuses on motor vehicle crashes.

The Model Minimum Uniform Crash Criteria (MMUCC) [CC] and General Estimates Systems (GES) [GES] define crash description schemas to be used by reporters, classifiers, analysts and users of traffic accident data in the United States. Table 1 gives the MMUCC classification of crashes according to the first harmful event.

Table 1 MMUCC classification of crashes according to the first harmful event [CC]

Noncollision	Collision	
	With Person, Motor Vehicle, or Non-Fixed Object	**Collision With Fixed Object**
• Overturn/Rollover • Fire/Explosion • Immersion, Full or Partial • Jackknife • Cargo/Equipment Loss or Shift • Fell/Jumped From Motor Vehicle • Thrown or Falling Object • Pavement Surface Irregularity (ruts, potholes, sinkholes, grates, etc.) • Gas Inhalation • Other Noncollision	• Pedestrian • Pedalcycle • Other Non-motorist (e.g., occupant of vehicle not in-transport, horseback rider) • Railway Vehicle (train, engine) • Animal (live) • Motor Vehicle in-Transport • Parked Motor Vehicle • Struck by Falling, Shifting Cargo or Anything Set in Motion by Motor Vehicle • Work Zone / Maintenance Equipment • Other Non-Fixed Object	• Impact Attenuator / Crash Cushion • Bridge Overhead Structure • Bridge Pier or Support • Bridge Rail • Cable Barrier • Culvert • Curb • Ditch • Embankment • Guardrail Face • Guardrail End • Concrete Traffic Barrier • Other Traffic Barrier • Tree (standing) • Utility Pole/Light Support • Traffic Sign Support • Traffic Signal Support • Fence

		• Mailbox • Other Post, Pole or Support • Other Fixed Object (wall, building, tunnel, etc.)

The MMUCC and GES classification schemata define the following set of factors relevant to a crash:

1. *Driving environment factors*:
    a. *Location of first harmful event*: on roadway, shoulder, median, roadside, parking zone, outside right-of-way, etc.;
    b. *Atmospheric conditions*: general atmospheric conditions at the time of the crash (temperature, visibility, wind, clouds, precipitation, other obscuration; see [REO2]);
    c. *Lighting conditions*: general light conditions at the time of the crash, including light from external roadway illumination fixtures, potential glare (see [REO2]);
    d. *Roadway surface conditions*: condition of road surface at the time of the crash (see [REO2]);
    e. *Road structure*: road functional classification and land use, horizontal roadway alignment (tangent or curve), vertical roadway alignment (level, downhill, uphill, crest, or sag), relation to junction, roadside structure, posted speed limit, traffic control devices, etc. (see [REO1]);
    f. *Temporary road structure*: temporary redesign of the road structure to accommodate temporary conditions such as construction, special events, and unplanned events (see [REO1]);
    g. *Traffic conditions*: traffic volume, backup due to prior crash, prior non-recurring incident, or regular congestion;
    h. *Obstructions in the roadway*: parked vehicles, animals, debris, and other obstructions in the roadway (see [REO2]);
2. *Vehicle factors*:
    a) *Vehicle contributing factors*: vehicle factors that may have contributed to the cause of the crash, e.g., tires, brakes, steering, powertrain, suspension, lights, mirrors, wipers, etc.;
    b) *Rollover type*: tripped or untripped;
    c) *Movement prior to critical event*: a maneuver performed prior to critical event, including no driver present, going straight, decelerating in traffic lane, accelerating in traffic lane, starting in traffic lane, stopped in traffic lane, passing another vehicle, parked in travel lane, leaving a parked position, entering a parked position, turning right, turning left, making U-turn, backing up, negotiating a curve, changing lanes, and merging;

d) *Driver maneuvered to avoid*: an action taken by the driver to avoid something or someone in the road, which may have subsequently contributed to the cause of the crash, including avoiding object in road, poor road conditions, animal in road, vehicle in road, non-motorist in road, hit & run, phantom vehicle, other avoidance maneuver, and no driver present;

e) *Corrective action attempted*: are avoidance maneuver taken by the driver of the vehicle in response to the impending danger within the critical crash envelope, including no avoidance maneuver; braking; releasing brakes; steering; braking and steering; accelerating; accelerating and steering; no driver present;

3. *Driver factors*:
   a. *Driver's vision obscured*: visual circumstances that may have contributed to the cause of the crash;
   b. *Driver distracted*: a distraction inside or outside the vehicle that may have influenced driver performance and contributed to the cause of the crash; sources of internal distraction include: manually operating electronic devices, talking on electronic hands-free devices, passengers, eating, personal hygiene; outside distractions include unplanned events, such as prior accidents, and scenic or unusual view;
   c. *Speed related*: indicates whether speed is a contributing factor to the cause of the crash; speed-related factors include: exceeded speed limit, too fast for conditions, and racing;
   d. *Contributing actions (including violations charged)*: failed to yield right of way; ran off roadway; ran red light; ran stop sign; disregard for other traffic sign; disregard for other road marking; improper turn; improper backing; improper passing; wrong side or wrong way; followed too closely; failed to keep in proper lane; operated vehicle in reckless or aggressive manner; operated vehicle in inattentive, careless, negligent, or erratic manner; swerved or avoided due to wind, slippery surface, motor vehicle, object, non-motorist in roadway, animal, etc.; over-correcting/over-steering;
   e. *Driver's physical and mental condition*: any relevant condition of the individual that is directly related to the crash, including physical impairment, emotional state (depressed, angry, disturbed, etc.), being ill (sick), fainted, asleep or fatigued, and under the influence of medications, drugs, or alcohol;
   f. *Sex*: male or female;
   g. *Age*: drivers of age 24 or younger classify as younger drivers; drivers between the ages of 25 and 64 are classified as middle-aged drivers, and drivers of age 65 or older are classified as older drivers;
   h. *Driver license jurisdiction*: not licensed / suspended / revoked / expired / canceled / denied; license class; local to province / state, other province / state, North America, or international.
4. *In-transport vehicle occupant factors*:
   a. *Seating position*;

   b. *Use of restraint systems*;
   c. *Airbag deployment*;
   d. *Possible ejection on impact*;
5. *Non-motorist (pedestrian, cyclist, animal rider, etc.) factors*:
   a. *Non-motorist action*: crossing roadway, waiting to cross roadway, walking/cycling along roadway with or against traffic (in or adjacent to travel lane), walking/cycling on sidewalk, in roadway (child playing, persons accessing parked vehicle, mechanic working on a disabled vehicle, etc.), adjacent to roadway (e.g., shoulder, median), working in trafficway (incident response, road construction, etc.)
   b. *Contributing factors*: no improper action; dart/dash on the roadway; failure to yield right-of-way; failure to obey traffic signs, signals, or officer; in roadway improperly (standing, lying, working, playing); disabled vehicle related (working on, pushing, leaving/approaching); entering/exiting parked/standing vehicle; inattentive (talking, eating, using electronic communication devices, etc.); not visible (dark clothing, no lighting, etc.); improper turn/merge; improper passing; wrong-way riding or walking;
   c. *Person's physical and mental condition*: any relevant condition of the individual that is directly related to the crash, including physical impairment, emotional state (depressed, angry, disturbed, etc.), being ill (sick), fainted, asleep or fatigued, and under the influence of medications, drugs, or alcohol;
   d. *Non-motorist location at time of crash*: intersection – marked crosswalk; intersection – unmarked Crosswalk; intersection – other location; midblock – marked crosswalk; travel lane – other location; bicycle lane; shoulder; roadside; sidewalk; median/crossing Island; driveway access; shared-use path or trail; outside of right-of-way.

Road users may be involved in a crash *directly* or *indirectly*. Direct involvement of a user implies being part of at least one of the loss events, such as suffering an injury or coming into contact with an injured road user. In particular, colliding road users are directly involved in the collision. ANSI D-16.1-2007 defines vehicles that are directly involved in an accident as "contact vehicles" [ANSI]. An example of an indirectly involved vehicle would be one that brakes suddenly and causes a following vehicle to perform an evasive maneuver and to subsequently crash into a drainage channel or oncoming traffic. Another example would be a vehicle travelling with its high-beam headlights on at night and blinding a driver of an oncoming vehicle in the opposite lane and this way contributing to a collision between the oncoming vehicle and a pedestrian walking along the shoulder of the opposite lane.

The types of crashes in scope of this analysis are primarily rollovers and collisions. Noncollisions other than rollovers include immersion (such as driving into flooded road, or a body of water), fire (either internal vehicle fire or being trapped in outside fire), being struck by falling or thrown objects (rocks, trees, etc.), impact due to pavement surface irregularity (ruts, potholes, sinkholes, grates, etc.), and an occupant falling out of a moving vehicle (this does not include an occupant being ejected from a vehicle as a result of a collision).

Rollover is a type of crash where a vehicle rotates at least one quarter turn in any nonhorizontal direction [GES]. The corresponding term for motorcycles *overturn*. Rollovers have a higher fatality rate than other types of crashes [Deu02]. In 2000, only 3% of all passenger vehicles involved in crashes were rollovers, but rollovers accounted for 20% of passenger vehicles involved in fatal crashes. *Untripped rollovers* occur when excessive cornering forces destabilize the vehicle, as a result of steering input, speed, and road-tire friction. *Tripped rollovers* are caused by forces from external objects, such as hitting a curb or colliding with another vehicle or a ravine.

Collisions are classified a *single-vehicle*, *two-vehicle*, or *multi-vehicle collisions* depending on the number of contact vehicles involved. Collisions may also include one or more *non-motorists*, i.e., pedestrian, cyclist, animal rider, occupants of vehicles not in-transport (such as legally parked vehicles), or persons outside the trafficway. Single vehicle collisions may be between a vehicle and one or more non-motorists, or between a single vehicle and other objects (see Table 1). Important factors are the type of vehicles colliding, such as the involvement of trucks, and potentially hazardous cargo, the relative speed at impact, and the absolute speed of each road user.

The vast majority of crashes occurring in North America are single- and two-vehicle crashes. Figure 1 shows an analysis of crashes recorded in the 2004 General Estimates System (GES) crash database, which includes 6,170,000 police-reported crashes of all vehicle types that occurred in the United States in 2004. These crashes involved 10,945,000 vehicles.

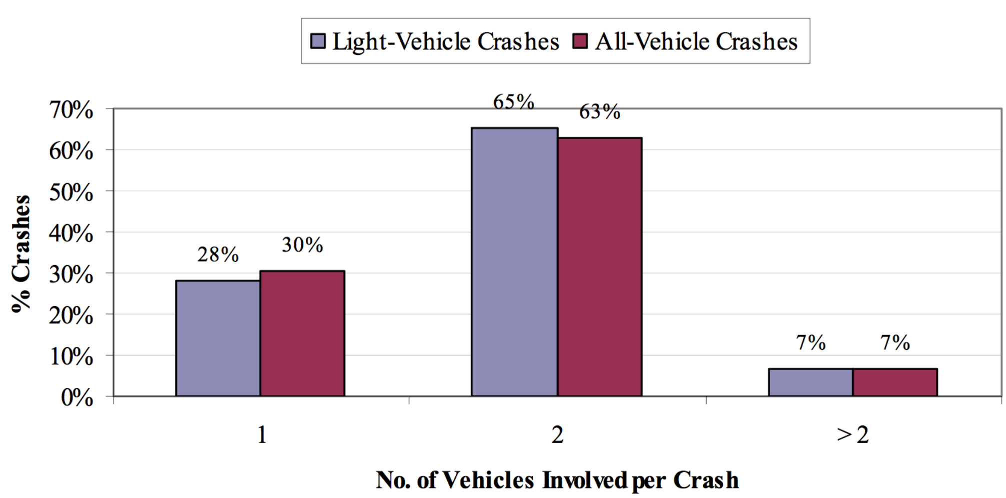


Figure 1 Distribution of light-vehicle and all-vehicle crashes by number of vehicles involved per crash (Figure 1 from [NSY07])

A crash may involve multiple harmful events. The most harmful event may or may not be the first one. For example, the first harmful event in a road departure may be a collision with a curb, which subsequently triggers a rollover at the roadside. Note that road departure is not listed Table 1 since a road departure per se does not imply a harmful event. Road departure may be subsequent to another harmful event, such as a collision with a vehicle in a roadway, or a road departure may lead to harmful events, such as striking pedestrians or infrastructure at the roadside and rollover. In the rare case where there is no curb and the road is adjacent to a flat and drivable surface, a road departure may not lead to any harmful event.

Two-vehicle collisions are characterized by the *impact configuration*. This factor is applicable to both collisions between motor vehicle and a motor vehicle and a pedalcycle. The impact configuration may be one of the following (Figure 2):

1. *Front-to-rear*,
2. *Front-to-front* (*head-on*),
3. *Angle* (includes *front-to-side*),
4. *Sideswipe* in same or opposite direction,
5. *Rear-to-side*, and
6. *Rear-to-rear*.

Each of these impact configuration types may show a different degree of overlap in terms how the colliding vehicles are aligned (Figure 2).

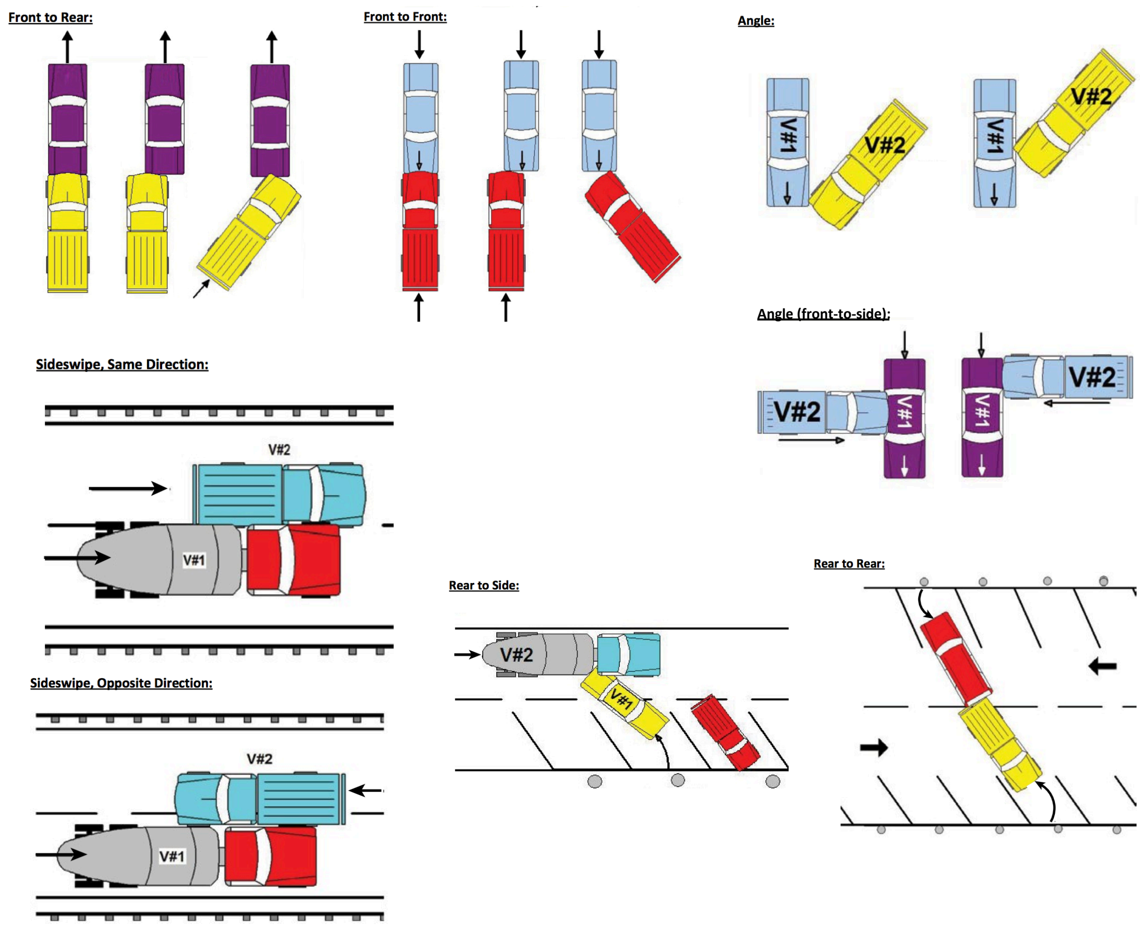


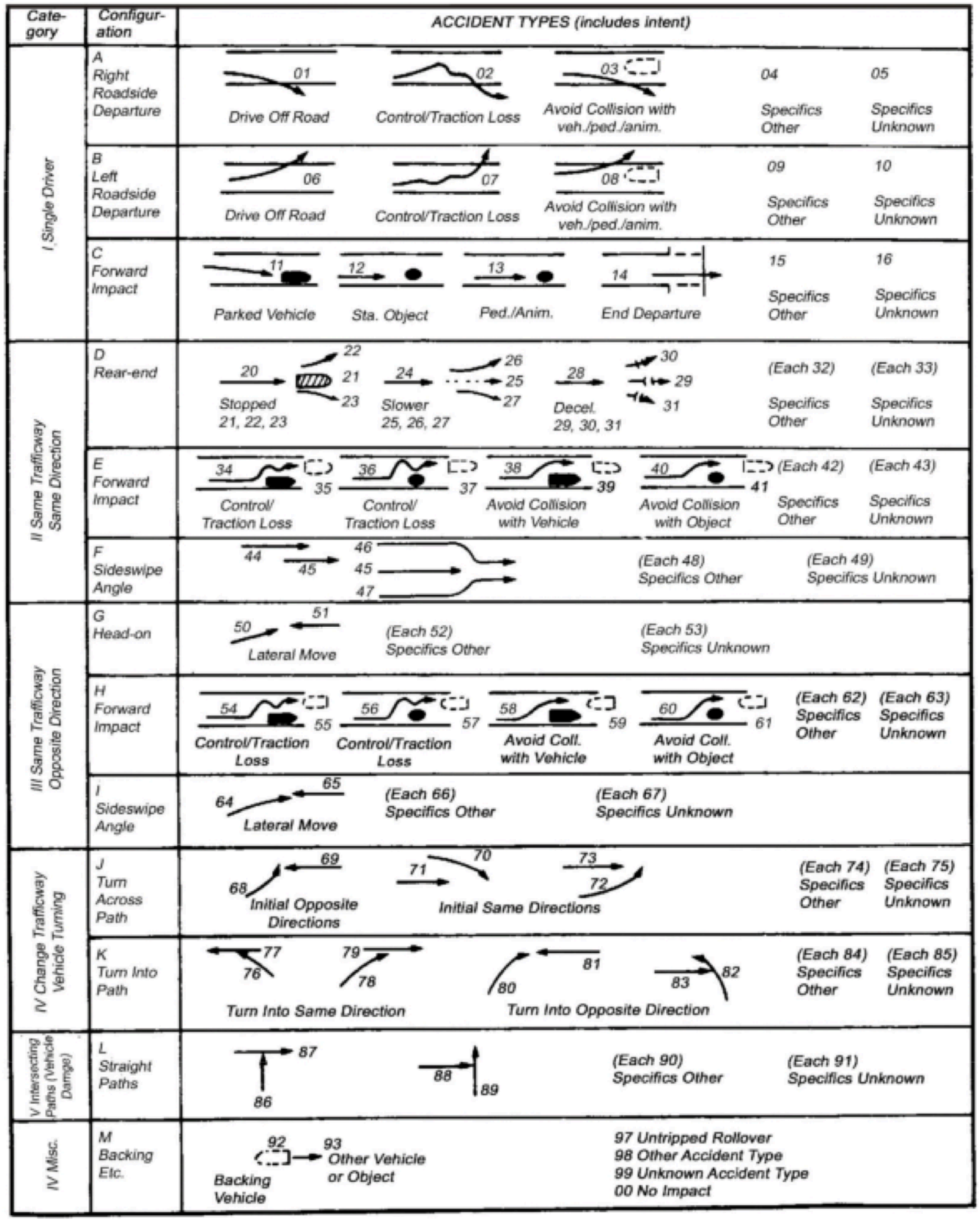
Figure 2 Impact configuration for two-vehicle collisions (Appendix F in [CC])

For a collision between a motor vehicle and a pedestrian, the following impact configurations are possible:

1. *Front*: vehicle driving forward and striking a pedestrian; depending on the position of the pedestrian, it may be front or front left or front right corner;
2. *Side*: vehicle is turning or sliding out of control and striking a pedestrian with one of its sides; and
3. *Rear*: vehicle is backing and striking a pedestrian.

The discussion so far shows that a crash is highly complex and multidimensional process with a multitude of factors. The GES coding scheme provides an overall *crash type* classification based on the first harmful event, impact configuration of participating road users, road configuration, and maneuver performed prior to the crash (Table 2; see [GES] for a detail description of each crash type).

Table 2 NHTSA GES Crash Types [GES]



3. Crash Severity

Crash situations have associated *crash severity*, which assesses the level of losses resulting from the crash. In general, losses include personal injury or death or property damage. Assessing severity in practice is usually a complex matter. In addition to direct injuries and deaths occurring in a crash, consequences of crash to human health and life may reach far beyond the crash occurrence. For example, a crash may cause an undiagnosed aneurysm in the brain of a person involved in the crash, which may lead to a sudden brain hemorrhage and the person's disability or death years after the crash. Similarly, in addition to direct property losses, such as vehicle and infrastructure damage, and indirect economic losses, such as impact on employment and productivity, there are also non-economic losses, such as reduced quality of life.

ISO 26262 considers only the risk of personal injury, which includes non-fatal and fatal injuries (deaths), and provides guidance on the use of different injury severity scores, such as the five-level Abbreviated Injury Scale (AIS). The AIS is maintained by the Association for the Advancement of Automotive Medicine (AAAM), which defines a classification guide with examples for each of the seven AIS levels [AIS15]:

1. AIS 0: no injuries;
2. AIS 1: light injuries such as skin-deep wounds, muscle pains, whiplash, etc.;
3. AIS 2: moderate injuries such as deep flesh wounds, concussion with up to 15 minutes of unconsciousness, uncomplicated long bone fractures, etc.;
4. AIS 3: severe but not life-threatening injuries such as skull fractures without brain injury, spinal dislocations below the fourth cervical vertebra without damage to the spinal cord, etc.;
5. AIS 4: severe injuries (life-threatening, survival probable) such as concussion with up to 12 hours of unconsciousness, paradoxical breathing;
6. AIS 5: critical injuries (life-threatening, survival uncertain) such as spinal fractures below the fourth cervical vertebra with damage to the spinal cord, intestinal tears, cardiac tears;
7. AIS 6: extremely critical or fatal injuries such as fractures of the cervical vertebrae above the third cervical vertebra with damage to the spinal cord, extremely critical open wounds of body cavities.

AIS classifies single injuries to a person; in the case of multiple injuries to a person, Maximum AIS (MAIS) and Injury Severity Index (ISI) [BOH74, BOM00] may be used.

Crash statistic can be used to determine the distribution of injuries that can be expected to occur in different crashes, e.g., [Kwe11, Abd17, YPA08, GBA14]. Physical parameters of crashes can be used to derive a statistical fit with the injury distribution. For example, the *Delta-V metric*, which is the change of a velocity vector experienced by a road user during a crash [LDK17], can be used to estimate the injury severity of an occupant in frontal crashes [GG08, KG12]. Impact point and impact angle are other relevant crash parameters that affect collision severity. For road departures and rollovers, the key parameters are vehicle speed and terrain structure at the crash site. Rollovers are the most injurious types of accidents compared to any other accidents [CK05]. An analysis of historical rollover data showed that occupant injury level correlated with the number of roof impacts, but also impact with fixed objects prior rollover, rollovers stopped by an impact with a fixed object, and failing to wear seatbelts were significant factors [DE04].

ISO 26262 provides a four-level severity classification of hazards, and specifically, crash types (see Table B.1 in [FuS]). The classification sets bounds on AIS levels and probability of occurrence of injuries at these levels. S0 corresponds to A0 and less than 10% probability of AIS 1-6. S1 corresponds to more than 10% probability of

AIS 1-6 (and not S2 or S3). S2 corresponds to more than 10% probability of AIS 3-6 (and not S3). S3 corresponds to more than 10% probability of AIS 5-6. Table B.1 in [FuS] provides examples of crash types for each severity class.

The GES crash database does not use the AIS scheme for severity, but instead uses the KABCO scale from police crash reports [NSY07]. KABCO classifies crash victims as K – killed, A – incapacitating injury, B – non-incapacitating injury, C – possible injury, O – no apparent injury, or ISU – Injury Severity Unknown. The KABCO coding scheme allows non-medically trained persons to make on-scene injury assessments without a hands-on examination, but is less precise than the AIS scheme.

Table 5 gives the ratios of people involved by maximum injury severity between light-vehicle crashes and all-vehicle crashes using the KABCO and AIS injury scales [NSY07]. The data summarizes the injuries recorded in the 2004 General Estimates System (GES) crash database. The 6,170,000 police-reported crashes of all vehicle types that occurred in the United States in 2004 involved a total of 15,342,000 people. About 2,819,000, or 18.4 percent of involved people were injured. "Died Prior" listed in the KABCO injury scale is indicated in police reports if the person died prior to the crash as a result of natural causes (e.g., heart attack), disease, drug overdose, or alcohol poisoning. About 0.02 percent of the involved people were fatally injured.

Table 3 Ratio of people involved in crashes in 2004 in the U.S. suffering an injury of a given severity (Table 5 in [NSY07])

Injury Severity		Light-Vehicle Crashes	All-Vehicle Crashes	Light/All
KABCO Injury Scale	None	0.8179	0.8163	1.00
	Possible	0.1092	0.1085	1.01
	Non-incapacitating	0.0482	0.0495	0.97
	Incapacitating	0.0192	0.0201	0.95
	Fatal	0.0018	0.0020	0.92
	Unknown	0.0037	0.0037	1.00
	Died prior	0.000025	0.000024	1.02
	Sum	1.0000	1.0000	
AIS Injury Scale	None	0.7806	0.7791	1.00
	Minor	0.1886	0.1894	1.00
	Moderate	0.0210	0.0214	0.98
	Serious	0.0067	0.0069	0.97
	Severe	0.0008	0.0009	0.97
	Critical	0.00040	0.00041	0.96
	Fatal	0.0018	0.0020	0.92
	Sum	1.0000	1.0000	
	Injured people per crash	0.555	0.549	1.01

A crash may result in multiple individuals injured and a range of property losses. It may be possible to meaningfully aggregate different losses by their kind and severity. For example, aggregate loss from a crash could be characterized by stating the number of individuals suffering injuries at each of the seven MAIS levels and the total value of property damage. In that case, the risk of a given crash type would be the joint probability distribution over these eight random variables. For some applications, such as comparing the severity of different crash types across road-network locations using summary statistics, all losses can be combined using the loss value method, which computes a total loss as a weighted sum of individual losses [CK05]. In essence, the method assigns specific monetary cost to each injury type and property damage. For example, the NHTSA pre-crash scenario analysis [NSY07] uses the following conversion from MAIS injury level per person to a U.S. dollar value to compute economic losses from motor vehicle crashes.

Table 4 MAIS Levels and Unit Costs in 2000 Dollars (Table 3 in [NSY07])

MAIS	Severity	2000 $
0	Uninjured	1,962
1	Minor	10,562
2	Moderate	66,820
3	Serious	186,097
4	Severe	348,133
5	Critical	1,096,161
6	Fatal	977,208

A method to measure non-economic losses involves summing up *functional years lost*, that is, the years of life lost to fatal injury and the years of functional capacity lost to nonfatal injury [NSY07]. Table 5 shows a mapping from MAIS levels to functional years lost.

Table 5 Functional years lost by MAIS per-unit basis (Table 4 in [NSY07])

MAIS	Severity	Functional Years Lost
1	Minor	0.07
2	Moderate	1.1
3	Serious	6.5
4	Severe	16.5
5	Critical	33.1
6	Fatal	42.7

4. Pre-Crash Scenarios and Crash Factors

Important factors contributing to a crash can be summarized as follows [NSY07]:

1. *Location*: road structure and location prior to crash;
2. *Pre-crash scenario*: depiction of vehicle movements and dynamics as well as the critical event occurring immediately prior to a crash;
3. *Driving condition*: lighting, atmospheric, and road surface conditions
4. *Travel speed*: low speed (0-30 km/h), moderate speed (30-60 km/h) vs. high speed (> 60 km/h);

5. *Driver condition*: driving error (recognition, decision, erratic); physiological impairment.

The National Highway Traffic Safety Administration (NHTSA) published a series of studies analyzing the pre-crash scenarios, their dynamic variations, and the causal and contributing factors of crashes recorded in the GES crash database. While these crashes involve human drivers only, the insights from these studies are also relevant to ADS-operated vehicles. Most importantly, ADS-operated vehicles will interact with human road users and must account for the errors of these users in traffic.

4.1 NHTSA's 36 Pre-Crash Scenario Catalog

The initial NHTSA study developed a pre-crash typology based on 2004 GES crash data, identifying 36 pre-crash scenarios that account for 99.4% of all the crashes [NSY07]. Later studies updated the analysis covering a longer period (2004-2008) and providing a more detailed summary of pre-crash scenarios for light vehicles [NRS13, NTB13, TSN13], heavy vehicles [TSN14], and pedestrians [SYN16].

Table 6 lists the 36 pre-crash scenarios, including a description and a mapping to the GES crash types. Tables 7 and 8 provide the frequency and the severity in terms of functional years lost, respectively, of each pre-crash scenario based on the GES 2004 crash data.

Table 6 NHTSA pre-crash scenario typology (summary based on [NSY07]); the 36 pre-crash scenario typology (that is, excluding the "other scenario") covers for 99.4% of all light-vehicle crashes

No.	Pre-Crash Scenario	Description	Crash Type
1	Vehicle Failure	Vehicle looses control due to catastrophic component failure and comes off road. Failure of tires, brakes, power train, steering system, and wheels contributed to about 95 percent of these crashes, with tires alone accounting for 62 percent of vehicle failure crashes. High-speed road, young driver, and rollover are overrepresented.	Run-off-road
2	Control Loss with Prior Vehicle Action	Vehicle is performing a maneuver, such as a turn, and loses control due to slippery road and comes off road. Dark, adverse weather, high-speed road, speeding, young driver, rollover are overrepresented.	
3	Control Loss without Prior	Vehicle is going straight and loses control due to slippery road and comes off road.	

	Vehicle Action	Dark, adverse weather, high-speed road, speeding, young driver, rollover are overrepresented.	
4	Running Red Light	Vehicle runs a red light and collides with another crossing vehicle (front-to-side). Inattention, female, young and older drivers are overrepresented.	Crossing paths
5	Running Stop Sign	Vehicle runs a STOP sign and collides with another crossing vehicle (front-to-side, angle, or front-to-rear). Inattention and young and older drivers are overrepresented.	
6	Road Edge Departure with Prior Vehicle Maneuver	Vehicle performs a maneuver, such as a turn or a lane change/pass, typically at night and in good weather conditions, and then departs the edge of the road (speed-related, inattention, alcohol, young driver).	Run-off-road
7	Road Edge Departure without Prior Vehicle Maneuver	Vehicle travels straight, typically at night and in good weather conditions, and then departs the edge of the road (speed-related, inattention, drowsiness, alcohol, young driver).	
8	Road Edge Departure While Backing Up	Vehicle is backing up, typically in daylight and good driving conditions, and then departs the edge of the road on shoulder, driveway, or parking lane (inattention, alcohol, young driver).	
9	Animal Crash with Prior Vehicle Maneuver	Vehicle is performing a maneuver, such as leaving a parked position or passing a vehicle, typically at night, and encounters an animal.	Animal
10	Animal Crash without Prior Vehicle Maneuver	Vehicle is travelling straight, typically at night, and encounters an animal.	
11	Pedestrian Crash with Prior Vehicle Maneuver	Vehicle is performing a maneuver, such as a left turn, typically in daylight, and encounters a pedestrian, typically at crosswalk. The pedestrian is dashing or playing in the roadway in 15% of these crashes.	Pedestrian
12	Pedestrian Crash without Prior Vehicle Maneuver	Vehicle is going straight, typically in daylight, and encounters a pedestrian. The pedestrian is running into the road or improperly crossing in 36% or 26%, respectively, of overall scenario crashes.	

		Darkness, adverse weather, low-speed road are overrepresented.	
13	Pedalcyclist Crash with Prior Vehicle Maneuver	Vehicle is performing a maneuver, such as a turn, typically in daylight, and encounters a pedalcyclist. The pedalcyclist fails to yield the right-of-way and is riding on the wrong side of the road respectively in about 13 and 24 percent of overall scenario crashes.	Pedalcyclist
14	Pedalcyclist Crash without Prior Vehicle Maneuver	Vehicle is travelling straight, typically in daylight, and encounters a pedalcyclist, typically at intersection. The pedalcyclist fails to yield the right-of-way and is riding on the wrong side of the road respectively in about 46 and 6 percent of overall scenario crashes.	
15	Backing Up into Another Vehicle	Vehicle is backing up, typically at a driveway or an alley and in daylight, at collides with another vehicle (rear-to-front/side/rear).	Backing
16	Vehicle(s) Turning – Same Direction	Vehicle is turning at an intersection and cuts across the path of another vehicle initially travelling in the same direction in an adjacent lane. Younger drivers are overrepresented.	Lane change
17	Vehicle(s) Parking – Same Direction	Vehicle is leaving a parked position, typically in daylight and clear weather, and encounters another vehicle travelling in the same direction. Adverse weather, inattention, and younger drivers are overrepresented.	
18	Vehicle(s) Changing Lanes – Same Direction	Vehicle is changing lane, typically in daylight and clear weather, and encounters another vehicle traveling in the same direction. High-speed road, inattention and younger drivers are overrepresented.	
19	Vehicle(s) Drifting – Same Direction	Vehicle is travelling straight, typically in daylight and clear weather, and then drifts into an adjacent vehicle traveling into the same direction. Speeding and young drivers are overrepresented.	
20	Vehicle(s) Making a Maneuver – Opposite Direction	Vehicle is passing another vehicle, typically in daylight and clear weather, and encroaches into another vehicle	Opposite direction

		travelling in the opposite direction. Dark, adverse weather, high-speed, speeding, male, inattention, and young drivers are overrepresented.	
21	Vehicle(s) Not Making a Maneuver – Opposite Direction	Vehicle is going straight or negotiating a curve and then drifts and encroaches into another vehicle traveling in the opposite direction. Dark, adverse weather, non-level road, alcohol, male, and younger drivers are overrepresented.	
22	Following Vehicle Making a Maneuver	Vehicle is changing lanes or passing or making a turn, typically in daylight and clear weather, and closes on a lead vehicle. Inattention, speeding, young drivers are overrepresented.	Rear-end
23	Lead Vehicle Accelerating	Vehicle going straight, typically in daylight and clear weather and an intersection-related location, and closes in (too fast) on an accelerating lead vehicle. Traffic signal, starting in traffic lane, inattention, speeding female, and young drivers are overrepresented.	
24	Lead Vehicle Moving at Lower Constant Speed	Vehicle going straight, typically in daylight and clear weather, and closes in on a lead vehicle moving at lower constant speed. Inattention, speeding, and young drivers are overrepresented.	
25	Lead Vehicle Decelerating	Vehicle going straight and following another vehicle, typically in daylight and clear weather, and the lead vehicle suddenly decelerates. Daylight, adverse weather, rural area, intersection-related, high-speed road, inattention, speeding, and younger driver are overrepresented.	
26	Lead Vehicle Stopped	Vehicle going straight, typically in daylight and clear weather, and closes in on a stopped lead vehicle. Intersection-related, inattention, speeding, and young drivers are overrepresented. In about 50% of these crashes, the lead vehicle first decelerates to a stop, typically in the presence of a traffic control device or to make a turn, and is struck afterwards by the following vehicle.	
27	Left Turn across	Vehicle is turning left, typically in daylight	Crossing

	Path from Opposite Directions (LTAP/OD) at Signalized Intersections	and clear weather, at a signalized intersection and cuts across the path of another vehicle straight crossing from an opposite direction. Intersection, low-speed road, vision obscured, inattention, female, and younger driver are over-represented.	paths
28	Vehicle Turning Right at Signalized Intersections	Vehicle is turning right, typically in daylight and clear weather, at a signalized intersection and turns into the same direction of another vehicle crossing straight initially from a lateral direction. Adverse weather, low-speed road, vision obscured, and younger and older drivers are over-represented.	
29	Left Turn across Path from Opposite Directions (LTAP/OD) at Non-Signalized Intersections	Vehicle is turning left, typically in daylight and clear weather, at an intersection without traffic controls and then cuts across the path of another vehicle traveling from the opposite direction. Vision obscured, inattention, and younger and older drivers are overrepresented.	
30	Straight Crossing Paths at Non-Signalized Intersections	Vehicle stops at a stop sign, typically in daylight and clear weather, at an intersection and then proceeds against lateral crossing traffic. Vision obscured, female, and younger and older drivers are over-represented.	
31	Vehicle(s) Turning at Non-Signalized Intersections	Vehicle stops at a stop sign, typically in daylight and clear weather, at an intersection and proceeds to turn left against lateral crossing traffic. Low-speed road, vision obscured, inattention, female, and younger and older drivers are over-represented.	
32	Evasive Action with Prior Vehicle Maneuver	Vehicle is turning, passing, or changing lanes, typically in daylight and clear weather, and then takes an evasive maneuver to avoid an obstacle. Dark, intersection-related location, and younger driver are over- represented.	Run-off-road
33	Evasive Action without Prior Vehicle Maneuver	Vehicle is going straight, typically in daylight and clear weather, and takes an evasive action to avoid an obstacle. Driveway/alley and younger driver are	

		over-represented.	
34	Non-Collision Incident	Vehicle is going straight, typically in daylight and clear weather. The first harmful events are fire or explosion (26%), pavement surface irregularities such as potholes (13%), injured in vehicle or fell from vehicle (10%), thrown or falling object (7%), and other non-collision events. Moreover, this scenario experiences many vehicle-contributing factors such as trailer hitch (10%), tires (9%), power train (7%), wheels (6%), brakes (2%), body or doors (2%), and exhaust system (1%).	Other
35	Object Crash with Prior Vehicle Maneuver	Vehicle is leaving a parked position, typically at night and in clear weather, and collides with an object on road shoulder or parking lane. The first harmful events are commonly parked motor vehicle (67%) and post, pole, or support (10%). Dark, wet/slippery road, urban area, low-speed road, alcohol, younger driver (71%), and hit-and-run are overrepresented	Object
36	Object Crash without Prior Vehicle Maneuver	Vehicle is going straight, typically at night and in clear weather, and collides with an object on the road. The first harmful events are commonly parked motor vehicle (15%), post, pole, or support (8%), tree (6%), and culvert or ditch (4%).	
37	Other	Other scenarios include on-road rollover, no driver present, hit-and-run, and crash types without any details or specifics.	Other

Table 7 Frequency of the pre-crash scenarios based on 2004 GES crash data (from [NSY07])

No.	Scenario	1-Frequency	Frequency	Rel. Freq.
1	Lead Vehicle Stopped	974,855	975,000	16.41%
2	Control Loss Without Prior Vehicle Action	528,930	529,000	8.90%
3	Vehicle(s) Turning at Non-Signalized Junctions	434,892	435,000	7.32%
4	Lead Vehicle Decelerating	428,067	428,000	7.20%
5	Road Edge Departure Without Prior Vehicle Maneuver	333,706	334,000	5.62%
6	Vehicle(s) Changing Lanes – Same Direction	338,309	338,000	5.69%
7	Animal Crash Without Prior Vehicle Maneuver	305,102	305,000	5.13%
8	Straight Crossing Paths at Non-Signalized Junctions	263,840	264,000	4.44%
9	Running Red Light	253,618	254,000	4.27%
10	Vehicle(s) Turning – Same Direction	221,791	222,000	3.73%
11	LTAP/OD at Signalized Junctions	220,206	220,000	3.71%
12	Lead Vehicle Moving at Lower Constant Speed	209,610	210,000	3.53%
13	LTAP/OD at Non-Signalized Junctions	189,816	190,000	3.19%
14	Backing Up Into Another Vehicle	130,701	131,000	2.20%
15	Vehicle(s) Not Making a Maneuver – Opposite Direction	123,699	124,000	2.08%
16	Control Loss With Prior Vehicle Action	102,617	103,000	1.73%
17	Vehicle(s) Drifting – Same Direction	97,973	98,000	1.65%
18	Following Vehicle Making a Maneuver	85,373	85,000	1.44%
19	Road Edge Departure With Prior Vehicle Maneuver	67,528	68,000	1.14%
20	Road Edge Departure While Backing Up	65,809	66,000	1.11%
21	Object Crash Without Prior Vehicle Maneuver	54,526	55,000	0.92%
22	Evasive Action Without Prior Vehicle Maneuver	56,199	56,000	0.95%
23	Vehicle(s) Parking – Same Direction	48,138	48,000	0.81%
24	Running Stop Sign	48,296	48,000	0.81%
25	Non-Collision Incident	45,910	46,000	0.77%
26	Vehicle Failure	42,147	42,000	0.71%
27	Pedestrian Crash Without Prior Vehicle Maneuver	39,324	39,000	0.66%
28	Vehicle Turning Right at Signalized Junctions	34,951	35,000	0.59%
29	Object Crash With Prior Vehicle Maneuver	30,301	30,000	0.51%
30	Pedalcyclist Crash Without Prior Vehicle Maneuver	24,071	24,000	0.41%
31	Animal Crash With Prior Vehicle Maneuver	23,322	23,000	0.39%
32	Pedalcyclist Crash With Prior Vehicle Maneuver	18,325	18,000	0.31%
33	Pedestrian Crash With Prior Vehicle Maneuver	17,118	17,000	0.29%
34	Lead Vehicle Accelerating	18,722	19,000	0.32%
35	Vehicle(s) Making a Maneuver – Opposite Direction	15,472	15,000	0.26%
36	Evasive Action With Prior Vehicle Maneuver	13,120	13,000	0.22%
37	Other	35,859	36,000	0.60%

Table 8 Severity of the pre-crash scenarios based on 2004 GES crash data (from [NSY07])

No.	Scenario	Years Lost	Rel. Yrs Lost
1	Control Loss Without Prior Vehicle Action	478,000	17.27%
2	Road Edge Departure Without Prior Vehicle Maneuver	270,000	9.76%
3	Lead Vehicle Stopped	240,000	8.69%
4	Vehicle(s) Not Making a Maneuver – Opposite Direction	206,000	7.44%
5	Straight Crossing Paths at Non-Signalized Junctions	174,000	6.29%
6	Pedestrian Crash Without Prior Vehicle Maneuver	144,000	5.21%
7	Vehicle(s) Turning at Non-Signalized Junctions	138,000	5.00%
8	Running Red Light	135,000	4.87%
9	LTAP/OD at Signalized Junctions	121,000	4.36%
10	LTAP/OD at Non-Signalized Junctions	113,000	4.09%
11	Lead Vehicle Decelerating	100,000	3.62%
12	Lead Vehicle Moving at Lower Constant Speed	78,000	2.81%
13	Vehicle(s) Changing Lanes – Same Direction	71,000	2.57%
14	Control Loss With Prior Vehicle Action	49,000	1.76%
15	Vehicle(s) Turning – Same Direction	47,000	1.68%
16	Pedalcyclist Crash Without Prior Vehicle Maneuver	39,000	1.42%
17	Vehicle(s) Drifting – Same Direction	37,000	1.32%
18	Evasive Action Without Prior Vehicle Maneuver	36,000	1.31%
19	Road Edge Departure With Prior Vehicle Maneuver	34,000	1.22%
20	Vehicle(s) Making a Maneuver – Opposite Direction	32,000	1.14%
21	Running Stop Sign	28,000	1.02%
22	Vehicle Failure	26,000	0.93%
23	Pedestrian Crash With Prior Vehicle Maneuver	24,000	0.88%
24	Animal Crash Without Prior Vehicle Maneuver	24,000	0.86%
25	Object Crash Without Prior Vehicle Maneuver	19,000	0.68%
26	Following Vehicle Making a Maneuver	18,000	0.67%
27	Non-Collision Incident	13,000	0.45%
28	Vehicle(s) Parking – Same Direction	11,000	0.41%
29	Pedalcyclist Crash With Prior Vehicle Maneuver	11,000	0.39%
30	Backing Up Into Another Vehicle	9,000	0.32%
31	Road Edge Departure While Backing Up	6,000	0.21%
32	Lead Vehicle Accelerating	4,000	0.15%
33	Vehicle Turning Right at Signalized Junctions	4,000	0.15%
34	Evasive Action With Prior Vehicle Maneuver	4,000	0.13%
35	Object Crash With Prior Vehicle Maneuver	3,000	0.10%
36	Animal Crash With Prior Vehicle Maneuver	2,000	0.06%
37	Other	21,000	0.75%

Table 9 summarizes the five dominant pre-crash scenarios. The two most frequent and severe pre-crash scenarios are control loss without prior vehicle action, which typically occurs on slippery roads, and following vehicle colliding with a stopped lead vehicle, typically due to inattention. Other frequent and severe pre-crash scenarios are road edge departure without prior vehicle maneuver, typically due to inattention; traversing unsignalized intersections, typically due to obscured vision and inattention; and drifting into the opposite lane at night or in adverse weather. The next three pre-crash scenarios by severity are running a red light, typically due to inattention; and left turns across path from opposite directions on signalized or unsignalized intersections, typically due to vision obscured or inattention.

Table 9 Dominant pre-crash scenarios (from [NSY07])

Scenario	Occurrence		Functional Years Lost		Direct Economic Cost	
	Rank	Frequency	Rank	Years	Rank	Cost ($)
Control Loss Without Prior Vehicle Action	2	529,000	1	478,000	1	15,796,000,000
Lead Vehicle Stopped	1	975,000	3	240,000	2	15,388,000,000
Road Edge Departure Without Prior Vehicle Maneuver	5	334,000	2	270,000	3	9,005,000,000
Vehicle(s) Turning at Non-Signalized Junctions	3	435,000			4	7,343,000,000
Straight Crossing Paths at Non-Signalized Junctions			5	174,000	5	7,290,000,000
Lead Vehicle Decelerating	4	428,000				
Vehicle(s) Not Making a Maneuver – Opposite Direction			4	206,000		

4.2 NHTSA's Vehicle-to-Pedestrian Pre-Crash Scenario Catalog

In another study, NHTSA analyzed pre-crash scenarios involving light vehicles and pedestrians [SYN16]. Even though the original 36 pre-crash scenario catalog also covers crashes involving pedestrians, this dedicated catalog provides a more detailed scenario breakdown. The study is based on 2011 and 2012 GES and Fatality Analysis Reporting System (FARS) crash databases. It focuses on those crashes where a light vehicle struck a pedestrian in first harmful event, which is about 90% of all crashes involving light vehicles and pedestrians. The studied population included 62,900 (overall) crashes from GES and 3,337 (fatal) crashes from FARS. In 2011 and 2012, pedestrian fatalities constituted about 14% of all traffic fatalities in the U.S. The study identified five priority pre-crash scenarios by frequency and severity (measured as comprehensive cost):

1. Vehicle going straight and the pedestrian crossing the road;
2. Vehicle going straight and the pedestrian in the road;
3. Vehicle going straight and the pedestrian adjacent to the road;
4. Vehicle turning left and the pedestrian crossing the road; and
5. Vehicle turning right and the pedestrian crossing the road.

Figure 2 illustrates each of the scenarios. Table 10 defines the pedestrian activities used in the scenarios. The top three scenarios account for 78% of crash costs. Scenario 1 is the most frequent pre-crash scenario and has the highest value of all pedestrian costs at 56%. Scenarios 4 and 5 account for 10% of the cost and address the higher frequency vehicle-turning scenarios observed in the crash data. Figures 4 and 5 provide frequency of the pedestrian activities and vehicle maneuvers in crashes (note that "going straight" includes negotiating a road curve).

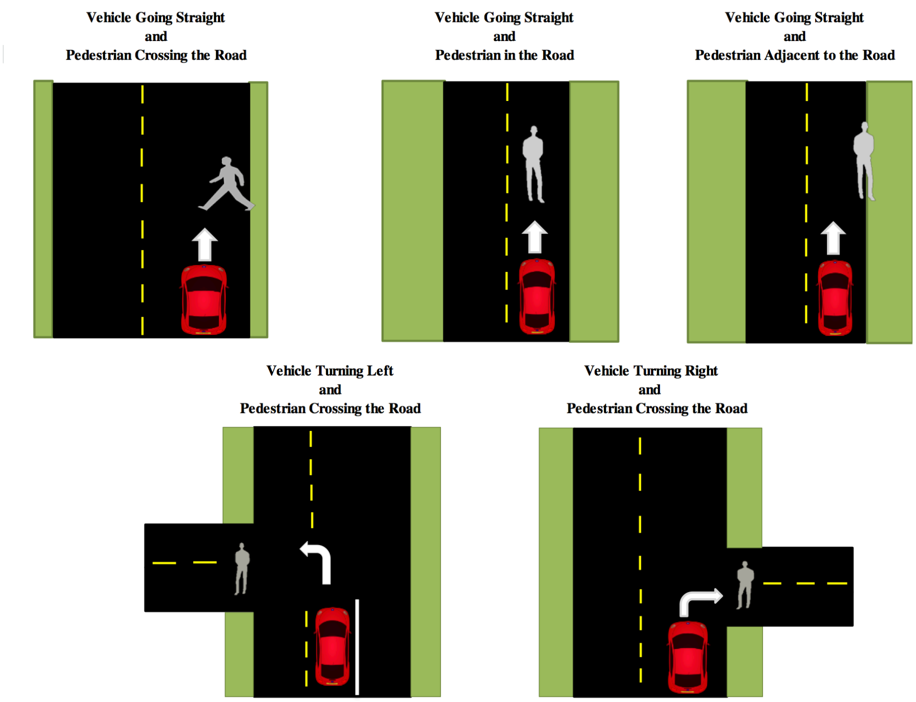
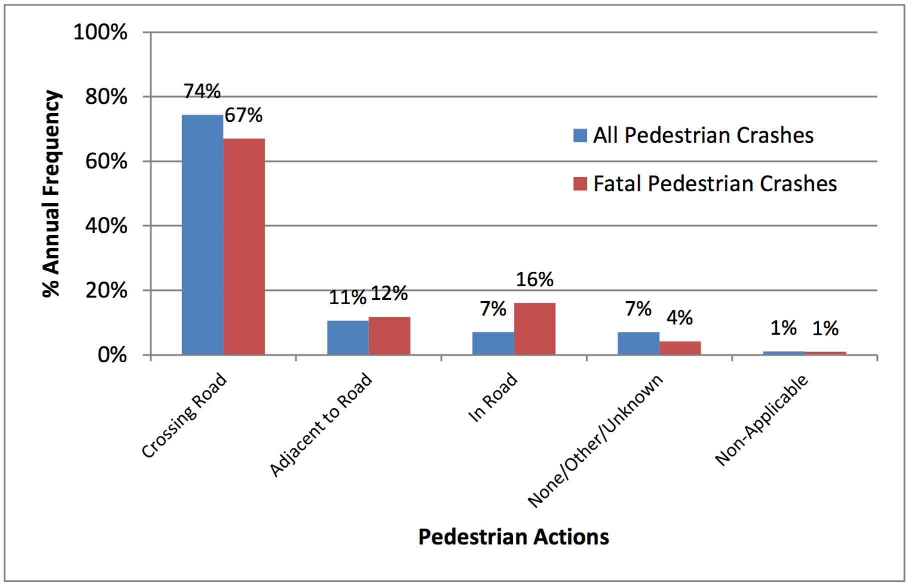


Figure 3 Five priority scenarios identified by NHTSA (from [SYN16])

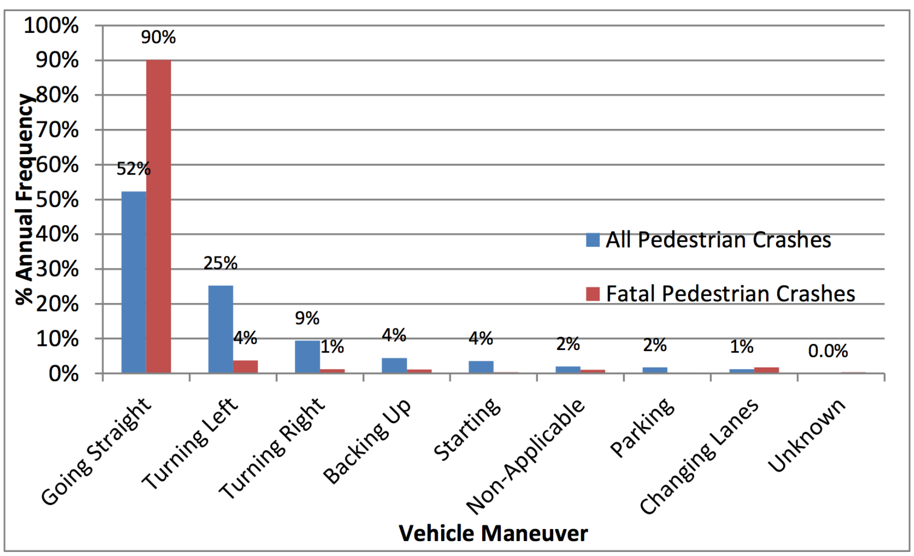
Table 10 Definitions of pedestrian activities used in the pre-crash scenarios (from [SYN16])

Pedestrian Category	Description
Crossing	Moving across the travel lanes to cross roadway
Adjacent to Road	Adjacent to road (shoulder, median); movement along roadway with/against traffic (in or adjacent to travel lane); movement on sidewalk, waiting to cross roadway
In Road	Disabled vehicle related (working on, pushing, leaving/approaching); entering /exiting a vehicle; in roadway - other (working, playing, etc.)
Non-Applicable	Going to or from school; jogging/running; movement along roadway - direction unknown; working in trafficway (incident response)
Other/Unknown	Actions/circumstances do not reflect other attributes; case report specifies actions/circumstances were unknown; no actions/circumstances prior to the crash specificately stated in report



2011-2012 average: GES = 62,900 total crashes; FARS = 3,337 fatal crashes

Figure 4 Pedestrian activity prior crash [SYN16]



2011 and 2012 average: GES = 62,900 total crashes; FARS = 3,337 fatal crashes

Figure 5 Vehicle maneuver prior crash [SYN16]

An analysis of crash contributing factors revealed that the majority of fatal crashes [SYN16]:

- occurred at higher impact speeds,
- involved pedestrians on the roadway outside of the crosswalk,
- occurred at non-junctions,
- were associated with darkness,
- had pedestrian alcohol involvement, and

- involved pedestrians 30 and older.

Some of the key pedestrian-related crash factors include [SYN16]:

1. *Pedestrian darting or dashing into the road*: 23% of all pedestrian crashes and 17% of fatal crashes; main scenario: Vehicle going straight and pedestrian crossing the road – nearly half (45%) of all crashes in this scenario are related to the pedestrian darting or dashing into the road.
2. *Impaired pedestrian*: 6% of pedestrians crashes and 19% of in fatal crashes; impaired; main scenario: vehicle going straight and pedestrian in the road – 26% of fatalities from these crashes involved an impaired pedestrian. Impairment includes: ill, blackout; asleep or fatigued; walking with a cane or crutches; impaired due to previous injury; deaf; blind; emotional (depressed, angry, disturbed, etc.); under the influence of alcohol; drugs or medication; and other physical impairment.
3. *Not visible pedestrian*: 4% of all pedestrian crashes and 19% of fatal crashes; main scenario: vehicle going straight and pedestrian adjacent, in, or crossing the road – significant amount of fatal crashes involve limited visibility of the pedestrian (32% adjacent, 21% in-road, 18% crossing). This factor specifies if the pedestrian was not visible to the driver due to blocked views, insufficient lighting, dark clothing, etc.
4. *Inattentive pedestrian*: 2% of all pedestrian crashes and 3% of fatal crashes; main scenario: vehicle going straight and pedestrian in-road – 9% of crashes involved an inattentive pedestrian (eating, talking, etc.).

Some of the key driver-related crash factors include [SYN16]:

1. *Driver view obstructed*: 13% of all pedestrian crashes and 8% of fatal crashes; main scenario: vehicle going straight and the pedestrian in the road – almost a quarter of these crashes include an obstruction. Visual obstructions include atmospheric obscuration, road geometry (curve, hill), glare, vegetation, building or other structure, another vehicle (possibly parked), inadequate defrost/defog, and inadequate lighting.
2. *Distracted driver*: 12% of all pedestrian crashes and 8% of fatal crashes; 6% percent of all pedestrian crashes and 3% of fatal crashes involve a driver who looked but didn't see the pedestrian; main scenario: vehicle turning right and pedestrian crossing – 22% of these crashes are due to a distracted driver.

Vehicle speed at impact is a main factor determining the severity of pedestrian injury. Figure 6 shows "the risk of severe injury and death in relation to impact speed in a sample of 422 pedestrians aged 15+ years struck by a single forward-moving car or light truck model year 1989–1999, United States, 1994–1998. Risks are adjusted for pedestrian age, height, weight, body mass index, and type of striking vehicle. Top panel shows average risk for pedestrians struck by cars vs. light trucks, standardized to the age distribution of pedestrians struck in the United States in years 2007–2009. Bottom panel shows average risk for pedestrians ages 30 vs. 70, standardized to the distribution of type of striking vehicle for pedestrians struck in the United States in years 2007–2009. Serious injury is defined as AIS score of 4 or greater and includes death irrespective of AIS score.” [Tef11]

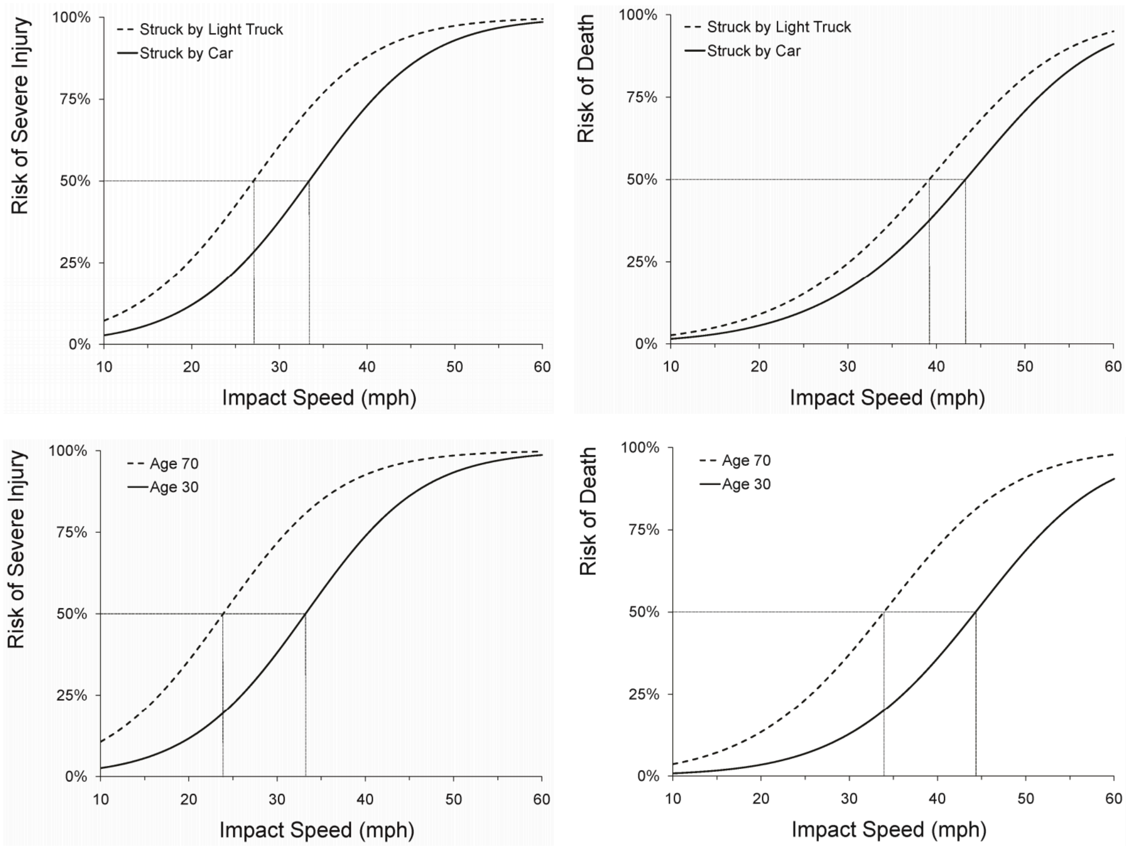


Figure 6 Risk of severe injury and death in relation to impact speed (from [Tef11])

4.3 Causal Crash Factors and Consequences for ADS Design

Figure 7 provides a taxonomy of causal factors for crashes [NMK95], and Figure 8 gives a detailed breakdown of primary causal factors (as defined in Figure 7) based on 1992-1993 data from NHTSA crash databases [RYN15]. The breakdown shows that driver error was the primary causal factor in three-quarters of the crashes; driver physiological condition was the primary causal factor in 14% of cashes; finally, road surface was the primary causal factor in 8% of crashes. Thus, in 89.4% of the crashes the primary causal factor was driver-related. These cases are a target to be addressed by driving automation [RYN15].

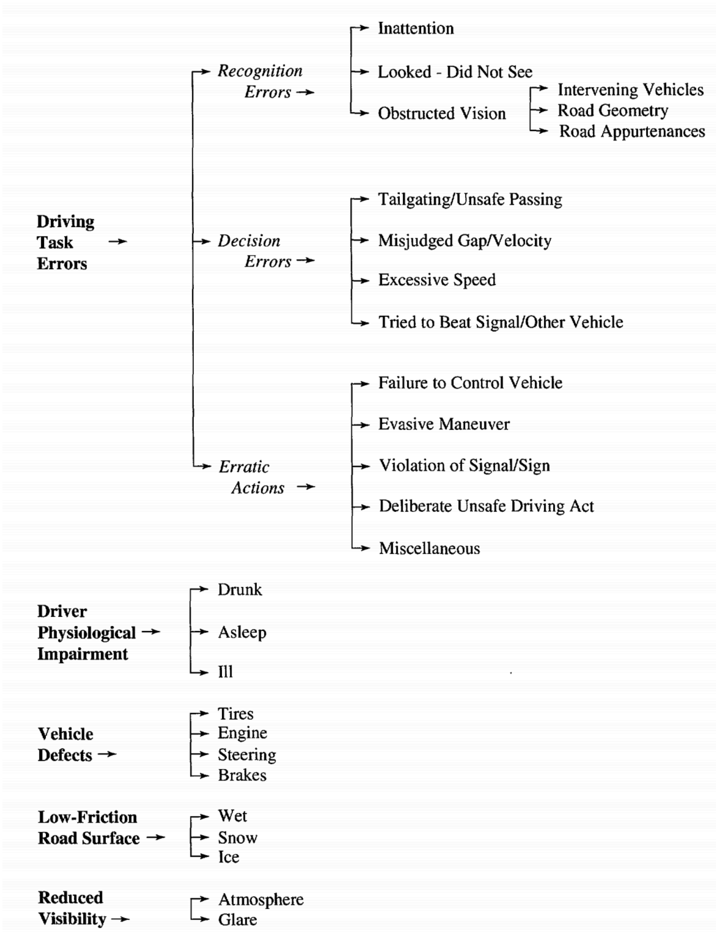


Figure 7 Causal factor taxonomy [NMK95]

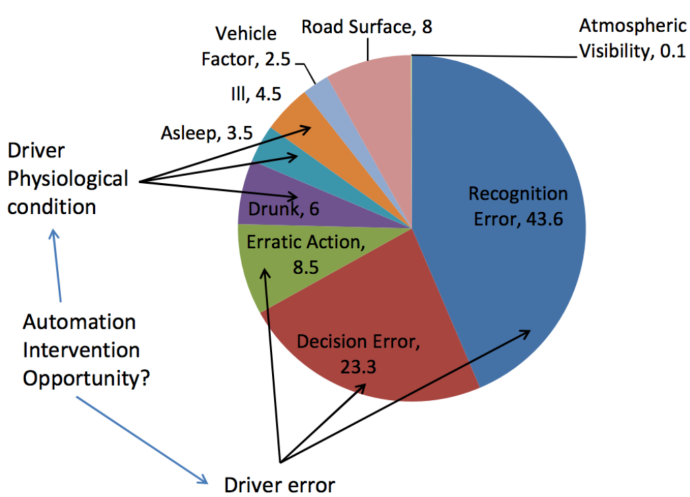


Figure 8 Critical causal factors for light-vehicle crashes (in % crashes) [RYN15]

Given that ADS-operated vehicles will interact with human-operated vehicles, ADS driving behavior must be designed to anticipate and handle human driver errors. The biggest factor are recognition errors due to driver inattention (Figure 8), but also decision errors, such as tailgating, unsafe passing, misjudged gap/speed, and failure to yield. Another aspect is anticipating potentially poor performance of human drivers on slippery roads, and recognizing erratic driving due to physiological condition (drowsy, drunk, or ill).

Rear-end collisions are the most common type of crashes (Table 7). An ADS-operated vehicle may reduce their risk by recognizing tailgaters and yielding to the, such as by lane changing or slowing down and letting them pass. An ADS may also include emergency maneuvers in the case of imminent rear-end collision, such as accelerating forward if the way ahead is clear or evading into an adjacent lane. The latter maneuver could expose the front vehicle to a potential rear-end crash, but would also afford the oncoming vehicle a longer braking distance. The high frequency of collisions at intersections motivates the need to ensure sufficient sensing range at intersections to detect any vehicles that may fail to yield the right of way, but also to include defensive driving behaviors such as delayed acceleration [NSC10]. Another known effect is the impact of waiting time on gap acceptance by human drivers at unsignalized intersections, such as at minor legs of cross intersections [MS81] or roundabouts [PSS05]. The longer drivers wait the shorter time gap there are willing to accept. Thus courteous behavior of letting in vehicles from minor roads in a zip-merge fashion, or close to it, could have positive safety effect.

The analysis of crashes involving pedestrians motivates the need to detect and track occluded spaces from which pedestrian may dart or dash on the roadway, such as from behind large vehicles parked at the curb, and apply defensive driving behaviors, such as leaving extra lateral space when approaching such space. Other potential measures include sharing sensor data among vehicles and infrastructure to reduce the amount of occluded spaces and implementing effective emergency maneuvers for avoiding collisions with pedestrians. The use of LIDAR should improve detection of pedestrians at night. Another area is the need to predict user behavior based on their characteristics. Pedestrian impairments are a major factor in the pre-crash analysis; they include ill, blackout; asleep or fatigued; walking with a cane or crutches; impaired due to previous injury; deaf; blind; emotional (depressed, angry, disturbed, etc.); under the influence of alcohol; drugs or medication; and other physical impairment. This fact motivates the need to recognize pedestrian impairments and accommodate them adequately in driving behavior. Another factor is potential pedestrian inattention, such as talking, eating, use of mobile devices; and age. In particular, children are often not fully aware of traffic rules and their ability to assess distances and gaps is poor [WP16]. Nearly one quarter of the pedestrians hit by vehicles in the United States in 2010 were under 16 years of age [WP16]. Extra cautious driving is necessary when children are present on or around the roadway, especially when they are unsupervised. Observational studies show that 33% of unaccompanied children performed no visual search before crossing, increasing to 48% at signalized intersections. Less than 6% of unaccompanied children look behind themselves for turning vehicles (Scenarios 4 and 5 in Figure 3) [MSD99]. Older pedestrians, that is, those over the age of 65, are more likely to be involved in severe road accidents than younger ones. They accounted for 19% of those killed in the United States in 2012. Physical limitations of older pedestrians include walking more slowly, poor balance, higher risk of slipping and falling, and also reduce agility of those using canes and crutches [WP16].

5. High-Level Safety Requirements on Driving Behavior and Performance

The *high-level safety requirements* (HLRs) on *driving behaviors and performance* capture important safety constraints that must not be violated in order to ensure safety. The high-level safety requirements apply to multiple on-road behaviors and need to be concretized for specific behaviors. The requirements are derived from the different types of possible crashes and exposure to these crashes. They are based on physics, traffic rules, and expected behaviors of road users. The current scope of this document focuses on collisions, road departures, and rollovers.

The HLRs are organized into categories ordered by priority:

1. *Vehicle stability*: Skid and roll stability is required for a vehicle to be controllable. Loosing control may result in colliding with other road users or objects, skidding off the roadway, and rollover.
2. *Assured clear distance ahead (ACDA)*: ACDA is the path distance ahead of the subject vehicle that the ADS can assure to be clear for driving and within which the ADS can bring the vehicle to a halt. ACDA is the minimum standard of care in driving in common law [LOT98]. Measures of ACDA include different types of sight distances, which depend on road geometry and the executed maneuver, and the stopping sight distance. Violating ACDA may lead to a crash, such as a collision, but also a noncollision (e.g., an immersion).
3. *Minimum separation*: The ADS has to assure minimum separation between the subject vehicle and other dynamic and static objects. Multiple measures characterize separation, including distance gaps, time gaps, time to collision, and lateral clearance. Minimum separation has to include sufficient safety margin to accommodate perception, prediction, and control uncertainties. The target values for many of the separation measures are maneuver- and situation-specific. Violating minimum separation may lead to a crash, typically a collision.
4. *Traffic regulations*: Traffic regulations are formal traffic rules required by law in a given geographic area. The majority of traffic regulations are safety-related. They control traffic conflict resolution, such as yielding rules at intersections and passing rules, and prescribe how different road users use the roadway, such as specifying traffic direction, lane restrictions, and parking restrictions. Violating traffic regulations, such as running a STOP sign or a read light, may lead to a crash, typically a collision.
5. *Driving best practices*: Driving best practices are informal traffic rules that refine and complement the formal rules. Examples include rules about how early to signal turns and how to respond to tailgating. Among others, an ADS-operated vehicle should use best practices to anticipate, recognize, and properly respond to likely mistakes of human road users such as those identified in the pre-crash scenarios. Disregarding best practices may increase crash risk.

Appropriate speed selection is a key safety factor. Each of these five requirement categories contribute to the determination of safe speed, in the given priority order:

1. Vehicle stability requirements put limits on safe speed at the most basic level based on tire-pavement friction and road geometry.
2. ACDA limits speed to ensure stopping sight distance or a maneuver-required distance, such as passing distance, to be within the sight distance.
3. Minimum separation requirements limit speed based on the distance to conflict points and the speed of other road users who may conflict with the subject vehicle.
4. Traffic regulations impose legal speed limits.
5. Best practices may further constrain the speed in some situations.

In normal driving, the safety requirements in all five categories apply.

Emergency situations require performance of emergency maneuvers, which aim at minimizing the crash risk. There are three categories of emergency situations and each one warrants special analysis:

1. *Near-crash situations*: In these situations a crash is imminent, but avoidable. In the case of fully or partially lost control, the top priority is the recovery of control. In the case of breached minimum separation, the required separation must be restored. In severe cases, an immediate collision avoidance maneuver may be required, such as emergency braking or steering. In near crash situations, maintaining vehicle stability and controlling separation are top priority. Traffic regulations have little applicability. However, best practices specific to near-crash situations and ADS should be identified and applied. An example of such practice for human drivers is to prefer emergency braking to emergency steering if both are feasible and sufficient to avoid a crash.
2. *Crash situations*: In these situations a crash is unavoidable. The required emergency maneuver aims at minimizing the crash severity. Maintaining vehicle stability is still required in order to ensure that the emergency maneuver can be effectively implemented. In the case of an imminent collision, a target selection step is required, which must consider severity of the collision with the target. The highest priority is to avoid collision with vulnerable road users, such as pedestrians and cyclists, since they are least protected and at highest risk of injury or death. If a collision with a pedestrian is unavoidable, emergency braking must be applied to reduce the impact speed. The next priority is to avoid collisions with cars. If a collision with a car is unavoidable, sideswipe, angle, and partial overlap collision configurations are normally less severe than head-on or front-to-side collisions. As with any avoidable collision, emergency braking must be applied to reduce kinetic energy, except when being rear-ended. Finally, if a collision with another object is unavoidable, the size, mass, density, and malleability of the object must be considered. Collisions with fixed objects such as trees or utility poles are often severe. Similarly, object that may come through the windshield, such as large animals, create a high risk. Malleable

object such as shrubs do not pose significant risk as such, but may obscure other more dangerous object.

3. *Situations requiring fallback*: In these situations, the ADS is about to or has left its Operational Design Domain or has experienced a failure that necessitates fallback performance that will transition the vehicle into a *minimal risk condition* [LA]. The maneuver should respect the requirements in all five categories, if feasible, but additional best practices specific to fallback performance, such as where it is safe to stop under given circumstances, should be identified and applied. The human driver task analysis [MA70] provides some of the best practices for emergency stops.

5.1 Vehicle Stability

Vehicle stability is concerned with preventing skidding and rollover. *Skidding* is a condition where one or more tires are excessively slipping relative to the road surface, and the overall handling of the vehicle has been affected as a result. Specific skidding conditions include *fishtailing*, *under-* or *oversteering*, *burnout*, or *skidding during braking*. Skidding may lead to collisions or road departures. *Rollover* is a type of crash where a vehicle tips over onto its side or roof. Rollovers have a higher fatality rate than other types of crashes [Deu02]. *Untripped rollovers* occur when excessive cornering forces destabilize the vehicle, as a result of steering input, speed, and road-tire friction. *Tripped rollovers* are caused by forces from external objects, such as hitting a curb or colliding with another vehicle or a ravine.

In normal driving, ADS should maintain a sufficient safety margin on vehicle stability. In emergency situations or on very slipper roads, ADS may operate the vehicle at the edge of stability.

5.1.1 Skid Stability

The overall skid stability requirement can be formulated as follows:

> *Skid stability: The ADS shall not cause excessive combined slip of any of the tires, that is, slip that would exceed the friction limit.*

This requirement translates into the requirement to limit longitudinal and lateral tire forces, and consequently, to limit the longitudinal vehicle acceleration.

In the case of braking, the longitudinal deceleration D_x is derived from Newton's Second Law:

$$k_m M D_x = F_b + F_r + F_d + F_g$$

F_b is braking force;
F_r is rolling resistance;
F_d is aerodynamic drag;
F_q is grade resistance;
k_m is rotational inertia coefficient; and
M is vehicle mass.

The braking force is given as

$$F_b = \mu_x F_n$$

μ_x is longitudinal tire-road friction coefficient;

F_n is normal force.

The normal force is the sum of the normal component of vehicle weight and the aerodynamic lift force. Aerodynamic lift can be ignored for passenger cars [GG16]. Thus, the normal force is given as

$$F_n = M\, g \cos \alpha$$

g is Earth's gravitational acceleration; and
α is grade angle.

Since road grades are typically less than 0.06 m/m (i.e., 6%), $\cos \alpha \approx 1$ and consequently:

$$F_n = M\, g$$

The rolling resistance is given as

$$|\, F_r \,| = C_{rr}\, F_n$$

C_{rr} is the rolling resistance coefficient. F_r is negative for braking and positive for traction. For modern tires, the coefficient ranges ranging from 0.007 to 0.014 for free rolling. It may increase to as high as 0.06 for strong braking or tractive forces (see Figure 2.17 in [GG16]).

Grade resistance is given as

$$F_q = M\, g \sin \alpha$$

Given that road grades are less than 6%, $\sin \alpha \approx \alpha \approx \tan \alpha = q$, where q is road grade (q = raise/run) and consequently:

$$F_q = M\, g\, \alpha$$

After substituting the forces into Newton's equation, we have

$$D_x = g\, (\mu_x + q - C_{rr}) + F_d/M)\ /\ k_m$$

For gentle braking at low speeds on level grade and declutched powertrain, the deceleration simplifies to

$$D_x = g\, \mu_x$$

In the case of acceleration, the longitudinal acceleration a_x is computed similarly, except that the braking force is replaced with tractive force, and the signs of acceleration and the terms corresponding to friction and rolling forces are reversed:

$$a_x = g (\mu_x - q - C_{rr}) - F_d/M) / k_m$$

The main factor limiting the longitudinal acceleration or deceleration is the maximum μ that can be achieved, which depends on the type of tire and the road surface conditions. Assuming that the vehicle is travelling on a horizontal tangent, modern radial tires in can achieve a maximum μ_x, denoted as μ_{xp} (p stands for peak), of 1.22 or 1.1 at 30 km/h on, respectively, dry or wet asphalt concrete in summer, but the maximum can go as low as 0.24 on icy surface (see Table 3.1 in [GG16]). The maximum longitudinal friction coefficient μ_{xp} is also further limited in curves, where part of the friction force is used to hold the vehicle in the curve.

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]:

$$e + \mu_y = v^2 / 127R$$

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; μ_y is the side friction coefficient; v is the vehicle speed in km/h; and R is the curve radius in meters. The formula ignores aerodynamic forces due to crosswind. 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 on curves.

Similarly to the longitudinal friction coefficient, the side friction coefficient is limited both by tire properties and road surface condition. The maximum side friction coefficient μ_{yp} is normally lower than the maximum longitudinal friction coefficient. The side friction coefficient is also reduced when accelerating or braking in the curve, which is approximated by the so-called *elliptic tire friction envelope* (see Figure 2.29 in [Pau15]). A more accurate interaction between the maximum longitudinal and side friction coefficients can be modeled using Pacejka's tire model, known as the *magic formula* [Pac05].

The above exposition approximates the friction on all four tires with a single friction coefficient. The grip and slip on individual tires may vary, however. In particular, load transfers due to braking, acceleration, or turning affect the normal forces acting on the tires, and the road surface conditions may be different for each tire (e.g., split μ).

One way to ensure stability is to implement slip control as part of the ADS or the underlying vehicle dynamics management system or both. The main idea is to estimate the combined slip on each tire during driving and ensure that it remains below the value that corresponds to the peak friction coefficient by controlling the tire forces with braking, acceleration, and steering actions.

In normal driving situations, the slip should be limited to be within a safety margin below the slip that corresponds to the maximum friction coefficient. The size of the margin needs to be chosen based on the system uncertainties in the vehicle state estimation and actuation.

In addition to controlling slip to remain in the stable region, the ADS must also have capabilities to recover from excessive slip.

5.1.2 Roll stability

Untripped rollovers are normally not a significant concern for most passenger vehicles because the center of gravity for most of such vehicles is relatively close to the ground compared to their track width. Consequently, excessive lateral forces will cause sliding before rollover could occur. However, tripped rollovers are a concern in near-crash or crash situations, where a vehicle may hit an object with the tires on one side, such as the curb, or go on a steep bank, such as when descending into a drainage channel at the roadside. The risk of tripped rollovers needs to be estimated in such situations.

5.2 Assured Clear Distance Ahead (ACDA)

Assured clear distance ahead (ACDA) is the path distance ahead of the subject vehicle that the ADS can assure to be clear for driving and within which the ADS can bring the vehicle to a halt. “Clear for driving” means free of obstructions, such as obstacles and damaged or flooded road surface, but it also relates to perceiving road geometry and traffic signs and signals, which may require slowing down or stopping ahead. ACDA is the minimum standard of care in driving in common law [LOT98]. Measures of ADAC include different types of sight and stopping distances, which depend on road geometry and the executed maneuver and other factors.

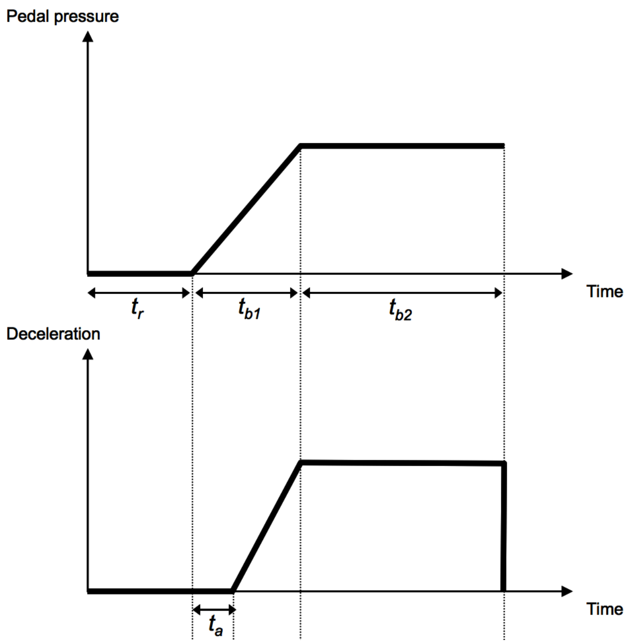


Figure 9 Idealized emergency braking profile [Gre07]

The key concepts related to ACDA are the following:

- *Sight distance* is the length of the roadway (or path) ahead that is visible to the driver [AA11].
- *Braking distance* is the distance travelled by the vehicle from the instant the driver applies the brakes (such as depressing the brake pedal) to the instant the vehicle comes to a stop [AA11]. This time interval includes both the time t_{b1} and t_{b2}, shown in Figure 9. Note that the actual vehicle deceleration starts after the *braking initiation time* t_a, which the underlying vehicle platform takes to process the brake request (including eliminating the brake pad clearance). The braking initiation time will typically be in the range of approximately 0.1-0.4 seconds, depending on the vehicle's braking system and the speed at which the brake pedal is depressed [Gre07]. Another study found the brake initiation time to vary 0.05 and 0.17 seconds [PP14]. Also note that additional time is required to reach maximum braking force and thus maximum deceleration, which is the *brake force build-up time* (t_{b1} – t_a). The total time from the initial brake application until maximum deceleration is reached, i.e., t_{b1}, will typically be in the range of approximately 0.3-1 seconds [Gre07].
- *Stopping distance* is the distance travelled by the vehicle from the instant the driver decides to brake to the instant the vehicle comes to a stop [AA11]. This distance consist of (1) the *brake reaction distance*, defined as the distance traveled during the *driver reaction time* t_r, that is, the time from the instant the driver decides to brake to the instant the driver applies brakes, and (2) the braking distance.
- *Stopping sight distance* is the distance travelled by the vehicle from the instant the driver sights an object necessitating a stop to the instant the

instant the vehicle comes to a stop [AA11]. This distance is same as the stopping distance except that *brake reaction distance* is replaced by *brake perception-reaction distance*, which is the distance travelled during *perception time* and *reaction time*. Perception time is the time required to detect and recognize the object.

ACDA is equal to sight distance, but it also places a constraint on driver behavior, or more precisely on vehicle speed selection, that is known as the *ACDA rule*:

The vehicle speed must be limited such as the minimum stopping sight distance does not exceed the sight distance.

The ACDA rule also applies to an ADS-operated vehicle. Another behavioral constraint placed by ACDA is that a passing maneuver must not be undertaken unless the sight distance is sufficient for safe passing; this sight distance is known as *passing sight distance*. The following discussion analyzes the components of ACDA, that is, the sight distance and the stopping sight distance, and the factors that influence them.

5.2.1 Factors Influencing Sight Distance

The sight distance is determined by the following factors:

1. *Perception range* is the maximum line of sight distance to a relevant object or road feature, such as road surface damage or a flooded section, within which the sensors on the vehicle can detect the object or feature in perfect atmospheric conditions. The distance depends on the sensors and perception algorithms used and properties of the object or feature, including size, reflectivity, and contrast (with respect to the background). Objects that are higher than the ground clearance, which is typically around 13 cm for passenger vehicles, will likely require avoidance.
2. *Sensor placement height* above ground affects sight distance in the presence of obstructions, such as vehicles, and crest curves.
3. *Atmospheric obscuration* such as precipitation or dust will reduce perception range.
4. *Lighting conditions* are relevant for sensors that rely on ambient illumination, such as cameras, and will impact their perception range.
5. *Obstruction,* such as vegetation, buildings, or parked vehicles*,* may further block the view and reduce the perception range.
6. *Road geometry*, including horizontal alignment, vertical alignment, and intersection configuration, influences how much of the road ahead is within the perception range.

The remainder of this section analyzes the influence of road geometry and the performed maneuver on sight distance.

Sight distance on horizontal and vertical tangents: On a straight and level road, the sight distance is equal the perception range.

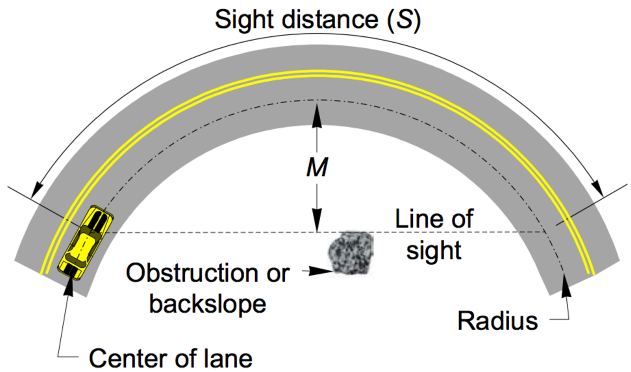


Figure 10 Sight distance at a horizontal curve [WS16]

Sight distance at horizontal curves: Figure 10 shows the sight distance at a horizontal curve, assuming level road. The sight distance S (m) is limited depending on the curve radius R (m) and the presence of a sightline obstruction and its distance M from the lane centerline M (m) [WS16]:

$$S = \frac{R}{28.65}\left[\cos^{-1}\left(\frac{R-M}{R}\right)\right]$$

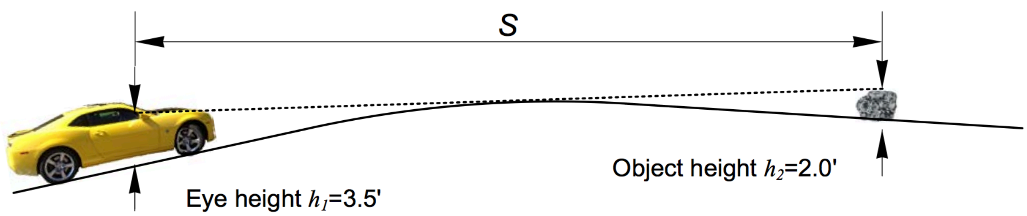


Figure 11 Sight distance at a crest curve [WS16]

Sight distance at crest curves: Vertical alignment also impacts the sight distance. Sag curves do not limit the sight distance, but crest curves do, as shown in Figure 11. For calculation of the sight distance at crest curves, see [WS16].

Sight distance at overlapping horizontal and crest curves: Vertical curves on a horizontal curve have an effect on which roadside objects are sightline obstructions. Crest vertical curves make roadside objects more likely to become sightline obstructions. Sag vertical curves make roadside objects less likely to be sightline obstructions [WS16].

Sight distance at intersections and sight triangles: Sight distance on a controlled approach to an intersection that necessitates a stop is based on the same principles and factors as previously discussed. In particular, the driver must be able to stop before entering the intersection if necessary, for example, at a STOP sign or on a red light. At any point during an approach to an uncontrolled intersection, the driver must be able to assure sufficient clearance from cross traffic in order to complete the planned movement through the intersection or be able to stop before entering the intersection. An *approach sight triangle* (see Figure 12) represents the distance d_b on the intersecting road that the approaching subject vehicle A can assure as clear given its distance from the intersection is d_a.

If d_b is insufficient, assuming vehicle B comes at speed limit plus a safety margin, to afford enough time for vehicle A to complete the movement, vehicle A needs to slow down and be prepared to stop. If during the approach the distance d_b assured as clear becomes sufficient to complete the movement, possibly by accelerating, slowing down, or maintaining speed, vehicle A may execute the movement without stopping. After stopping at the intersection, there should be enough visibility to the sides to ensure a safe departure. This visibility is represented by a *departure sigh triangle* (see the discussion in Section 4.8.1.4 [RAE1]; also see Section 1310.05 in [WS16]). When the subject vehicle approaches the intersection on major road or on green light, the cross-traffic must yield; however, the driver should still check for potential mistakes of other drivers who may fail to yield.

Sight triangles can also be used for other types of cross traffic, such as pedestrians or cyclists crossing the roadway.

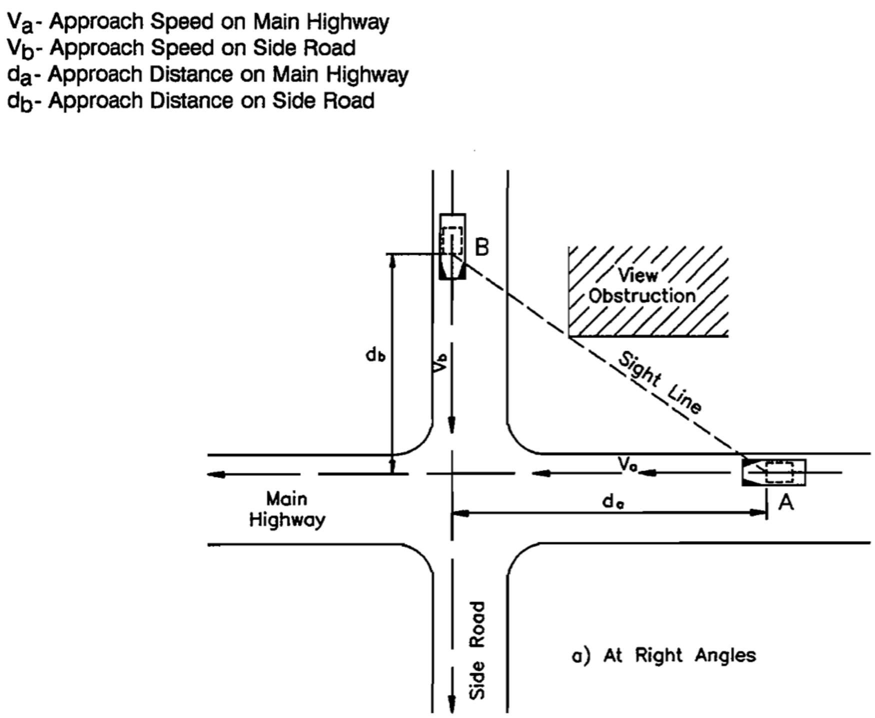


Figure 12 Approach sight triangle at right angle cross intersection [GDS85]

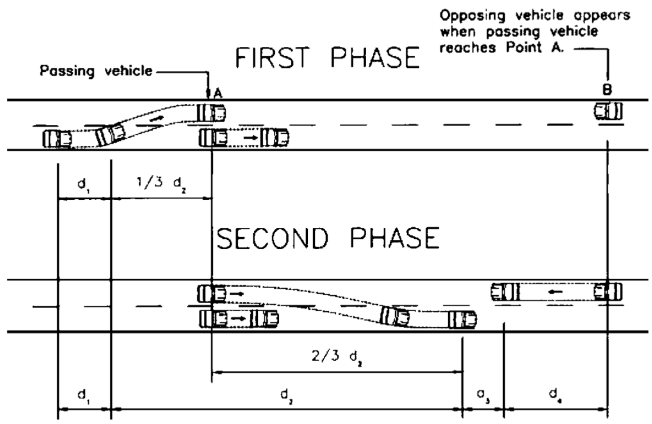


Figure 13 Representation of the passing maneuver and the passing sight distance [HGR08]

Passing sight distance: A subject vehicle intending to pass another vehicle on a two-lane road must ensure sufficient sight distance to complete the maneuver; this distance is known as *passing sight distance*. Figure 13 illustrates a typical passing maneuver [HGR08]:

- d_1 is the distance travelled during the initial acceleration to the point of encroachment on the left lane;
- d_2 is the distance travelled on the left lane during passing;
- d_3 is a clearance distance to the opposing vehicle; and
- d_4 is the distance travelled by the opposing vehicle for two-thirds of the time the passing vehicle occupies the left lane.

The passing sight distance is defined as a sum of these four distances, i.e., $d_1 + d_2 + d_3 + d_4$. The passing maneuver may not be attempted unless the sight distance, which may be limited by the previously discussed factors, such as visibility and road geometry, is at least as large as the passing sight distance.

5.2.2 Factors Influencing Stopping Sight Distance

The stopping sight distance SSD is the sum of brake perception-and-reaction distance and braking distance and can be computed as follows [FFK97].

$$SSD = 0.278\, V\, t_{pr} + V^2 / 254\, (f \pm G)$$

where:
SSD = stopping sight distance (m);
V = initial speed (km/h);
t_{pr} = driver perception-reaction time (s);
f = tire-pavement friction coefficient; and
G = percent grade/100, with + for upgrades and – downgrades.

This calculation ignores the brake initiation and raise time (t_{b1} in Figure 9), which normally does not impact the SSD significantly (see [PP14]).

Based on the formula, factors that impact the SSD are

1. *Initial speed*: This is the only factor over which the driver has direct control.
2. *Grade*: Upgrade shortens the SSD, and downgrade lengthens it.
3. *Friction coefficient*: The difficulty of determining the friction coefficient introduces significant uncertainty into the SSD calculation.
4. *Perception-reaction time*: For an ADS, this time includes the complete time needed to process sensor input and produce control commands to the underlying vehicle platform. This time may depend on the scene complexity.

In order to satisfy the ACDA rule, the sight distance must exceed the SSD by a safety margin, which accommodates uncertainties, especially f, and the standstill distance gap to the object.

While the minimum braking distance in the SSD formula above uses the friction coefficient in order to reflect maximum braking force, the driver-selected speed V should be such as to allow stopping with a comfortable deceleration, for example, 0.2 g. In that case, 0.2 replaces f in the SSD formula.

5.3 Minimum Separation

Minimum separation ensures a safety buffer around the subject vehicle, in addition to ACDA, in order to avoid collisions. ACDA imposes a speed limit and influences intersection approach and passing maneuvers to ensure a clear distance ahead, even when no object or other vehicles are (yet) visible. When approaching other objects, including dynamic ones, additional measures are required to ensure sufficient clearance from these objects, both longitudinally and laterally, and on all sides of the vehicle.

5.3.1 Traffic Conflicts

Traffic conflicts represent breaches of minimum separation. 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]. In a conflict, the separation between the conflicting users is diminishing until the conflict is resolved by the evasive action or a collision occurs. Different road configurations and maneuvers create opportunities for different types of conflicts. Figure 14 presents the maneuvers in the increasing order of relative severity of the potential conflict:

1. A *side-to-side, same direction conflict* occurs between vehicles traveling in adjacent lanes in the same direction when they get too close to each other laterally. This conflict normally occurs as a result of a driver error, such as when a vehicle inadvertently veers off the center of a lane or as a result of an improperly initiated lane change. This conflict may result in a sideswipe, same direction collision.
2. A *sequential conflict* occurs between a front vehicle and a following vehicle, both traveling in the same direction in the same lane, when the front vehicle is slower than the following one. As a special case, the front vehicle is stopped when being approached by the following vehicle. This conflict may lead to a rear-end collision.
3. A *diverge conflict occurs* in a similar situation as sequential conflict, but with the front vehicle slowing down to make a turn at an intersection, driveway, or a highway exit. As a special case, it may also occur when the front vehicle slows down to make a lane change in busy traffic. This conflict may also lead to a rear-end collision.
4. A *merge conflict* occurs when a vehicle merges into another lane and getting to close to one or more vehicles in the target lane laterally or longitudinally. The merge may occur at an intersection, driveway, highway entry ramp, and lane drop location, or simply as a result of a lane change, including at the end of a passing maneuver. This conflict may lead to a range of collision types, including rear-end, angle, and sideswipe (same direction). A particular case of a merge conflict may occur on a multi-lane highway where two vehicles, one on the left and another on the right of the target lane, attempt to merge into the same gap on target lane.

5. A *weave conflict* occurs when vehicles traveling in the same direction need to cross paths, such as at a highway interchange or a weave entry/exit ramp, and get too close to each other. This conflict can also be understood as an extreme case of lane changing where multiple vehicles perform lane changes in opposing lateral directions.
6. A *cross conflict* occurs at intersections when lanes cross at level and the vehicles traveling on the crossing paths get too close to each other near the cross point. The conflict may also occur when driveways are aligned at opposite sides, effectively creating a cross intersection. Different subtypes of this conflict correspond to different crossing angles and directions (see Figure 13). This conflict may result in angle (including front-to-side), but also rear-end (for some skewed crossing conflicts) and front-to-front (for some opposed crossing conflicts) collisions.
7. A *side-to-side, opposite direction conflict* occurs between vehicles traveling in adjacent lanes in opposite directions when they get too close to each other laterally. This conflict normally occurs as a result of a driver error, such as when a vehicle inadvertently veers off the center of a lane or as a result of an improperly executed passing maneuver lane change. This conflict may result in a sideswipe, opposite direction collision.
8. A *head-on conflict* occurs when vehicles approach each other head on. This conflict normally occurs when passing on a two-lane road or in constrictions where vehicles traveling in opposite directions share the same lane. The conflict may also occur as a result of a driver mistake to travel in a lane in the wrong direction. The conflict may result in a head-on collision.

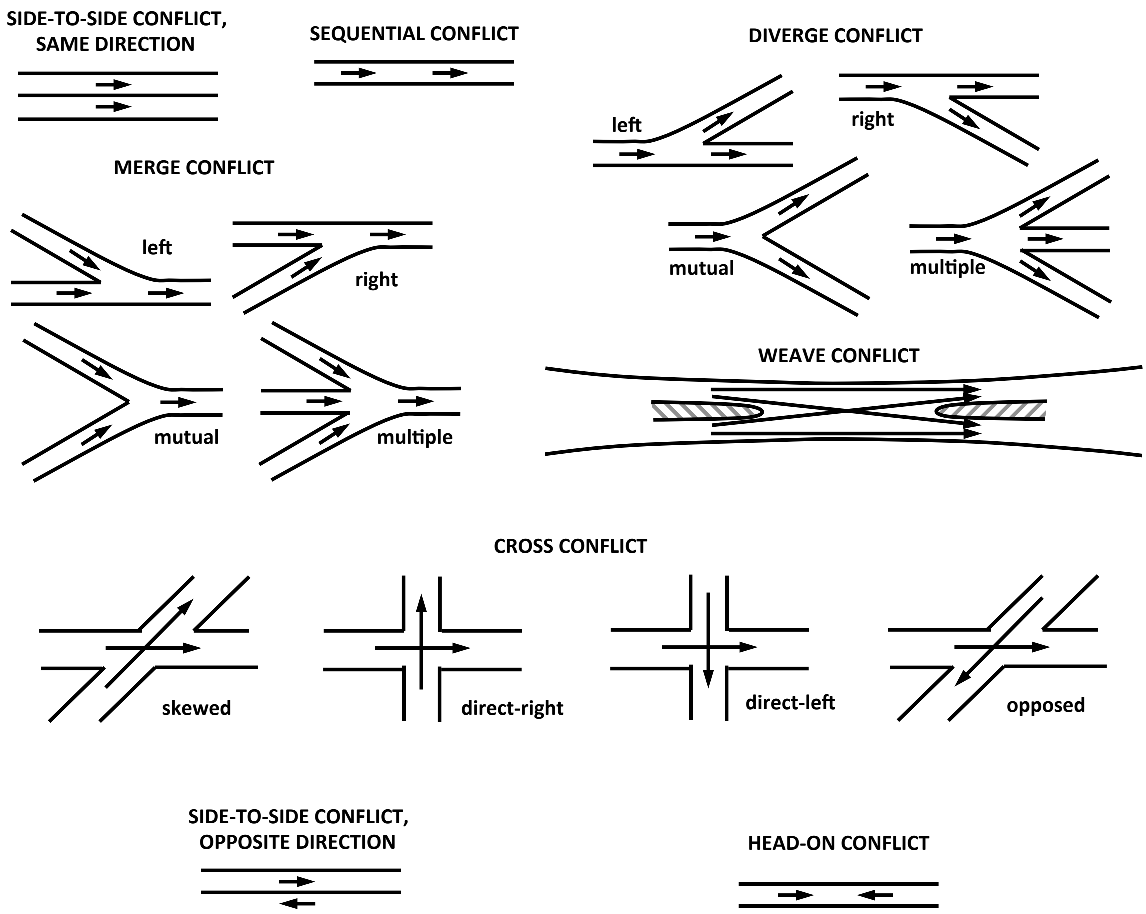


Figure 14 Conflict types ordered by severity (left-to-right, top-down); (diverge, merge, weave, and cross conflicts from [GDS85])

5.3.2 Longitudinal Separation

The key measures of longitudinal separations include [DP15]:

1. *Distance gap*: Longitudinal distance along a travelled path between one vehicle's leading surface and another vehicle's trailing surface. Distance gap can also be defined between a vehicle's front or trailing surface and the closest side of another object.
2. *Time gap*: Time interval for a following vehicle's leading surface to reach the current location of the trailing surface of a vehicle ahead. Time gap can also defined between a vehicle's front or trailing surface and the closest side of another object.
3. *Time to collision (TTC)*: Time interval required for one vehicle to strike another object if both objects continue on their paths at their current accelerations.
4. *Required deceleration*: Amount of constant deceleration required by the subject vehicle to avoid crash, if that vehicle decelerated instantly.

5.3.2.1 Distance Gaps

Figure 15 illustrates the concept of a distance gap. The corner lines mark the vehicle front. (*Distance) gap* represents path length separating one vehicle's leading surface and another vehicle's trailing surface, rather than the line-of-sight distance (range). The leading and trailing surfaces include any attachments, such as a bike rack or lumber (see Figure 16). Gap also should not be confused with *headway*, which is the path length between a reference location on one vehicle, such as front or rear axle or bumper, and the same location on another vehicle [DP15]. Headway is not a useful measure of separation in traffic safety because of different vehicles having different lengths. Headway is used in traffic flow analysis to represent vehicle spacing.

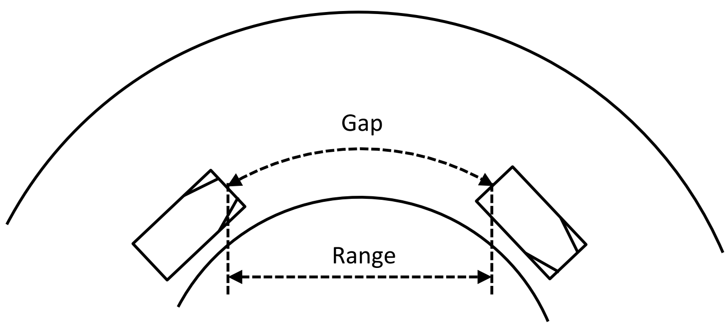


Figure 15 Illustration of gap between two vehicles

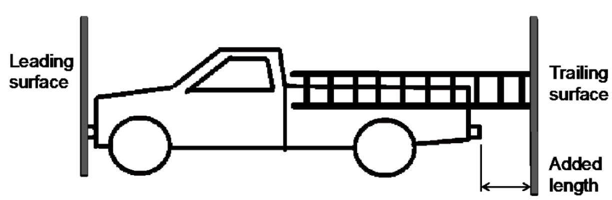


Figure 16 Leading and trailing surfaces of a vehicle (from [DP15])

Different types of gaps are used depending on the road configuration and subject vehicle maneuver [DP15]:

1. Vehicle following in single lane (Figure 17);
2. Lane change between lanes in same direction (Figure 18);
3. Merging on an entry ramp (Figure 19);
4. Passing on a two-lane road (Figure 20);
5. Approach at an intersection (Figures 21 and 22); and
6. Left turn across path from opposite direction (Figure 23).

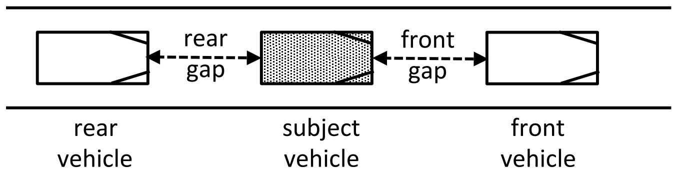


Figure 17 Gaps during vehicle following in a single lane [DP15]

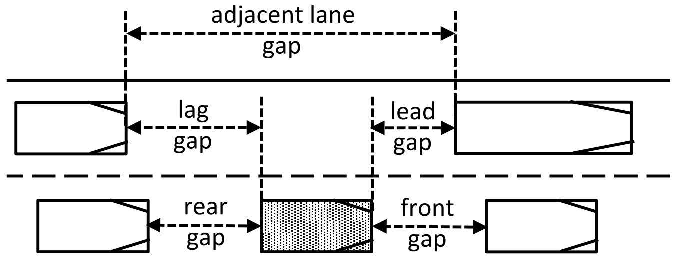


Figure 18 Gaps during lane changing [DP15]

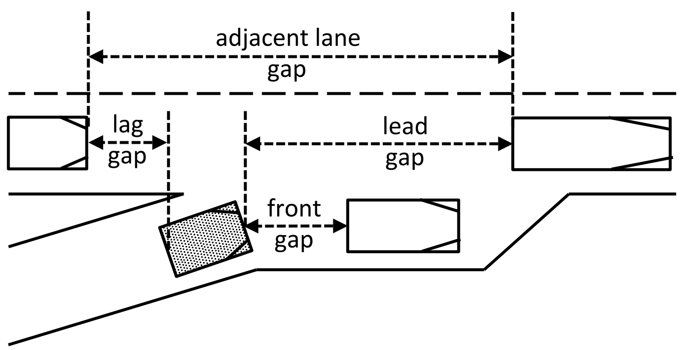


Figure 19 Gaps during merging from an entry ramp [DP15]

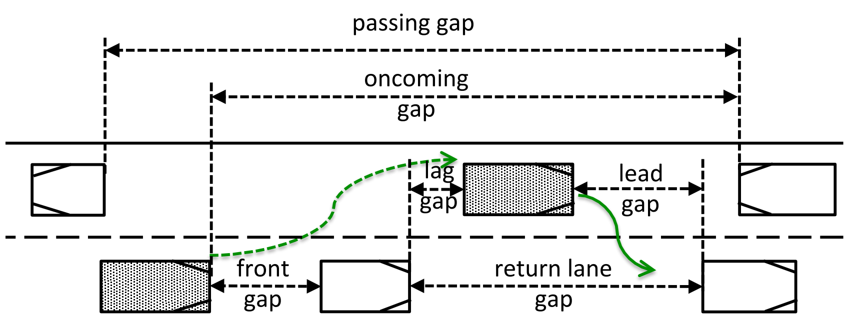


Figure 20 Gaps during passing on a two-lane road [DP15]

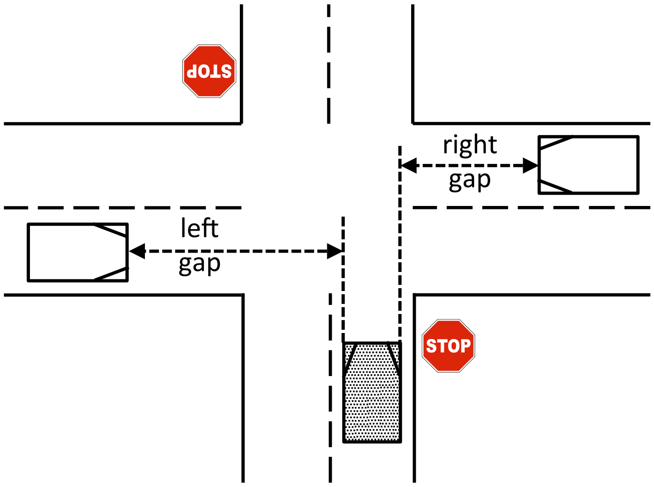


Figure 21 Gaps on approach at a cross intersection [DP15]

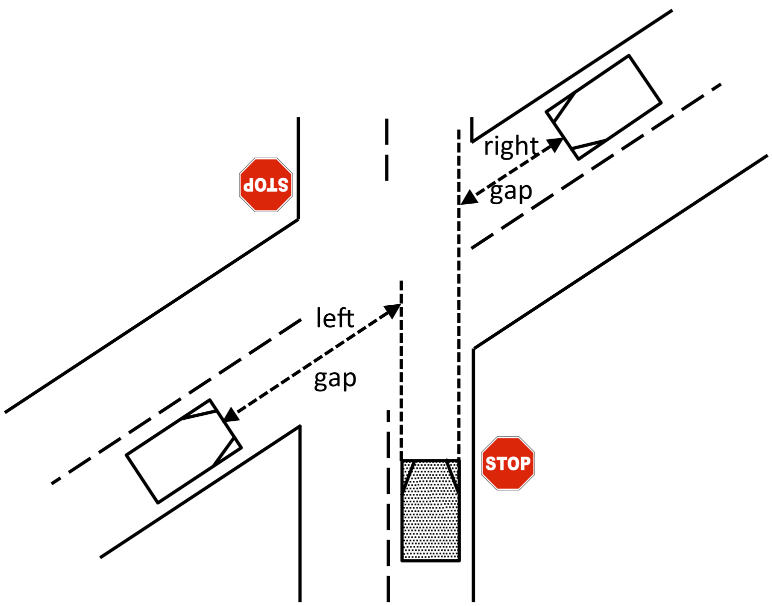


Figure 22 Gaps on approach at a cross-skewed intersection [DP15]

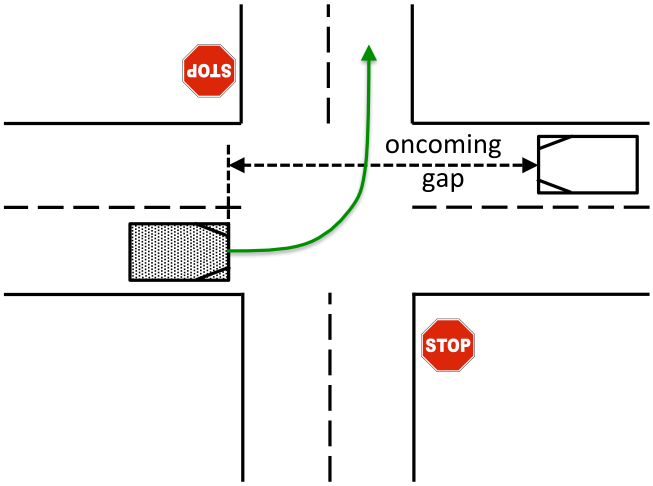


Figure 23 Oncoming gap during a left turn across path from opposite directions at a cross intersection [DP15]

The gaps in Figures 17-23 can be also used for encounters of the subject vehicle with cyclists or pedestrians, such as following a cyclist riding or pedestrian walking along the curb (cyclist or pedestrian would correspond to front vehicle in Figure 17), overtaking a cyclist or pedestrian walking along the curb (Figure 20), and approaching a cycle or pedestrian cross traffic (Figures 21-23).

5.3.2.2 Time Gaps

Time gaps are the temporal equivalents of distance gaps. *Time gap* is defined as the time required by the following vehicle, assuming it continues at constant speed, to travel the distance gap to the front vehicle. Time gap is calculated by dividing the distance gap by the following vehicle speed. Time gaps are used to measure separation between a moving vehicle and another road user that is moving in the same direction as the subject vehicle, or a stationary object or location, such as a conflict point at an intersection (Figures 21-23). Time gaps are mainly used to measure front and rear gaps (Figure 17), but are also used for the other scenarios in Figures 18-23, except when vehicles travel in opposite directions, such as the oncoming gap in Figure 20.

Time gaps provide a speed-independent measure of the gap between a vehicle and another object. Time gap depends on the speed of the following vehicle only. The speed difference between the vehicles determines whether the distance gap and time gap remain constant or change over time. When the following vehicle travels the distance gap, the new gap to the front vehicle is same, smaller, or larger, depending whether the front vehicle travels at the same, faster, or slower speed, respectively.

Distance gaps are still needed in some situations. In particular, the gap to the front vehicle when the speed of the following vehicle is zero is measured as a distance gap since the time gap is infinite. This distance gap is also known as *standstill distance gap* and it provides an important safety buffer for several possible scenarios:

1. the front vehicle rolls back a little, especially on an upgrade;
2. the rear vehicle is approaching too fast; the subject vehicle may be able to move forward a bit to give the rear vehicle more space to stop or it may be able to escape to an adjacent lane;
3. if being rear-ended is unavoidable, larger gap makes it is less likely for the subject vehicle to also hit the front vehicle;
4. aiming for a larger distance gap provides a safety margin if the subject vehicle failed to stop at the desired gap for some reason;
5. the gap may be used by a pedestrian; and
6. the front vehicle becomes disabled, the following subject vehicle may should be able to drive out its gap.

The standstill distance also affords better visibility, especially in front of large vehicles such as buses or trucks. As an additional safety consideration, when located at the end of a queue, it is prudent to observe a standstill distance gap that can accommodate a vehicle entering from an adjacent lane. This strategy affords an escape gap to vehicles in adjacent lanes, for example, in case of an imminent read-end collision situation.

The standstill distance gap in naturalistic driving depends on driver and situation; however, an average of about 3 meters is common. For example, one study analyzed standstill distance gap in queues at signalized intersections in both urban and suburban locations in Delaware finding gaps with a mean of 2.77 m, a minimum of 0.91 m, a maximum of 6 m, and a standard deviation of 0.97 m, based on sample size of 556 [VSP13]. Another study analyzed standstill distance in stop-and-go scenarios at highways in seven cities in Iowa and found standstill distance gaps with a mean between 3 and 3.81 m, and a standard deviation between 1.2 and 1.7 m [Hou15].

Most driving handbooks recommend a time gap of at least 2-3 seconds for human driers when following a vehicle, which is know as the *two-second rule* or *three-second rule*. This time gap is a minimum that applies in good driving conditions. The time gap should be increased to 5-6 seconds in the presence of the following factors [AA17, MA70]:

1. slippery road surface;
2. curve driving (reduced braking performance);
3. when towing a trailer;
4. poor visibility (poor lighting, precipitation, obscuration);
5. oversize front vehicle that obscures forward visibility;
6. front vehicle carrying protruded loads;
7. front vehicle with better braking performance than the subject vehicle, such as lighter vehicles and motorcycles;
8. front vehicles that make frequent stops, such as buses, waste collection trucks, and mail delivery vehicles;
9. roadway sections where traffic intersects, merges, and diverges; and

10. certain front vehicle behaviors, such as diverging or erratic driving; the front vehicle may reverse in some case, which may force the subject vehicle to reverse too.

The minimum time gap requirement is mainly due to human perception-reaction time. When the front vehicle brakes, it will take at least the perception-reaction time for the following vehicle to start braking too. Therefore the time gap must exceed the perception-reaction time. Average perception-reaction time for human drivers is around 1.5 second, although this value is highly depended on a range of driver and environmental factors and has significant variance [LD12]. An additional factor influencing the required time gap is potential differences in braking performance of the front and following vehicle; in particular, light vehicle typically are capable higher deceleration rates than heavy vehicles. Finally, the road friction may be different at the current location of either vehicle.

For human drivers, following time gaps of less than one second are considered highly risky [Vog03]. Following a vehicle too closely is referred to as *tailgating*. Some countries have an official minimum following time gap and failing to observe this minimum constitutes a traffic offence. For example, Germany has an official catalog of traffic fines, and the catalog foresees fines when the following distance is under 0.9 s [BK]. A naturalistic driving study based on 25,000 headways recorded at two locations on a four-lane road and one location at a two-lane road in the midtown area of a large mid-southern city in the U.S. fund most common time headways being from 1.4 to 2.2 s [MLD00]. Overall, 49.4% of the drivers were in compliance with the two-second rule, whereas 50.6% were not. Another study collected following data covertly on 125 drivers following an instrumented test vehicle in the UK on busy motorways and urban roads [BWM09]. The study found that the type of lead vehicle had an impact on the following distance, with trucks and vans being followed more closely than passenger cars, but the type of road (motorway or urban road) and the level of flow had little impact.

An ADS is normally capable of much shorter perception-reaction time than a human, and thus is capable of driving safely with shorter time gaps than human drivers. For example, automated platoons of trucks may safely use time gaps as low as 0.5 seconds or even lower [BH17]. However, differences in braking performance, especially in adverse weather, still must be accounted for. Further, in traffic that includes both human- and ADS-operated vehicles, human drivers may not feel comfortable to be followed by ADS-operated vehicles at distances that would be considered tailgating for human-operated vehicles. Thus, it seems prudent for an ADS-operated vehicle to observe the two-second rule, unless it follows another ADS-operated vehicle in a platooning mode where shorter gaps could be applied.

While a driver has a direct control of the front gap, the driver does not have direct control of the rear time gap. The driver must monitor the rear time gap to detect potential tailgating by the rear vehicle and then respond by applying appropriate resolution strategies, which are discussed in Section 5.5. When an emergency braking becomes necessary while being tailgated, the subject vehicle may be forced to perform an evasive steering maneuver, such as escaping to an adjacent lane if feasible, in order to avoid a rear-end collision.

The lead and lag time gaps when changing lanes (Figures 18 and 19) are subject to similar safety limits as front and rear time gaps, that is, the two-second rule applies. A study of lane changing in naturalistic driving observed the mean value of accepted lead time gaps ranging between 1.47 and 1.82 seconds; in the same study, the mean value of accepted lag time gaps ranged between 1.58 and 1.82 seconds [GB07].

Right and left time gaps in Figures 21-23 that are accepted by the subject vehicle depend on the planed intersection movement and its expected duration. In essence, the subject vehicle, which must yield to the other traffic in these scenarios, must be able to complete the intersection movement and clear the intersection before any of the other vehicles reaches the intersection.

5.3.2.3 Time to Collision (TTC)

Time to collision (TTC) is defined as the time interval required for one vehicle to strike another object if both objects continue on their paths at their current accelerations [DP15]. This TTC definition is also referred to as the *acceleration-based TTC*, originally proposed by Hayward [Hay72], because it assumes constant acceleration. An alternative is the velocity-based TTC, which assumes constant velocity. Acceleration-based TTC is preferred over velocity-based TTC [DP15]. Both measures are similar in car following situations where both vehicles use moderate acceleration and deceleration, but they differ significantly in crash avoidance situations, which normally involve strong decelerations.

5.3.2.3.1 Computing TTC

In simple vehicle following scenarios (Figure 17), *the speed-based TTC between the subject vehicle and the front vehicle is computed as the distance gap divided by the relative speed of the front and the subject vehicle*. If the front vehicle or object is stationary, then the speed-based TTC and the time gap coincide. The acceleration-based TTC for the vehicle following scenario has multiple cases, resulting from a quadratic equation [SNN13]. If both vehicles have equal acceleration, then the TTC is same as in the constant speed case since the acceleration-related terms cancel out. Otherwise, TTC equals the smaller positive number of these two solutions to the quadratic equation [SNN13]:

$$(((v_1 - v_2)^2 - 2(a_1 - a_2)d)^{1/2} - (v_1 - v_2))/(a_1 - a_2)$$

or

$$(-((v_1 - v_2)^2 - 2(a_1 - a_2)d)^{1/2} - (v_1 - v_2))/(a_1 - a_2).$$

where

d is the initial distance between the front and the following vehicle;
v_1 and a_1 are, respectively, initial speed and acceleration of the front vehicle; and
v_1 and a_1 are, respectively, initial speed and acceleration of the following vehicle.

Computing TTC in the general case where the colliding objects have arbitrary shapes in 3D and travel on arbitrary paths is complex. Many methods for computing TTC exist, each making a different set of simplifying assumptions. Most methods consider a projection of the objects onto a 2D plane. The simplest abstraction is to consider each object as a point traveling on straight paths that intersect at an arbitrary angle (Figure 24; see [MH02] for details). In this method, a collision occurs when the arrival times of each object at the intersection point are not further apart than some threshold δ, i.e., $|t_1\text{-}t_2| < \delta$, in which case TTC $\approx t_1 \approx t_2$. This method is sensitive to selecting an appropriate δ [JNG13].

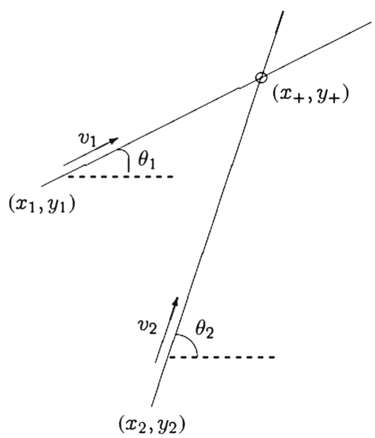
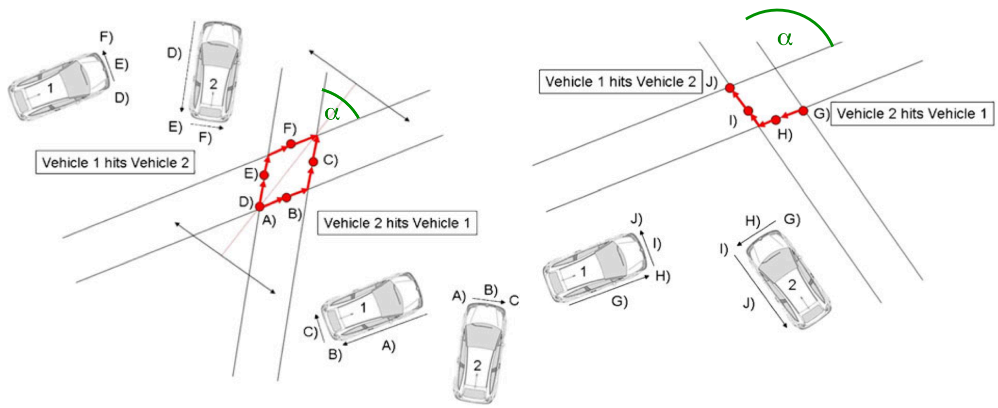


Figure 24 Collision analysis for two objects abstracted as points moving on straight intersecting lines [MH02]

A more precise approach is to abstract the objects as bounding shapes, such as circles, ellipses, or boxes. Oriented bounding boxes are good approximations for most vehicles, and oriented ellipses are good approximations for pedestrians and cyclists. Circles provide very fast collision check, but may lead to false positives.
Collision checking and TTC computation methods based on bounding circles, ellipses, and boxes are discussed elsewhere [HLG14].

When the objects are abstracted as oriented bounding boxes, many different collision configurations are possible. Jiménez et al. [JNG13] analyze possible collision configurations for two vehicles, each moving in forward direction, and identify ten distinct crash configurations at angle, where a corner of one box hits of one of the sides of the other box (Figure 25); this includes the rare possibility of a corner hitting one of the ends of a side, that is, a corner-to-corner collision. Figure 25 shows the possible locations of the point of first contact on the sides of the polygon outlining the intersection of the swept areas of the bounding boxes and on each of the vehicles. The possible configurations depend on the angle between the two approach paths: six configurations (A though F) are possible when the angle is less than 90 degree and four (G though J) are possible when the angle is more than 90 degree. When the angle is perfectly 90 degree, two front-to-side configurations, including three corner-to-corner ones, are possible. When the angle is 0 degree, which corresponds to vehicle following, two front-to-rear configurations, including four corner-to-corner ones, are possible. When the angle is 180 degree, one front-to-front configuration, including two corner-to-corner ones, are possible. Additional cases are possible when one of the two vehicles or both move in reverse. This case analysis can be used to derive a method for computing TTC [JNG13].



Six possible crash configurations when α < 90 degrees

Four possible crash configurations when α < 90 degrees

Figure 25 Collision analysis for two vehicles abstracted as oriented bounding boxes moving on straight intersecting paths [JNG13]

The calculation of TTC needs to further consider paths of different shapes, such as in the case of a vehicle making a left turn across the path of an oncoming vehicle (Figure 23). Najm et al. analyze a range of scenarios involving two light vehicles and provide methods of calculating TTC for these scenarios (see Section 4 in [NTB13]). Similarly, Swanson et al. analyze a range of light-vehicle and pedestrian scenarios and provide methods of calculating TTC for these scenarios (see Section 5 in [SYN16]).

In practice, one needs a general method that can handle all the different cases efficiently. Existing concepts and algorithms in computer graphics [Eri04] lead to a general and efficient method for collision checking and computing TTC using oriented bounding boxes and arbitrary paths; see [Sch14] for details.

5.3.2.3.2 TTC vs. Time Gap

TTC and time gap are complementary. TTC represents an urgency to brake in order to avoid a collision. Time gap is, in a sense, "one step further away" from a crash than TTC [Vog03]. Table 11 captures this idea in the case of vehicle following. Small TTC is possible only for small time gaps, which would imply an imminent collision. However, for a small time gap TTC may also be large or even undefined ("infinite"), when both vehicles travel with similar speed and acceleration but are close to each other. Even though TTC does not indicate an imminent crash, this situation is risky and changes in the acceleration of either vehicle may immediately lead to a small TTC. Further, TTC properly captures the situation of a potential head-on collision, whereas time gap is not inappropriate in that case since it ignores the speed of the oncoming vehicle.

Table 11 Relationship between TTC and time gap for vehicle following [Vog03]

TTC **Time gap**	*Small*	*Large*
Small	Danger imminent	Impossible
Large	Potential danger	Safe

As a further consideration, TTC must be used with other parameters to assess safety. For example, two situations having the same TTC of 1 s but different relative speeds of 10 km/h vs. 100 km/h, respectively, will likely have very different outcomes. Even if the relative speeds are the same, speeds relative to ground also matter.

There is no consensus in the literature about which threshold for TTC should be used to identify dangerous situations for human drivers; suggestions range from 1.5 s in urban areas [Sve98] to 5 s [MJ92]. On the other hand, TTC above 6 seconds are generally considered as not indicative of an imminent danger, assuming speeds up to 120 km/h. A time gap of 6 s at 120 km/h corresponds to 200 m distance gap, which is sufficient to accommodate a typical emergency stopping distance on dry pavement of 128 m [LD12].

A study of naturalistic driving at a rural intersection in Sweden analyzed time gaps and TTC in vehicle following [Vog03]. The study found that in 30% of the cases of vehicle following at the measured locations time headways were under 2 s and that the TTC was under 1 s in less than 0.1 % of the cases.

5.3.2.3.3 TTC-Related Measures

The following TTC-related measures are used to provide a more complete assessment of the criticality of a situation:

1. *Minimum TTC* is the minimum value of TTC during an encounter with another vehicle or object [DP15]. This value represents a worst case TTC value throughout the encounter, such as during a maneuver.

2. *Adjusted TTC* “is the amount of spare time the driver had based on the avoidance response chosen by the driver.”[Bro05] “Adjusted TTC takes into account the relative velocity at time of collision (corresponding to collision severity), and the mean accelerations of the front and following vehicles (assessing the appropriateness of driver’s braking response).”[DP15] “Positive values indicate the amount of extra time the driver had based on the deceleration profile. Negative values indicate how much earlier the driver would have needed to begin the response in order to have avoided the collision.” [Bro05].
3. *Minimum Adjusted TTC* is the minimum value of Adjusted TTC during an encounter with another vehicle or object. [DP15]
4. *Time exposed TTC (TETTC)* is a time interval over which the TTC is less than some exposure threshold [DP15]. TETTC takes time as a measure of exposure into account.
5. *Time integrated TTC (TITTC)* is a weighted time interval over which the TTC is less than some exposure threshold, with times weighted by how far below that threshold the time to collision is at each moment [DP15]. In contrast to TETTC, TTITTC also accounts for the magnitude of TTC violating some threshold over time.

5.3.3 Lateral Separation

In addition to longitudinal separation, lateral separation is also relevant. Scenarios where lateral separation needs to be monitored include lateral separation between vehicle traveling in adjacent lanes in the same or opposite directions and during lane change and passing maneuvers, and also between a vehicle and lane or roadway edges or other objects.

For example, when overtaking a cyclist or pedestrian, sufficient *lateral clearance*, which is defined as the distance between the extreme right side of the vehicle and the extreme left side of the pedalcycle, must be observed (Figure 26). The Ontario Highway Act specifies this lateral clearance to be minimum 1 m when overtaking cyclists. Figure 27 shows the typical required operating space of a cyclist.

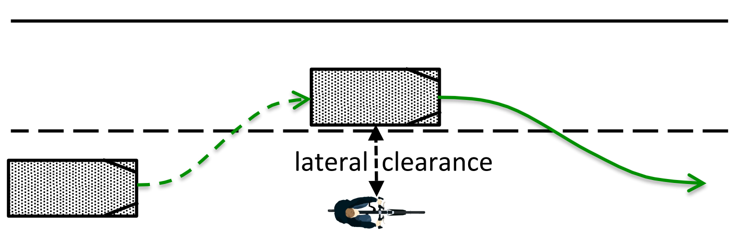


Figure 26 Lateral clearance when overtaking a cyclist

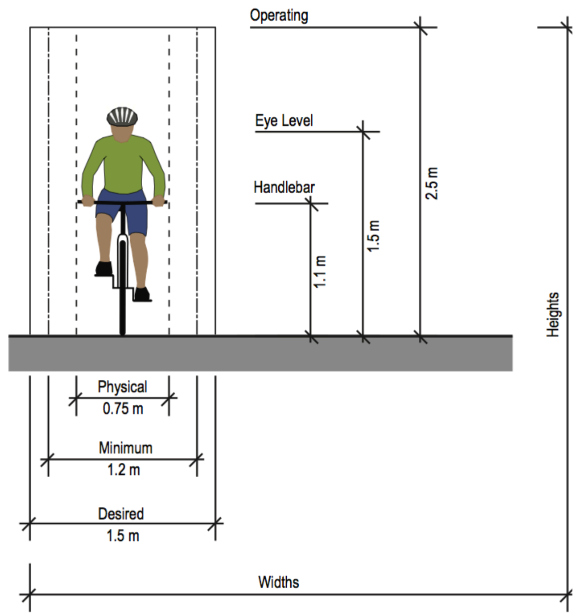


Figure 27 Typical operating space of a cyclist [BF12]

German guidelines recommend the following lateral clearance when passing these types of road users [BK]:

1. single track vehicles (motorcycles and pedalcycles) – 1.5 m;
2. passenger cars and trucks – 1 m; and
3. stopped school and transit buses – 2 m.

Lateral separation can also be described using time-based measures. For example, *time to line crossing*, used in lane keeping, is the time interval required for a vehicle to cross a longitudinal pavement marking line, such as the directional dividing line, assuming it continues at its current lateral acceleration [DP15].

5.4 Traffic Regulations

Traffic regulations are formal traffic rules enacted as law in a given geographic area. In Canada, each province is responsible for maintaining its roads and establishing traffic regulations through provincial highway traffic laws. Provinces delegate some responsibility for maintenance and creation of additional traffic regulations to municipalities through bylaws. The traffic regulations for Ontario are set in the Highway Traffic Act (HTA). They are supplemented by additional regulations established under the Act by the Ontario's Minister of Transport and the municipalities.

The majority of traffic regulations are concerned with traffic safety; however, some regulations are concerned with other aspects, such as environment, e.g., idling or noise pollution prohibitions, or traffic flow, e.g., restrictions on lane use such as bus lanes.

Safety-related traffic regulations in the HTA include the following categories of rules:

1. *Speed rules*: The HTA sets statutory speed limits and makes provision for posted speed limits. It also requires drivers to drive with "due care"; in effect, this requirement is related to the ACDA rule. Some traffic regulations, such as in Ohio, refer to the ACDA rule explicitly (Ohio Revised Code, 0 4511.21 [A]). The HTA also prohibits unnecessary slow driving that would "impede or block the normal and reasonable movement of traffic," except "when the slow rate of speed is necessary for safe operation having regard to all the circumstances." The HTA requires slow vehicles to be marked as such.
2. *Following distance rules*: The HTA requires drivers to observe a following distance that is "reasonable and prudent having due regard for the speed of the vehicle and the traffic on and the conditions of the highway."
3. *Overtaking and passing rules*: These rules regulate passing, such as when it is prohibited, and reacting to being passed, such as making space.
4. *Right of way at intersections and driveways*: These rules regulate when to yield right of way to other vehicles, including prohibition of blocking an intersection.
5. *Required behavior at railway crossings*: These rules include the stopping and other requirements at railway crossings.
6. *Rules of yielding to pedestrians*: These rules regulate yielding to pedestrians at pedestrian crossovers and other locations.
7. *Duties of pedestrians*: These rules include prohibiting pedestrians from entering roadway when impractical for a driver to stop and regulate walking along roadway.
8. *Obeying signs*: These rules require road users to obey regulatory signs and signals. They also specify where to stop when required by traffic control devices.

9. *Signaling of turns and stops*: These rules require vehicles to signal turns and stops using appropriate lamps or hand signals.
10. *Restrictions on where to drive*: These rules prohibit driving on paved shoulder, left of directional dividing line unless passing, and driving wrong way in one-way traffic.
11. *Restrictions on parking on roadway*: These rules generally prohibit parking on roadway and specify exemptions.
12. *U-turn prohibitions*: These rules specify when making a U-turn is not allowed.
13. *Use of passing beam*: These rules prohibit the use of high beams when approaching oncoming traffic or when following.
14. *Reacting to emergency vehicles*: These rules prescribe required behavior in the presence of approaching and passing emergency vehicles.

5.5 Driving Best Practices

Driving best practices are informal traffic rules that are consistent with the traffic laws and refine and complement the legal rules. These rules are often documented in official driver handbooks. In Canada, each province, including Ontario [ODH], has its own driver's handbook. For example, the Ontario Driver's handbook refines the general following-distance 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.

It is prudent to also apply best practices that address likely road users mistakes that may lead to crashes, such as those identified by the pre-crash scenario analyses. Examples of such failures include failure to yield at intersections or tailgating. Strategies that help address these failures include [NSC10]:
1. *Delayed acceleration at intersections*: when the light turns green, as the first car in the queue, delay entering the intersection by two seconds; and
2. *Yielding to tailgaters*: when being tailgated, change lane or slow down and allow the tailgater to pass.

Other areas addressed by best practices include driving behavior when interacting with animals on or near the roadway, dealing with adverse weather conditions, and dealing with heavy vehicular and pedestrian traffic in complex urban scenarios, which is often specific to the social norms at a given geographic location. In particular, an ADS needs to be aware of obstructed or occluded spaces that may harbor road users; these road users may suddenly appear in the roadway. It would be desired for the ADS to reduce speed and plan emergency maneuvers before reaching such locations.

Both formal traffic rules and best practices will likely need to be more comprehensive and specified more precisely for ADS to follow than the current rules for human drivers. Finally, new traffic rules that are specific to ADS will also be needed, including those addressing dilemma situations in crash mitigation.

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