WISE Requirements Analysis Framework for Automated Driving Systems

Automated Driving System (ADS) Task Analysis

Part 2: Structured Road Maneuvers

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Document history

Updates	*Date*	*Contributor(s)*
Version 0.1 created	February 17, 2018	Krzysztof Czarnecki[1]
Version 0.2 Analysis of lane changing added	July 21, 2018	Krzysztof Czarnecki[1]

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Abstract

This document defines a maneuver catalog for driving on structured roads. It also provides a maneuver analysis method and a multi-dimensional organization of the maneuvers. The catalog is divided into primary maneuvers, which include lane maintenance; lane changing; and swerves and turns out of and into a lane; and secondary maneuvers, including passing and overtaking; handling intersections; handling pedestrian, cyclist, and railway crossings; and joining and leaving traffic. Each maneuver is analyzed for its pre- and post-conditions, triggers, procedures and variants, and behavior modifiers. The modifiers include variations in road structure, interaction with road users, encounters with animals and other obstacles, and variations in environmental conditions. Each maneuver definition includes related terminology, such as maneuver-specific gaps and events, and safety requirements. The maneuvers can be used to specify the tactical behavior of an ADS-operated vehicle and to derive driving scenarios for simulation, closed course, and field tests.

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1. Scope

This document defines

1. a taxonomy of structured-road maneuvers;
2. a maneuver analysis method; and
3. a multidimensional organization of the maneuvers.

Structured roads are those with well-defined lane structure. *Maneuvers* are driving tasks mainly concerned with the tactical aspects of driving, including Object Detection, Evaluation, and Response (OEDR) functions, to be executed by a Level 3, 4, or 5 Automated Driving System (ADS) [LA]. The multidimensional organization provides a systematic approach to analyze and organize the maneuver requirements and scenarios. This document does not provide detailed requirements on maneuver; rather, it provides a template, including requirements seeds, for eliciting and organizing the detailed requirements with respect to a target Operational Design Domain (ODD) [LA].

The presented maneuver taxonomy and analysis are part of the WISE Requirements Analysis Framework for Automated Driving Systems and relies on the following existing concepts and other documents:

1. *Operational world model ontology*: This ontology defines the elements in the road environment that are relevant to driving, such as road structure, road users, and environmental conditions. The ontology is defined elsewhere [O18a,O18b]. The operational world model also includes a model of the subject vehicle [ODD18]. This document assumes that the subject vehicle is a passenger car, but most of the analysis should apply to other types of vehicles. The document also assumes that the ADS-operated subject vehicle interacts mostly with human road users, including human-operated vehicles, and that the vehicle is not hauling a trailer.
2. *High-level driving quality requirements (HLQRs)*: The maneuvers are subject to high-level driving quality requirements, which include safety, comfort, progress, and fuel efficiency. The HLQRs for safety and comfort are defined elsewhere [S18, C18]. Progress and fuel efficiency HLQRs will be specified in a future version of the WISE framework.
3. *Basic motion control tasks*: The structured road driving maneuvers are realized using basic motion control tasks. These tasks are low-level operational tasks, such as acceleration, speed maintenance, and steering, and are defined elsewhere [BM18]. Vehicle stability, which is the first of the five high-level safety requirements on driving behavior [S18], is enforced by each basic motion control tasks. Thus, the maneuvers must be defined such as to map to the basic motion control tasks within the subject vehicle's stability envelope. For example, if a maneuver were to invoke a basic motion control task requiring acceleration that would result in skidding, the underlying basic motion control layer would not fulfill this request.

The presented tactical driving tasks are classified into normal driving maneuvers and emergency maneuvers [ODD18]. In contrast to normal driving, emergency maneuvers deal with emergencies, such as imminent crashes, systems failures, and ODD departures.

The maneuver definitions build on existing taxonomies of driving tasks, such as NHTSA's human driver task analysis for driver education [MA70], its adaptation for automated driving [BH04], National Cooperative Highway Research Program's reports on specific maneuvers (e.g., [RCB06, HS08]), and other scientific literature in transportation research and human driver modeling. While there are many valid ways to decompose the space of maneuvers, the design of the proposed taxonomy was driven by two objectives: (i) achieving compositional structure; and (ii) supporting a multidimensional organization. The compositional structure is reflected in the classification of maneuvers into so-called primary and secondary ones and enables reuse of behavior descriptions of primary maneuvers in the definition secondary ones. The multidimensional organization acknowledges the multitude of internal and external factors that influence the subject vehicle behavior, and, in conjunctions with adequate content management tooling, the organization will enable a multi-view exploration and maintenance of the behaviors.

This document focuses on the vehicle behavior in terms of its actual movements, including position, heading, velocity, and acceleration, and interactions with other road users and elements, rather than the ADS behavior in terms of vehicle control inputs, such as the commanded steering, braking, and throttle inputs.

The scope is limited to driving on structured roads, and it assumes right-hand traffic. Other types of driving environment that are out of scope of this document include

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

The current version of this document focuses on driving on non-access-controlled urban and rural roads. Access-controlled freeway driving will be addressed in future versions of this document.

The presented maneuver catalog is work in progress, and the analysis sections for some maneuvers are still to be developed (TBD). This version is shared publicly for timely dissemination of the early results. For comments and suggestions, please email the author.

2. Primary and Secondary Maneuvers in Normal Driving on Structured Roads

Primary maneuvers for structured roads are maneuvers representing primitive vehicle movements defined with respect to the lane structure. A vehicle driving on structured roads performs single primary maneuver at any time, such as lane maintenance or lane change.

Secondary maneuvers for structured roads are common extensions or sequential compositions of the primary maneuvers. For example, a right turn maneuver at an intersection is a secondary maneuver that normally involves lane maintenance as an underlying, primary maneuver. The subject vehicle performing a right turn maintains its lane, which merges with the lane of the intersecting road. Thus, the right turn can be defined as lane maintenance extended with the capability to handle merging lanes. As another example, passing a vehicle is a secondary maneuver that sequentially composes two or three primary maneuvers: lane change and lane maintenance, possibly followed by another lane change into the original lane.

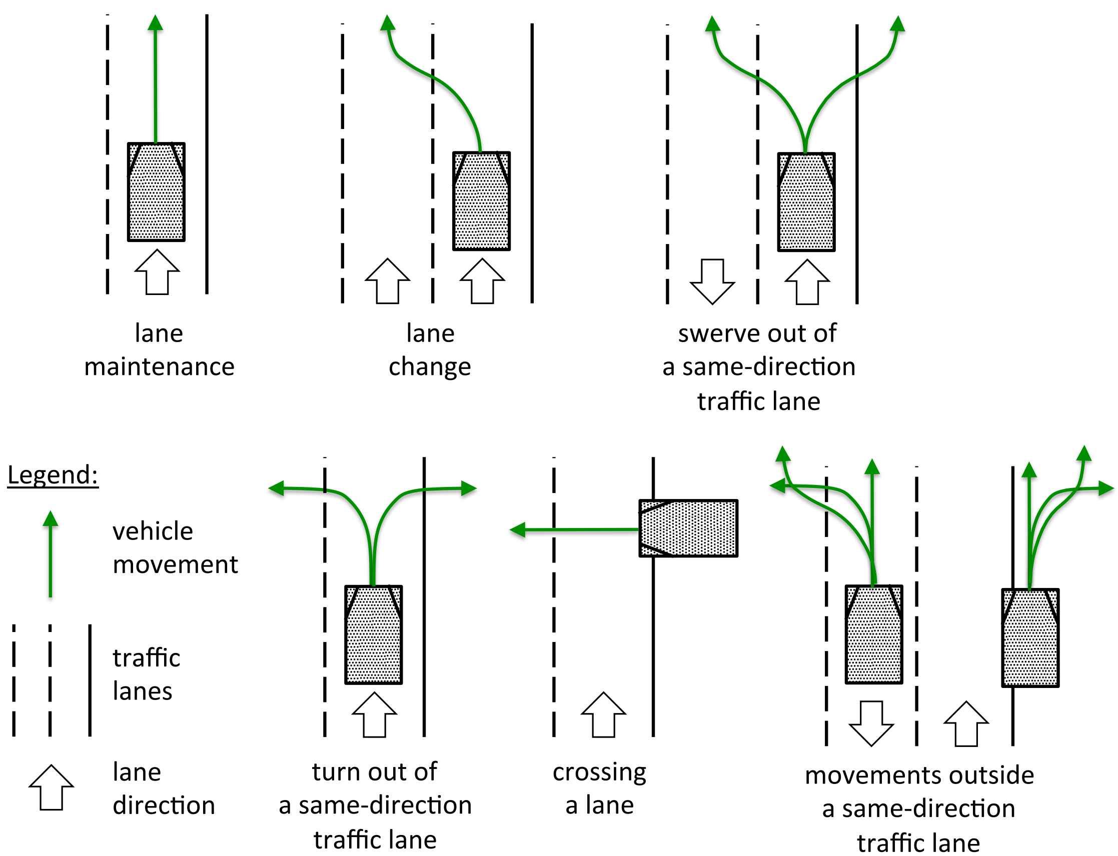

Figure 1 Illustration of primary maneuvers (for conciseness, opposite and reverse variants not shown)

The primary maneuvers are defined with respect to the transversal lane structure (Figures 1 and 2). Traffic lanes are intended for the movement of a single line of vehicles in the lane direction ("same-direction"). A vehicle either travels within a traffic lane in the direction of the lane (lane maintenance), or enters or leaves the lane. Entering or leaving can be accomplished by a turn, swerve, or crossing movement. Swerves between adjacent same-direction traffic lanes are referred to as lane changes. All other swerves out of a traffic lane or into it are referred to simply as such. Similarly, turns out of a traffic lane or into a lane and crossing a lane are also referred to as such. Note that driving in traffic lanes in opposite direction or driving on parts of the roadway that are not traffic lanes are temporary conditions. Therefore, the only long-term primary maneuver is lane maintenance, and the remaining primary maneuvers serve *transitional* purposes, such as switching lanes, obstacle avoidance that requires a lane departure, overtaking, turning about, and joining and leaving traffic. Finally, each of the forward primary maneuver has a corresponding primary maneuver executed in reverse.

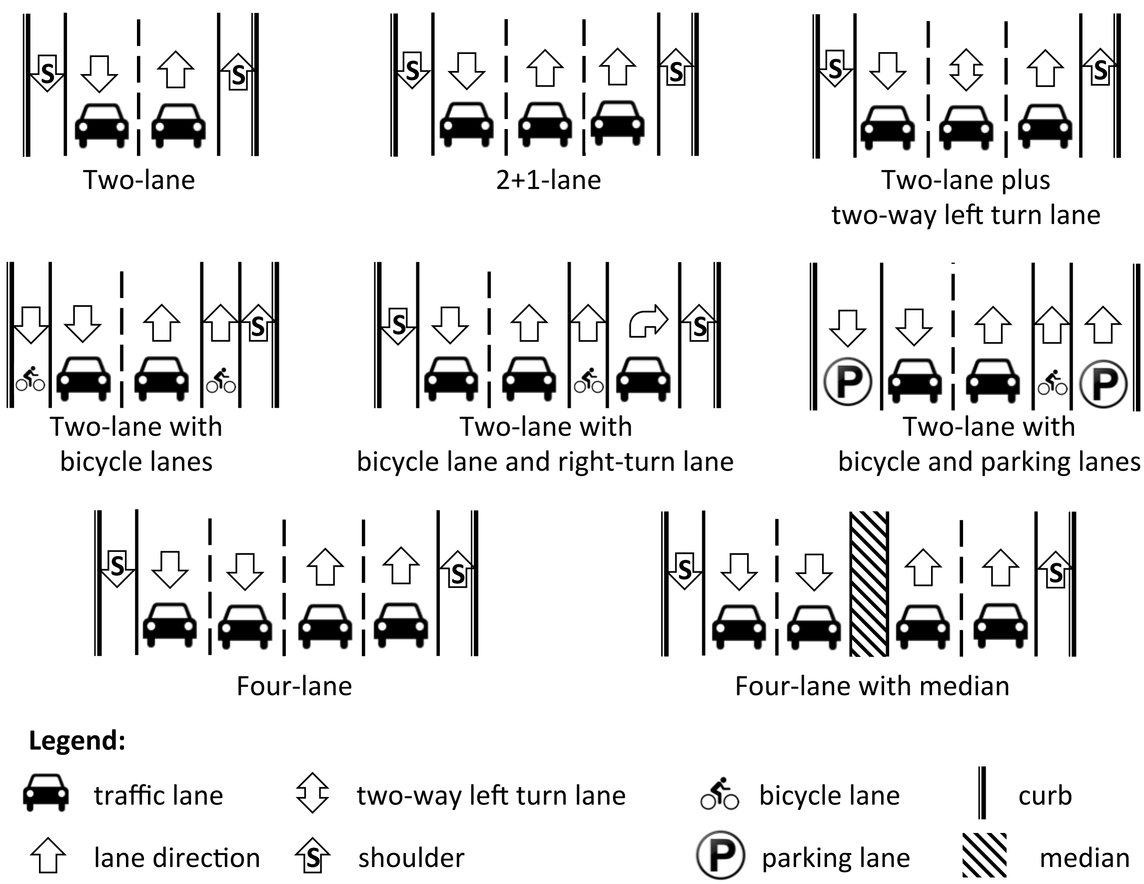

Figure 2 Examples of common lane configuration patterns

More completely, primary maneuvers are

1. *Lane maintenance*: driving forward within a traffic lane consistent with its direction of travel; this maneuver includes both unobstructed driving and responding to road users (e.g., vehicle following) and other obstacles in the roadway;
2. *Lane changing*: swerving forward from a traffic lane across its boundary into a parallel traffic lane that has the same direction of travel as the original one and is consistent with the subject vehicle driving direction;
3. *Swerving out of a same-direction traffic lane*: swerving forward across the boundary of the travelled lane, which is a traffic lane consistent with the direction of travel, into the opposite traffic lane or a roadway part that is not a traffic lane, such as parking lane, turnout, bicycle lane, or shoulder;
4. *Swerving into a same-direction traffic lane*: opposite of swerving out of a same-direction traffic lane, that is, swerving forward from a traffic lane that is opposite to the direction of travel or a roadway part that is not a traffic lane into a traffic lane that is consistent with the direction of travel;
5. *Turning out of a same-direction traffic lane*: turning forward across the boundary of the travelled lane, which is a traffic lane consistent with the direction of travel, for example, into a driveway;
6. *Turning into a same-direction traffic lane*: opposite of turning out of a same-direction traffic lane, that is, turning forward into a traffic lane consistent with the direction of travel;
7. *Crossing a lane*: driving forward across a lane while not maintaining another lane that crosses the former one; for example, a left turn out of the travelled lane is followed by crossing an opposite lane before reaching a driveway on the left; intersection handling (secondary maneuver) covers the case of crossing a lane while maintaining another lane that crosses the former one;
8. *Turning, swerving, and longitudinal movements outside a same-direction traffic lane*: forward movements that originate and terminate within adjacent non-traffic lanes or within traffic lanes against the direction of travel; examples include driving along a bike lane, turning from a bike lane into a driveway, driving within a traffic lane against traffic during overtaking, and turning from a traffic lane travelled against traffic during overtaking into a driveway.
9. *Reverse driving maneuvers*: any of the previous forward primary maneuvers (1-8), but executed in reverse driving direction, such as a reverse turning out of a same-direction traffic lane into a driveway.

Secondary maneuvers are

1. *Overtaking*: crossing the directional dividing line in order to pass an obstacle in the traveled lane, followed by a return to the travelled lane;
2. *Passing*: lane change followed by passing one or more vehicles traveling in the original lane, possibly followed by a return into the original lane;
3. *Intersection handling*: approach to an intersection and movement to a desired departure lane (includes handling circular and non-circular intersections);

4. *Interchange handling*: approach to an interchange and movement to a desired departure lane (includes using acceleration lanes, entry and exit ramps, and weaving areas);
5. *Pedestrian crossing handling*: moving through different types of pedestrian crossings;
6. *Cycle crossing handling*: moving through different types of cycle crossings;
7. *Railway crossing handling*: moving through different types of railway crossings;
8. *Turnabouts*: switching into a parallel travel lane that has the opposite direction of travel; turning about may involve a U-turn or a three-point turn; and
9. *Joining and leaving traffic*: different maneuvers to join and leave traffic involving curb parking and driveways.

Secondary maneuvers extend or sequentially compose the primary maneuvers. Overtaking can be understood as a composition of a swerve out of a same-direction traffic lane across the directional dividing line followed by a swerve back into the original lane. Passing is a lane change followed by lane maintenance, possibly followed by lane change back into the original lane. Handling of intersections, interchanges, and the different types of crossings is normally a specialization of lane maintenance, that is, lane maintenance while dealing with merging lanes or crossing lanes or crossing pedestrian paths or rail tracks, often composed with lane changing to merge into the desired lane for intersections and interchanges. Turning about may be composed of turns out of a lane and into a lane, crossing a lane, and reverse maneuvers. Joining and leaving traffic is typically achieved using swerves or turns out of a lane or into a lane, crossing a lane, or reverse maneuvers.

Each of the primary and secondary maneuvers is analyzed with respect to *behavior modifiers*, which are influence factors related to the driving environment, mission, or the subject vehicle state that the maneuver behavior needs to account for in some special way.

The operational world model ontology [O18a, O18b] provides a list of potential *driving-environment-related behavior modifiers*, which are driving environment elements or conditions to which the subject vehicle may need to respond:

1. horizontal curves;
2. vertical curves;
3. cross-section design (lane and road-side structure);
4. regulatory traffic signs and signals and other traffic control devices;
5. intersecting vehicular lanes, rail tracks, and pedestrian and cyclist facilities;
6. temporary structure;
7. bridges and tunnels;
8. road users, including emergency vehicles;
9. animals;
10. other obstacles in the roadway;
11. visibility conditions;

12. lighting conditions;
13. wind; and
14. road surface conditions.

When analyzing interaction with other road users, different types of conflict should be considered, as illustrated in Figure 3.

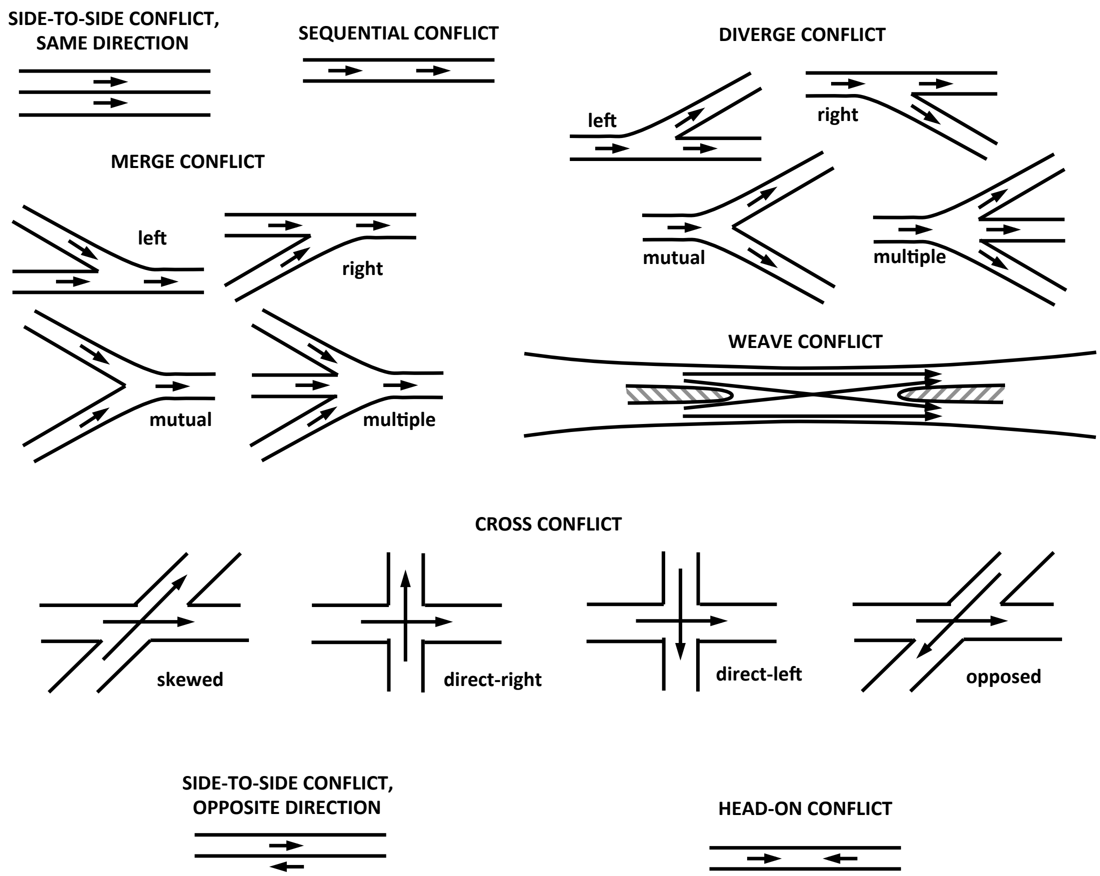

Figure 3 Different types of conflicts among road users, ordered by severity (partly based on Figure E2-1 from [GDS85])

Other behavior modifiers are related to the mission or the state of the vehicle, such as trip urgency, whether the subject vehicle is occupied or unoccupied, whether it hauls a trailer, its remaining fuel or battery charge, driving style preferred by occupants, low tire inflation, or a flat tire. Future versions of this document will analyze these additional modifiers.

The analysis of the modifiers must consider combinations and potential interactions among them, that is, the impact of a modifier on the maneuver behavior may be different based on the presence or absence of other behavior modifiers.

3. Emergency Maneuvers on Structured Roads

Emergency maneuvers are maneuvers aimed at minimizing the risk of a crash in emergency situations, such as in near-crash situations, crash situations, safety-critical system failures, and ODD violations. Crash risk minimization means that driving qualities other than safety, such as comfort, progress, or fuel efficiency, may play little or no role in their execution. For example, crash avoidance and mitigation maneuvers may involve deceleration and jerk levels far beyond those considered comfortable for the vehicle occupants.

The following types of emergency maneuvers are considered:

1. *Crash avoidance maneuvers*: These maneuvers are performed in near-crash situations.
    a. *Stability recovery maneuvers*: the objective of these maneuvers is to recover vehicle stability, such as skid and roll stability.
    b. *Emergency braking maneuvers*: the objective of these maneuvers is to avoid a near crash, such as a near collision, a near road departure, or near immersion, by applying braking.
    c. *Emergency steering and braking maneuvers*: the objective of these maneuvers is same as the previous, but by using both emergency braking and evasive steering.
2. *Crash mitigation maneuvers*: These maneuvers are performed in crash situations, that is, when a crash is unavoidable, in order to minimize the crash severity.
    a. *Emergency braking to mitigate a crash*;
    b. *Emergency steering and braking to mitigate a crash*;
3. *Fallback maneuvers*: These maneuvers are performed to brig the vehicle to a *minimal risk condition* [LA] after a system failure that prevents the completion of the trip or when the vehicle is about to or has exited its ODD.
    a. *Emergency pullover to the side of the road*: the maneuver is to move to the side of the road at the closest available location and stop there;
    b. *Limp to a stop location*: when the vehicle can do so safely, it may limp to a more desirable location than the closest side of the road, such as a parking lot; and
    c. *Emergency stop in lane*: in extreme cases, such as a steering tie-rod failure, the vehicle may be incapable of steering to the side of the road.

4. Maneuver Analysis Method

Maneuver analysis followed in this document involves these steps:

1. *Defining the maneuver objective*. For example, the objective of lane maintenance is to drive within the boundaries of a given traffic lane in the direction of the lane, while responding to various interfering elements in the

driving environment, including road users, other obstacles, and environmental conditions.

2. *Determining maneuver parameters*. Maneuver parameters are used in the behavior definition. They are normally established iteratively, as the individual behaviors that are part of the maneuver are analyzed.
3. *Determining entry*. Entry conditions are preconditions required to initiate the maneuver.
4. *Determining triggers.* These are conditions or events that trigger the maneuver.
5. *Determining exit conditions* Exit conditions include conditions that must be met in order to terminate the maneuver, but also conditions that the maneuver should guarantee upon termination, whether it was an orderly completion of the maneuver or an abort. This step also identifies the maneuvers that may follow.
6. *Determining maneuver duration range*. Except for lane maintenance, most maneuvers have short duration, in the order of seconds to minutes.
7. *Base case behavior analysis*. Base case represents the simplest form of the maneuver. For example, the base case for lane maintenance is driving in a traffic lane on straight, flat, and level road, with no interference from other road users or obstacles, and in good environmental conditions. Behavior analysis considers one of the underlying longitudinal basic motion control tasks at a time: acceleration, deceleration, and maintaining speed (cruising or stopped) [BM18]. For the base case of lane maintenance, the behaviors to be analyzed would include acceleration, deceleration, and maintaining speed on straight, flat, and level road, with no interference from other road users or obstacles, and in good environmental conditions. The base case for a maneuver may include a *procedure*; for example, lane change starts with signaling, followed by lateral movement into the target lane. For each of the analyzed behaviors, scoring with respect to the driving qualities, namely, safety, comfort, progress, and energy consumption, is established. Further, perception and control requirements related to the maneuver are also identified.
8. *Behavior analysis in the presence of combinations of behavioral modifiers*. The effect of each behavioral modifier on the base case is analyzed, considering the different basic motion control tasks, driving qualities, procedure, and perception and control requirements. Subsequently, behavioral interactions among subsets of modifiers are analyzed and the specific behaviors due to interactions are specified.

5. Primary Maneuvers in Normal Driving on Structured Roads

The following subsections analyze the primary maneuvers.

5.1 Lane maintenance (LM)

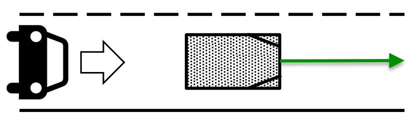

Figure 4: Lane maintenance

Objective: The task is to drive forward within the boundaries of a given traffic lane in the direction of the lane (Figure 4), while responding to various interfering elements in the driving environment, including road users, other obstacles, and environmental conditions. The subject vehicle must not cross either of the lane boundaries.

Parameters: Lane maintenance may take parameters determining the tradeoffs between extra safety, progress, comfort, and fuel efficiency. For example, the policy of accommodating requests by other vehicles to merge in front of the subject vehicle may be more or less generous depending on trip urgency.

Entry condition: The subject vehicle is set-up for forward movement. The vehicle position and heading in a traffic lane are such that the vehicle can plan and execute a feasible path to continue driving within the lane boundaries without crossing them. The vehicle can enter this maneuver from any of the other primary emergency maneuvers that places it into a traffic lane in the direction of travel.

Exit condition: The task is terminated whenever the subject vehicle starts executing a maneuver to leave the lane or has crossed the lane boundary, whichever occurs first. The vehicle can subsequently enter any of the other primary maneuvers that are applicable to the vehicle pose at that time or an emergency maneuver.

Duration: The maneuver may extend over long periods of time, even hours, such as when driving on a highway in low traffic.

Perception: For the base case, the task requires perceiving lane boundaries and the position and heading of the subject vehicle in relation to the lane boundaries and the lane centerline within the stopping sight distance and with sufficient accuracy. Based on existing experience in automated driving, maximum acceptable uncertainty is about 10 cm for position and 1 degree for heading. Note that the lane boundary may be temporarily occluded within the stopping sight distance, for example, by another vehicle changing lanes in front of the subject vehicle. As long as the ADS of the subject vehicle can infer the lane boundaries with certainty, for example, based on observing them before the occlusion has occurred, the requirement would be satisfied. Additional elements must be perceived as discussed in the cases related to behavior modifiers.

Control: This maneuver is realized through longitudinal and lateral motion control tasks in basic motion control, and must respect the vehicle stability and motion comfort scoring of these tasks.

LM0. *Base case analysis*

Driving environment assumptions:

1. straight, flat and level road;
2. sufficiently wide lane (accommodates the vehicle width and minimum lateral clearance to lane boundaries; the later depends on localization accuracy);
3. lane boundaries may or may not be delineated by lane boundary marking (such as pavement marking or flexible lane delineator bollards);
4. no obstacles on the roadway (no road users in the vicinity of the subject vehicle, no other obstacles or road surface damage); and
5. good visibility, lighting, and road surface conditions.

Desired behavior in the base case is to trace the centerline of the lane. This best practice refines the formal traffic rule requirement to drive within a traffic lane in the direction of the lane.

In addition to scoring as specified in the longitudinal basic motion control tasks [BM18], the closeness to the lane centerline, with deviations measured as cross-track error and heading error should be assessed. In particular, unintended crossing of lane boundary would constitute a failure of this task.

Vehicle speed must respect the ACDA rule [S18]. In particular, the stopping sight distance must remain within the sight (perception) distance. Sight distance is one within which the ADS can perceive the road boundaries and any driving environment elements that may require a response, such as upcoming curves, other road users, regulatory traffic signs, and obstacles. Stopping sight distance is the distance required to being a vehicle to a stop after detecting the need to stop (e.g., an obstacle).

It terms of progress requirements, the vehicle should select the highest operating speed that is safe and legal. In this base case, the maximum safe speed is determined by the ACDA rule, and the maximum legal speed is determined by the statutory speed limit that applies to the travelled road.

Analysis in the presence of behavior modifiers

The main impact of the behavior modifiers on lane maintenance behavior, including their interactions, is as follows.

LM1. *Horizontal curves*

Horizontal curves impose an additional speed limit due to vehicle stability. The following formula relates the side friction coefficient μ_y required to hold the subject vehicle in a curve of radius R in meters and superelevation e in m/m when travelling at a constant speed v in km/h (see [S18] for a detailed explanation):

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

Thus, the speed limitation due to the centripetal force depends on the curve radius, the available peak road friction, and the superelevation of the curve. Most roads in Ontario adopt maximum superelevation of 0.06 m/m on curves. The formula ignores aerodynamic forces due to crosswind (listed as a separate modifier).

The second factor limiting the speed is the ACDA rule. When driving on a horizontal curve, the sight distance is computed differently than on a tangent. Figure 5 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]:

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

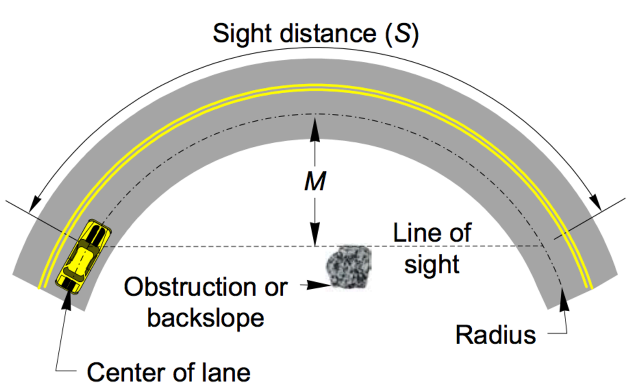

Figure 5 Sight distance at a horizontal curve [WS16]

The stopping sight distance is also affected on a curve since the side friction force necessary to keep the vehicle in the curve reduces the peak longitudinal friction coefficient, and thus the maximum available longitudinal braking force. The exact reduction of the stopping sight distance depends on the tire model, but the overall result is that curve stopping sight distance is longer than the tangent stopping sight distance.

The desired procedure to navigate curves is as follows [MA70]:

1. On approach to a curve, decelerate to the safe speed for traversing the curve before entering the curve. This step will reduce the need to brake in the curve and thus provide more safety margin to deal with unexpected situations that require braking.
2. Traverse the curve, while tracing the lane centerline, at constant, safe speed.
3. If the curve is followed by a tangent that allows a higher safe speed than the curve, initiate acceleration to this speed on exiting the curve.

When traversing composite curves of different radii, braking in a curve may be necessary to reduce the speed for the next curve of a smaller radius. While the vehicle speed could be reduced to the minimum of the maximum speeds for each section of the composite curve before entering the first curve, there is a potentially significant tradeoff with progress. For example, when a sharp corner follows a flat and long curve, it may be reasonable to brake just before the sharp corner while still in the flat curve.

LM2. *Vertical curves*

Crest curves limit the sight distance and thus impact the ACDA rule, potentially reducing the safe speed limit (Figure 6; see [WS16] for calculations).

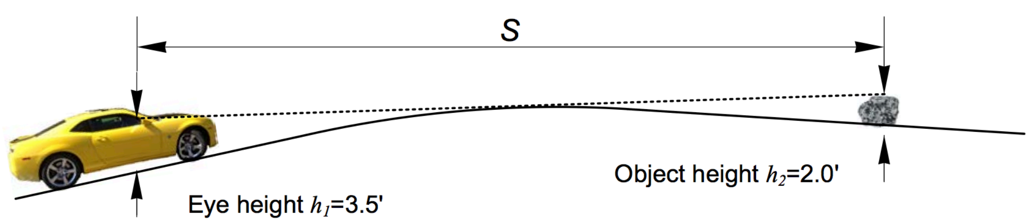

Figure 6 Sight distance at a crest curve [WS16]

Vertical and horizontal curves interact with respect to sight distance. Crest vertical curves make roadside objects more likely to become sightline obstructions for horizontal curves. Sag vertical curves make roadside objects less likely to be sightline obstructions [WS16].

Accelerating on an upgrade is more friction-limited than accelerating on a downgrade. Similarly, decelerating on a downgrade is more friction-limited than decelerating on an upgrade. This aspect is covered by the basic motion control tasks and vehicle stability.

LM3. *Cross-section design (lane and road-side structure)*

Transversal lane structure impacts lane maintenance in combination with other road users, such as the presence of adjacent lanes and driveway access points creating the possibility of other vehicles merging into the lane of the subject vehicle (see road user modifier – LM8).

The roadside design, including its furniture, vegetation, and drainage channel, interacts with the road user and animal modifiers since other road users and animals may suddenly emerge from occluded spaces. Also, certain types of other obstacles may be co-related with roadside design, such as potential for falling rocks.

Finally, the roadside design impacts planning and execution of emergency maneuvers.

LM4. *Regulatory traffic signs and signals and other traffic control devices*

The main type of regulatory signs affecting lane maintenance is speed control signs. Another type of traffic control devices affecting lane maintenance is vertical deflections. They both impose speed limits.

STOP and YIELD signs and regulatory signals relate to intersecting lanes and pedestrian and bicycle facilities. Thus, they are handled in secondary maneuvers that extend lane maintenance, such as handling intersections and pedestrian crossings. An exception is the regulatory signal that accompanies the "school zone maximum speed when flashing" sign, which imposes a speed limit when the signal is flashing.

LM5. *Intersecting vehicular lanes, rail tracks, and pedestrian and cyclist facilities*

These roadway configuration aspects are handled by secondary maneuvers like intersection handling and pedestrian crossing handling.

Responding to vehicles diverging into and merging from driveways is part of lane maintenance and covered under LM8.

LM6. *Temporary structure*

Temporary structure may redefine lane structure through road and lane closures and temporary lane re-assignment. An ADS needs to recognize the new temporary lanes and the additional traffic control devices, such as work zone speed limits, in order to navigate through the temporary structure.

The analysis of this aspect is out of scope of the current version of this document.

LM7. *Bridges and tunnels*

Normal driving in bridges and tunnels requires special considerations:

1. Tunnels interact with horizontal curves, limiting the perception distance. Vertical curves in a tunnel also limit perception distance by limiting sight across a sag.
2. Driving in tunnels may require increasing conspicuity by using headlights.
3. Bridges may have an increased risk of slippery road surface conditions and strong crosswinds.

Emergencies in tunnels and on bridges also require special consideration.

1. Potential fires in tunnels need to be recognized before entering.
2. Fallback maneuvers initiated in tunnels and on bridges should normally aim at completely traversing the tunnel or bridge before stopping at the side of the road.

LM8. *Road users*

The subject vehicle must respond appropriately to other road users, including cars, trucks, buses, motorcycles, cyclists, and pedestrians.

A number of specific behaviors induced by the presence of other road users are considered:

1. Responding to traffic in adjacent lanes;
2. Road user following;
3. Responding to being followed by a vehicle;
4. Responding to diverging front vehicle;
5. Responding to vehicles merging in front;
6. Responding to vehicles merging in rear;
7. Responding to being overtaken;
8. Respond to opposing traffic in lane;
9. Respond to vehicles crossing in front;
10. Passing vehicles parked at the curb and partly on the host vehicle lane with sufficient passing space in the lane;
11. Responding to pedestrians intending to enter the roadway (individuals and groups);
12. Responding to pedestrians in the roadway (individuals and groups);
13. Responding to cyclists;
14. Responding to motorcycles performing lane splitting; and

15. Responding to emergency vehicles.

When interacting with road users, both their normal and aberrant behaviors need to be considered. The vehicles and pedestrians lead to a multitude of behavioral interactions: the different numbers and configurations of road users may interact among themselves and with the subject vehicle, and the interactions depend on the road configuration, other obstacles, and environmental conditions.

LM8.1 *Responding to traffic in adjacent lanes*

The presence of traffic in adjacent lanes or shoulder may require adjusting the lateral position of the subject vehicle off the centerline of the traveled lane in order to accommodate minimum lateral clearance or to provide an extra margin on the minimum lateral clearance to the adjacent traffic.

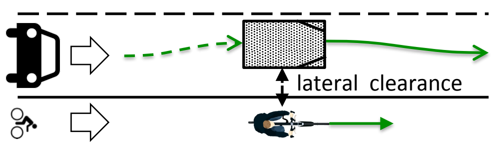

Figure 7 Double swerve within lane in response to a cyclist in an adjacent bicycle lane

This adjustment may be implemented as a *double swerve within the travelled lane* (Figure 7), or by driving *offset* from the lane centerline for extended distances if required. A *swerve in lane* implements the lateral movement from the centerline to the offset position.

The magnitude of the lateral adjustment depends on type of the adjacent traffic, its position in the adjacent lane(s) or shoulder, and its direction of travel.

German guidelines recommend the following lateral clearance when passing these types of road users [S18]:

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.

A minimum of 1.5 m lateral clearance to pedestrians walking along the curb should also be observed.

In the case of stopped school buses, passing or overtaking may be prohibited, depending on the local traffic rules and the signaling on the bus, in which case the subject vehicle traveling behind the bus must stop and wait.

Ensuring minimum lateral clearance on both sides of the subject vehicle is the first priority when deciding the lane position. Given that this constraint is satisfied, and the only present or expected adjacent traffic are cars, trucks, and buses, extra lateral clearance may be added for opposite traffic (because of the higher relative speed and thus higher severity of a potential collision). In the presence of vulnerable road users, such as pedestrians, pedalcyclists, and motorcycles, extra lateral clearance should be added to protect these users. The subject vehicle speed should be reduced when passing a pedestrian or a pedalcyclist. Maximum passing speed of 30 km/h is a reasonable target; the risk of a severe pedestrian injury when struck by a car at 30 km/h is about 10%; that risk increases close to 40% for a strike at 50 km/h (see [S18] for a more detailed discussion).

Further, child pedestrians or child cyclists require extra lateral clearance, because they are less familiar with proper behavior in traffic and are more likely to suddenly move into the path of the subject vehicle than adult road users. A further speed reduction for children and elderly is warranted since they are at a higher risk of severe injury than middle-aged adults. For example, the risk of severe injury when struck by a car at 30 or 50 km/h for 70 year olds is about double of that for 30 year olds (see [S18]). Similarly, extra lateral clearance should be observed in the case of impaired road users, such as visibly disabled, intoxicated, erratic drivers, cyclists, or pedestrians (see [S18]).

LM8.2 *Road user following*

Road user following is the case of lane maintenance where another road user (e.g., car, truck, bus, tractor, motorcycle, and bicycle) travels in front of the subject vehicle in the same lane and direction as the subject vehicle and constrains the vehicle's movement. The road user in front could also be a pedestrian or a group of pedestrians; the need to follow a single or a group of pedestrians is rare, but may be required in some cases, such as following a precession until there is an opportunity to pass or overtake. For narrow road users travelling side-by-side in the lane, such as single-track vehicles and pedestrians, there can be more than one front road user simultaneously.

The remaining description focuses on the single front vehicle following case.

Figure 8 shows the gaps during vehicle following in a single lane.

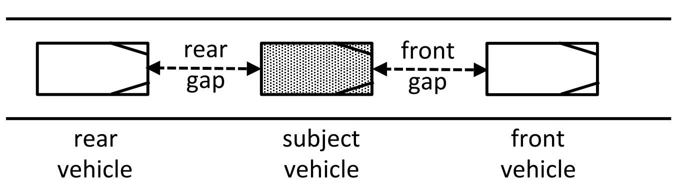

Figure 8 Gaps during vehicle following in a single lane [DP15]

Vehicle following is divided into two modes:

1. *front-vehicle approach*: the subject vehicle needs to decelerate as it approaches a slower front vehicle, and
2. *gap maintenance*: the subject vehicle maintains a minimum gap to the front vehicle.

Lane maintenance that is not constrained by other vehicles is called *free driving*.

A scenario may follow this sequence of modes:

1. free driving;
2. front-vehicle approach;
3. gap maintenance;
4. free driving, as the front vehicle recedes or diverges.

As any driving task, vehicle following is subject to driving qualities. The key driving qualities affecting vehicle following are safety, traffic flow, and comfort.

The main safety concern in vehicle following is maintaining sufficient front gap (Figure 8). This includes minimum time gap when vehicle is in motion, and minimum distance gap at standstill. A range of factors require increasing the minimum front gap to 5-6 seconds:

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.

These requirements are discussed in detail elsewhere [S18].

In terms of comfort and traffic flow, the vehicle following behavior should aim at achieving a smooth, comfortable ride and damping of traffic flow disturbances. In particular, smooth transition between time gap at non-zero speed and distance gap at standstill should be achieved (e.g., see [FS09, FM17]). Further, the following gain should not be positive in order not to amplify the disturbances (see J2944:2015-06 for car following driver performance measures). Dampening of flow-disturbances can be improved by perceiving the state and intentions of multiple vehicles ahead, such as in the case cooperative driving based on wireless communication (see [CA18] for cooperative adaptive cruise control performance requirements).

Cooperative driving may also allow to safely reduce gaps in order to improve road utilization.

While following, the subject vehicle must respond to merging vehicles (LM8.5 and LM8.7). While maintaining a safe gap, the gap should not be too large to invite other vehicles to cut in. Further, the subject vehicle must balance the front and rear gap (LM8.3) and also anticipate potential sudden stops affecting vehicles in front, such as responding to pedestrians or animals darting into the roadway or crashes.

In order to perform the vehicle following task, the ADS must perceive the front gap and the subject and front vehicle speed, and preferably also acceleration, with sufficient certainty. The ADS should perceive the brake and signal indication lights in order to anticipate deceleration of the front vehicle. It should also perceive events ahead the front vehicle that may necessitate braking of vehicles ahead of the front vehicle, such as stopped vehicles and road users or animals entering the roadway. Finally, the ADS should perceive the conditions in which the front gap needs to be increased.

LM8.3 *Responding to being followed by a vehicle*

Normally, the rear vehicle is responsible for maintaining adequate rear gap (Figure 8). However, the subject vehicle must monitor the rear gap and the braking response of the rear vehicle when braking itself. In particular, when following and being followed closely, the subject vehicle should increase the front gap in order to have more maneuvering space should the front vehicle suddenly decelerate; the increase of the front gap should be limited when there is a potential of a cut in from an adjacent lane, such as in dense traffic. Further, when the rear vehicle is being tailgated, tailgating response strategies discussed elsewhere [S18] should be considered.

LM8.4 *Responding to diverging front vehicle*

When the front vehicle is diverging, that is, making a lane change or a turn while the subject vehicle continues in the travelled lane, the subject vehicle may need to decelerate in anticipation of the front vehicle slowing down. Ideally, the front vehicle signals the diverging maneuver giving an advance notice to the subject vehicle.

A special case is when the front vehicle approaches another vehicle stopped in front of it and then suddenly diverges just before that stopped vehicle. The subject vehicle must be able to detect the stopped vehicle and react by braking or evasive steering as soon as possible.

LM8.5 *Responding to vehicles merging in front*

Another vehicle may intend to merge in front of the subject vehicle through a lane change (Figure 9) or when joining traffic from curb parking or a driveway (Figure 10).

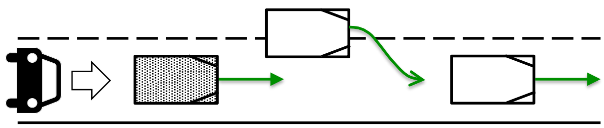

Figure 9 Responding to a lane changing vehicle merging in front

The subject vehicle needs to be able to perceive the merge intent of the other vehicle, both by detecting signal lights and the movement of the other vehicle.

Vehicles intending to merge in front of the subject vehicle through a lane change would normally indicate it using signal lights and possibly a "nudging" lateral movement. The subject vehicle should accommodate this request by decelerating to increase the front gap when feasible. When being followed, the rear vehicle is expected to slow down in order to maintain a safe rear gap. The subject vehicle must react to the other vehicle cutting in front of it, that is, the other vehicle proceeding with the merge in front of the subject vehicle even if the gap is not sufficiently large.

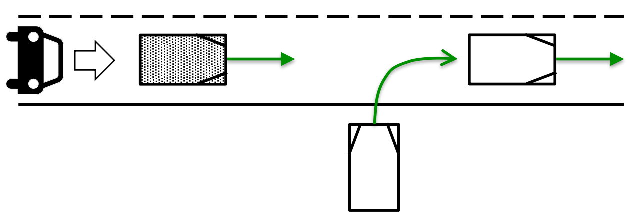

Figure 10 Responding to a vehicle turning into a lane and merging in front

The subject vehicle has priority over a vehicle joining traffic (such as through a swerve or turn into the traffic lane of the subject vehicle); this means that the vehicle joining traffic must await a sufficient gap in order to join traffic without causing the subject vehicle to decelerate. The subject vehicle must react to the other vehicle cutting in front of it, however.

When the merging vehicle cuts in, the subject vehicle must decelerate to avoid a collision, while monitoring proper braking reaction of the rear vehicle, and then restore a sufficient front gap, i.e., in good driving conditions, no less than one second time gap when moving and no less than 3 m distance gap at standstill (see [S18]). In extreme cases of a cut in, the subject vehicle may have an opportunity to execute an emergency steering maneuver to escape into an adjacent lane. Also, when the subject vehicle recognizes that two vehicles (see Figure 11), one from the lane left to the travelled lane of the subject vehicle and the other from the lane to the right, initiate a lane change into the same gap in front of the subject vehicle, the subject vehicle should decelerate more aggressively, if possible, in order to leave space for the resolution of the merge conflict. The subject vehicle should also use the horn to warn the two vehicles of the conflict situation.

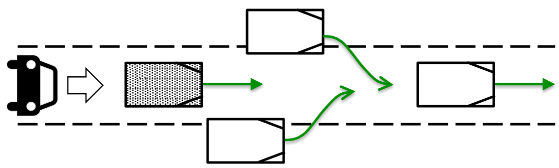

Figure 11 Responding to merge conflict from opposite sides in front

LM8.6 *Responding to vehicles merging in rear*

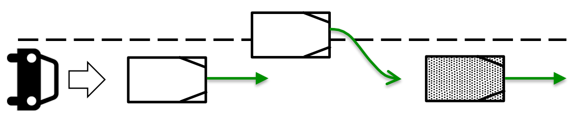

Figure 12 Responding to a lane changing vehicle merging in rear

The subject vehicle should accommodate another vehicle merging in rear by accelerating to increase the rear gap when there is no front vehicle or the front gap is sufficient. Normally, the rear vehicle is expected to slow down to provide most of the required rear gap increase.

The subject vehicle needs to be able to perceive the merge intent of the other vehicle, both by detecting signal lights and the lateral movement of the other vehicle.

LM8.7 *Responding to being overtaken*

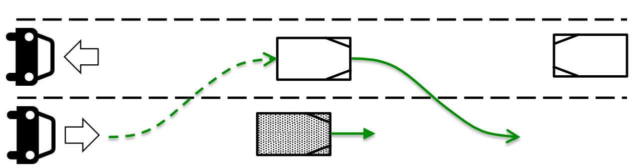

Figure 12 Responding to being overtaken

When being overtaken by another vehicle, the subject vehicle should decelerate in order to allow for a safe lane return of the overtaking vehicle, which includes ensuring sufficient front gap for the overtaking vehicle to merge and to shorten the exposure of the overtaking vehicle to potential oncoming traffic on the opposite lane. In the case of the oncoming gap misjudged by the overtaking vehicle, the overtaking vehicle may wish to return into the rear gap of the subject vehicle when that gap is closer than the front gap; in that case, the subject vehicle may accelerate to help the overtaking vehicle to return into its rear gap. Also, whenever the oncoming gap turns out to be too short for the overtaking vehicle, the subject vehicle should, in addition to longitudinal speed adjustments, swerve out of the lane to the right, for example, onto the shoulder, if feasible, in order to allow for the opposing vehicles to pass.

In normal driving situations, the response to being overtaken should ensure safe return while minimizing unnecessary delays of the subject vehicle and the following vehicles.

The subject vehicle must perceive the overtaking vehicle and also the assured clear distance ahead of that vehicle (see [S18]) and its opposing traffic in order to judge the necessary response.

LM8.8 *Respond to opposing traffic in lane*

The subject vehicle may be subjected to opposing traffic in a number of scenarios:

1. *Constrictions*: A roadway constriction, such as vehicles parked on both sides of the roadway, may allow only one vehicle at a time to pass through it. In this case, the subject vehicle will need to negotiate its passage with the opposing traffic.
2. *Forced overtaking*: The opposing vehicle in the travelled lane may have forced overtaking another vehicle on the opposite lane even though the oncoming gap to the subject vehicle was insufficient for this maneuver. The subject vehicle may need to slow down in order to allow for the overtaking vehicle to safely return to the opposite lane. In extreme cases, the subject vehicle may need to perform an emergency maneuver by steering to the right in order to avoid a collision with the opposing traffic.
3. *Incursion from opposite lane*: The opposing vehicle may cross the directional dividing line unintentionally (e.g., due to driver fatigue), or because of extra wide cargo, or as a result of an obstacle avoidance maneuver. The subject vehicle may need to emergency steer to the right in order to avoid a collision.
4. *Wrong driving*: The opposing vehicle may be driving in the travelled lane of the subject vehicle in the wrong direction in error. The subject vehicle may need to emergency steer in order to avoid a collision.

LM8.9 *Respond to vehicles crossing in front*

The case of another vehicle crossing in front of the subject vehicle (Figure 13) typically occurs when the other vehicle leaves a driveway and crosses the travelled lane of the subject vehicle to join opposite traffic. It also occurs when the other vehicle makes a U-turn from or into a lane to the right of the travelled lane of the subject vehicle. Note that cross traffic at intersections and crossings is handled separately by secondary maneuvers.

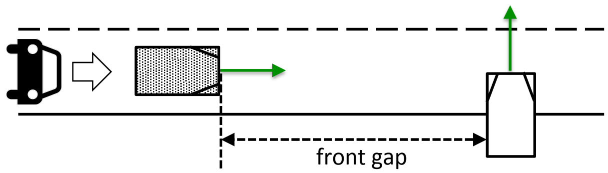

Figure 13 Responding to a vehicle crossing in front

The subject vehicle will normally have priority; however, it must react when the crossing vehicle forces its way, or is already crossing (for example, the subject vehicle and the crossing vehicle may be at opposite ends of a curve and invisible to each other on initial approach). Based on a predicted trajectory and time-to-collision calculation, the subject vehicle recognizes whether it is on a collision course with the other vehicle, in which case it must decelerate. The subject vehicle must ensure that the other vehicle cleared the path ahead before the subject vehicle can proceed.

The subject vehicle should observe a minimum front distance gap to the crossing vehicle of 3 m and right and left lateral clearance at least 1 m (same as the recommended minimum lateral distance for cars and trucks [S18]). The front gap corresponds to the typical minimum distance between the stop line and the vehicles traveling in the crossing lane closest to the stop line; this distance assumes 1.15 m of lateral clearance between the crossing vehicle and the edge of the roadway, 1.25 m minimum distance between the roadway edge and the stop line, and 0.6 m width of the stop line, which are standard parameters in Ontario [OMT11].

LM8.10 *Passing vehicles parked at the curb and partly on the subject vehicle lane with sufficient passing space in the lane*

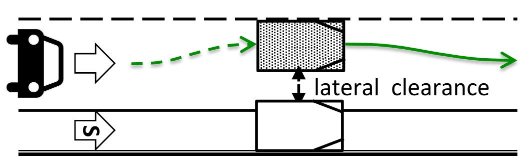

Figure 14 Passing a parked vehicle with sufficient passing space in the lane

Minimum lateral clearance to the parked vehicle is 1 m [S18]; however, the subject vehicle needs to detect doors that are open or being open on the left side of the parked vehicle.

There is also the possibility of the parked vehicle joining traffic; the parked vehicle should announce this maneuver using directional signal, but it may fail to do so.

Also, extra caution is needed to early detect and react to pedestrians who may suddenly emerge from behind a parked vehicle.

LM8.11 *Responding to pedestrians intending to enter the roadway (individuals and groups)*

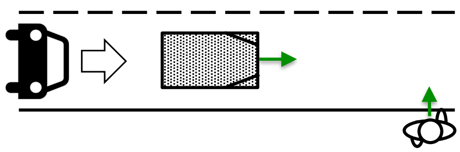

Figure 15 Responding to a pedestrian intending to enter the roadway

Normally, the vehicle has priority outside of marked pedestrian crossings. However, the ADS should have capability to detect the intent of pedestrians to immediately enter the roadway, and it should slow down when pedestrians with such intent are detected ahead. The presence of a shoulder and a boulevard create a safety buffer between the vehicle and the pedestrian intending to enter the roadway. The subject vehicle should also signal its intent to the pedestrian using appropriate visual means (such as using external lighting, see the upcoming SAE J3134 standard).

Some indications of the immediate intent include walking or running towards the edge of the roadway without slowing down, resuming walking or running after stopping at the edge, or making certain hand gestures.

LM8.12 *Responding to pedestrians in the roadway (individuals and groups)*

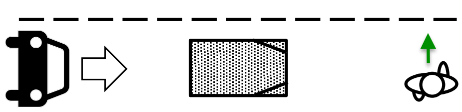

Figure 16 Responding to a pedestrian in the roadway

Pedestrians may enter the roadway for a wide range of reasons [O18b], including

1. *crossing* the roadway mid-block;
2. *walking along* the curb on the roadway, especially where no sidewalk is available;
3. *accessing vehicles* parked at the curb;
4. *performing work*, such as cleaning or repair; and
5. *playing* on the roadway; for example, some city bylaws allow and regulate playing road hockey on public roads;
6. *retrieving an object,* such as a soccer ball;

7. *riding skateboard, roller skates,* and *in-line skates* and similar devices on the roadway; and
8. *lying on the pavement*, such as fainted or struck by another vehicle.

The subject vehicle must stop and wait for a crossing pedestrian until the path ahead is clear. It may pass or overtake pedestrians walking along or performing work at the curb. It should stop for a pedestrian lying on the pavement and call for help.

The subject vehicle must observe front gap and right and left lateral clearance to a pedestrian of minimum 1.5 m [S18]. The minimum distance for should be larger for children, who may not have experience in traffic and may be unfamiliar with traffic rules.

When passing or overtaking a pedestrian, the subject vehicle should reduce speed below 30 km/h.

The subject vehicle must initiate emergency braking or steering for pedestrians dashing or darting onto the roadway in front of the vehicle.

Extra caution is needed to early detect and react to pedestrians who may suddenly emerge from occluded spaces, such as parked vehicles, stopped vehicles in the adjacent lane, and roadside vegetation.

LM8.13 *Responding to cyclists*

Cyclists may be riding along the roadway on different parts of it:
1. shoulder;
2. bike lane;
3. shared curb lane;
4. vehicular lane; and
5. lane splitting, i.e., on the lane boundary.

The subject vehicle may be following a pedalcycle (LM8.2) or drive in adjacent lane (LM8.1), or be responding to the pedalcycle merging in front (LM8.5) or crossing in front (LM8.9). The pedalcycle may also be stopped in the roadway.

The subject vehicle must observe front gap and right and left lateral clearance to a pedalcycle of minimum 1.5 m [S18]. The minimum distance for child riders, who may not have experience in traffic and may be unfamiliar with traffic rules, should be larger.

The ADS should perceive hand signals of cyclists ahead and accommodate their turns and merges.

The subject vehicle must initiate emergency braking or steering for pedalcycles that enter the roadway suddenly in front of the vehicle or make a sudden turn into the path of the subject vehicle.

LM8.14 *Responding to motorcycles performing lane splitting*

Motorcycles are treated similar to cars (LM8.1-10). However, *lane splitting*, that is, driving along the boundary of two lanes on a multi-lane road, deserves special attention. Lane splitting is legal in some jurisdictions, but may still occur anywhere even if illegal.

The subject vehicle should try to keep the required lateral clearance of 1.5 m from motorcycles, if feasible.

LM8.15 *Responding to emergency vehicles*

Emergency vehicles that are using flashing red or red and blue lights, or siren or bell sounding, require priority treatment in traffic. The subject vehicle must recognize an emergency vehicle with its signals on approaching from any direction and pull to the right curb of the roadway on two-way roadways or the nearest edge on multi-lane roads and stop parallel to the curb in order to make space for the emergency vehicle to pass safely. The subject vehicle should not block the shoulder where emergency vehicles may use it, such as on highways. The subject vehicle may resume driving once the emergency vehicle is a certain distance away. In Ontario, this distance is 150 m.

LM9 *Animals on the roadway or the roadside*

Several best practices concern responding to animal encounters in traffic. The main deciding factor is the animal size [O18b]. Small animals in the roadway normally do not pose any risks to vehicle occupants. In low-speed areas with no traffic, it may be possible to stop and wait for small animals crossing the roadway or to creep forward to force them out of the way. Unsupervised medium size and large animals that are in the roadway or may likely enter the roadway and are detected well in advance require speed reduction and potentially stopping. Driving around animals is not advisable as their behavior is largely unpredictable. Suddenly appearing medium size and large animals require emergency braking. Large animals may also require emergency steering. Wild animals often travel in groups; thus, sighting one crossing animal increases the risk of additional animals crossing the road. Animal activity also depends on the time of the day and the lighting conditions.

LM10 *Other obstacles in the roadway*

Small objects that fit under the car or clearly recognizable light objects, such as transparent plastic bags, usually do not require trajectory adjustment. Larger objects in the path of the subject vehicle normally require steering to avoid them, while maintaining sufficient lateral clearance, and potentially slowing down depending on the amount of steering. When passing the obstacle is not passible without departing the lane, other maneuvers such as lane change, overtaking, or an out-of-lane swerve are necessary to allow progress. When approaching a constriction, such as a narrow roadway section with vehicles parked on both sides, the subject vehicle must be able to judge whether there is enough space to proceed through the constriction. Also, negotiation with oncoming traffic may be required (see LM8.8).

LM11 *Visibility conditions*

Reduced visibility, for example due to precipitation or other atmospheric obscuration, reduces perception distance and thus affects the ACDA rule. Minimum clearance to other road users and objects should also be increased (see [S18]), because of the increased risk of human road user mistakes, such as driving too fast for the conditions or simply not seeing obstacles, and also the likely reduced accuracy of object tracking and localization.

LM12 *Lighting conditions*

Poor lighting conditions have similar effects as poor visibility and necessitate similar responses. Additionally, the ADS must avoid blinding human road users with headlights, which requires the appropriate use of low and high beam and keeping enlarged following distance.

LM13 *Wind*

Strong cross-winds may affect vehicle stability, especially in slippery conditions. They are particularly common and risky on long and exposed bridges. Head and tailwinds affect speed control and energy consumption.

LM14 *Road surface conditions*

General roads surface conditions include accumulation of precipitation; contamination, such as oil, salt, sand, mud, and leaves; and surface texture and damage (see [O18b]). Slippery road surface affects vehicle stability, especially in horizontal and vertical curves (such as starting on upgrade), the ACDA rule (by reducing the stopping sight distance), and requires increasing minimum separation. Road surface cover affects visibility of road marking.

5.2 Lane changing (LC)

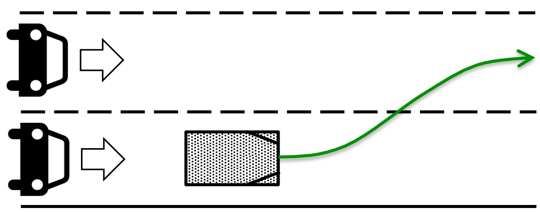

Figure 17 Lane changing

Objective: The task is for the subject vehicle to swerve from the current traffic lane driven forward in the direction of the lane into a parallel traffic lane that has the same direction of travel as the original one, while responding to various interfering elements in the driving environment, including road users, other obstacles, and environmental conditions.

Whenever the subject vehicle swerves and enters, even partially, the adjacent traffic lane that has the same direction as the original lane, the swerve is considered a lane change.

Lane changes are classified by *reason* as follows [O18b]:

1. *Discretionary lane change*: optional lane change performed to optimize some driving quality, such as progress (e.g., changing into a faster lane);
2. *Mandatory lane change*: lane change necessitated by routing, such as getting into the lane required for a turn or an exit, or by a lane drop or closure.

Lane changes are classified by *target lateral location* in the target lane as follows:

1. *Full lane change*: the target location is the lane center line in the target lane;
2. *Offset lane change*: the target location is offsets from the lane center line in the target lane;
    a. *Offset within target lane*: the target location places the vehicle within the boundaries of the target lane;
    b. *Lane splitting*: the target location results in the subject vehicle occupying both lanes.

Lane changes are classified by the *lateral motion profile* as follows (see [BM18] for details):

1. *Continuous*: the lateral motion from the original lane into the target location is smooth;

2. *Discrete*: the lateral motion from the original lane into the target location is performed in steps with stops in between, such as stopping the lateral movement just before entering a gap in the target lane.

A special case is when the source and target lanes are not adjacent, e.g., when three or more lanes are available in one direction. Normally, such case is handled by multiple lane changes, but a single lane change spanning multiple lanes could also be used.

Parameters:
1. Target lateral position in the target lane (centerline or some offset);
2. Dynamism of the lane change (targets for maximum lateral acceleration and jerk);
3. Parameters influencing decision parameters (gap acceptance and relative speeds);
4. Parameters influencing the lane change intent signaling, such as whether the vehicle only uses its signal lights or also a "nudging" lateral movement to indicate the desired target gap even if the gap is initially too small.

Entry condition: The subject vehicle is set-up for forward movement. The vehicle is located within a traffic lane with position and heading such that the vehicle can execute the lane change maneuver, or is lane splitting. Most commonly, the vehicle will enter this maneuver from lane maintenance, but a lane change could also follow a swerve or turn into a lane, or an emergency maneuver.

Trigger: The following conditions or events may trigger a lane change:
1. Moving towards or into a lane required for a planned turn or exit;
2. Blocked lane;
3. Lane drop;
4. Traffic speed;
5. Passing a slow vehicle;
6. Passing a vulnerable road user;
7. Desired or undesired lane function (passing, through, or shared curb lane);
8. Unsatisfied lane restriction (e.g., high occupancy lane, bus lane); and
9. Pavement quality.

Lane splitting can be part of a passing maneuver triggered by obstacles that do not necessitate a full lane change.

Exit condition: The task is terminated whenever the subject vehicle achieves its target lateral position in the target lane, or whenever another primary or emergency maneuver is initiated, such as a turn out of the lane. Lane splitting is normally followed by another lane change to settle in a lane completely.

The maneuver can only be successfully executed if there is a sufficiently long drivable connection between the current and target lanes.

A lane change may be *aborted* before the subject vehicle settles into the selected target gap, for example when the target gap is closing, in which case the subject vehicle returns into its original lane.

Duration: The maneuver normally takes seconds to execute; typical durations are anywhere between 5 and 10 seconds.

Perception: For the base case, the task requires perceiving the boundaries of the lanes and the position and heading of the subject vehicle in relation to the lane boundaries within the stopping sight distance and with sufficient accuracy. Additional elements must be perceived as discussed in the cases related to behavior modifiers.

Procedure: A lane change has the following steps:

1. Gap acceptance;
2. Intention communication;
3. Deceleration or acceleration to align with a target gap; and
4. Lateral movement into the gap (merge).

Control: This maneuver is realized through longitudinal and lateral motion control tasks in basic motion control, and must respect the vehicle stability and motion comfort scoring of these tasks.

LC0. *Base case analysis*

Driving environment assumptions:

1. straight, flat and level road;
2. sufficiently wide, adjacent source and target traffic lanes (accommodates the vehicle width and minimum lateral clearance to lane boundaries; the later depends on localization accuracy);
3. the subject vehicle can drive across the boundary of the adjacent lanes;
4. lane boundaries may or may not be delineated by lane boundary marking (such as pavement marking);
5. no obstacles on the roadway (no road users in the vicinity of the subject vehicle, no other obstacles or road surface damage); and
6. good visibility, lighting, and road surface conditions.

The lane change can proceed unobstructed and the trajectory is mainly subject to safety and comfort requirements related to vehicle dynamics. The lane change is executed as follows:

1. *Gap acceptance*: not applicable as there is not traffic in the target lane;

2. *Intention communication*: the vehicle must signal the lane change using directional signal light sufficiently ahead of the lateral movement;
3. *Deceleration or acceleration to align with a target gap*: not applicable as there is not traffic in the target lane;
4. *Lateral movement into the gap*: The lane change in the unobstructed case would be a continuous one. The range of possible lane change trajectory dynamics are discussed elsewhere [C18, BM18].

Vehicle speed must respect the ACDA rule [S18], in same way as in the lane maintenance maneuver.

Analysis in the presence of behavior modifiers

The main impact of the behavior modifiers on lane changing behavior, including their interactions, is as follows.

LC1. *Horizontal curves*

Similar to lane maintenance, horizontal curves impose additional speed limits due to vehicle stability and the ACDA rule.

If feasible, a lane change is preferably executed on tangents rather than on curves.

LC2. *Vertical curves*

Similar to lane maintenance, vertical curves impact the ACDA rule, and thus speed limit, and may also limit acceleration or deceleration capacity. The latter may be relevant when interacting with other road users, such as when aligning with the target gap (LC8).

LC3. *Cross-section design (lane and road-side structure)*

First, at least two adjacent traffic lanes of same direction must be present.

Further, the boundary between the adjacent traffic lanes must be drivable along the length of the maneuver; for example, outer separations between such lanes would prevent a lane change. The subject vehicle must be able to judge whether the boundary is drivable and sufficiently long before initiating the lane change.

The presence of additional lanes creates the possibility of more interference from other road users, such as vehicles changing lanes into the same gap from each side (Figure 19).

The roadside design has similar impact as for lane maintenance.

LC4. *Regulatory traffic signs and signals and other traffic control devices*

The same signs, imposing speed limits, as for lane maintenance are applicable to lane changing.

Additionally, lane changes may be prohibited over a certain stretches of the roadway, as posted by no passing zone signs; however, these are more commonly applied to overtaking on two-lane roads.

LC5. *Intersecting vehicular lanes, rail tracks, and pedestrian and cyclist facilities*

Same considerations as for lane maintenance apply here.

LC6. *Temporary structure*

Same considerations as for lane maintenance apply here.

Lane changes may be prohibited in work zones.

LC7. *Bridges and tunnels*

Same considerations as for lane maintenance;

Lane changes on bridges and in tunnels, especially in traffic, should be avoided.

LC8. *Road users*

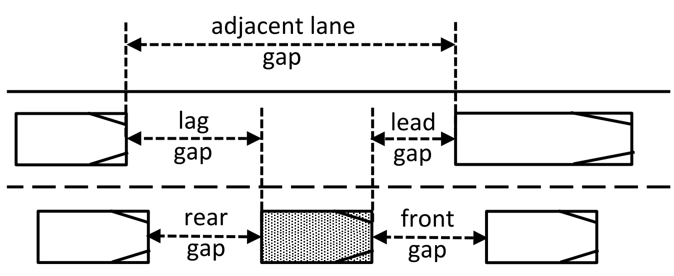

Figure 18 Gaps during lane changing [DP15]

In contrast to lane maintenance, lane changing is concerned not only with the front and rear gap in the source lane, but also with the adjacent lane gap, and the resulting lead and lag gaps (see Figure 18).

Minimum gaps must be ensured, with similar constraints and considerations as the front gap (see [S18]).

Additionally, the stability of the target gap (i.e., the adjacent lane gap) must be considered; in essence, by the time the subject vehicle slides into the target gap, which may be shrinking, the resulting lead and lag gaps must be acceptable (i.e., at least 2 seconds in good driving conditions).

The lane change procedure in the presence of front and rear and lead and lag vehicles is as follows:

1. *Gap acceptance*: Select a sufficiently large and stable target gap in the target lane; a smaller gap may also be selected with the hope that signaling and a discrete lane change may prompt the lead and lag vehicles to widen the target gap;
2. *Intention communication*: Signal the lane change using directional signal light sufficiently ahead of the lateral movement;
3. *Deceleration or acceleration to align with the target gap*;
4. *Lateral movement into the gap*: The lane change may be continuous if the gap is sufficiently large or it may be discrete, pausing the lateral movement until the target gap is wide enough. Sufficient front and rear gap in the source [S18] lane must also be maintained while the subject vehicle moves across the lane boundary. If the target gap is not wide enough or if another vehicle is merging into the target gap from the other side, abort the lane change and return to the target lane. Also, if another vehicle attempts to enter the same gap as the subject vehicle, the merge conflict must be recognized and the lane change aborted (Figure 19).

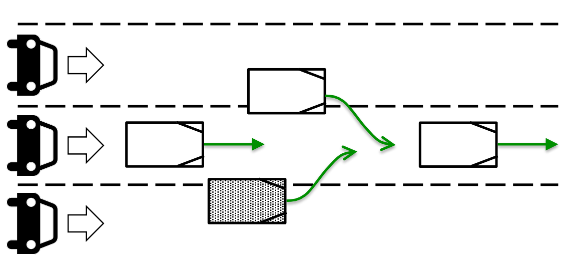

Figure 19 Merge conflict during a lane change

A number of specific behaviors induced by the presence of other road users are considered (other than the already considered front and rear and lead and lag vehicles):

1. *Responding to diverging front or lead vehicle*: The front vehicle or the lead vehicle may signal divergence; the subject vehicle must anticipate the front or lead vehicle deceleration, which may affect lane change planning.
2. *Responding to vehicles merging in front*: Same considerations as for lane maintenance apply here. Also, the subject vehicle should avoid a lane change into the original lane of the merging vehicle at the same time.
3. *Responding to vehicles merging in rear*: Same considerations as for lane maintenance apply here.
4. *Responding to being overtaken*: This case normally does not occur on a multilane road when the subject vehicle can change lanes; however, a vehicle performing such maneuver (in error) should be accommodated similarly as in lane maintenance.
5. *Respond to opposing traffic in lane*: Same considerations as for lane maintenance apply here. Evasive steering maneuver into opposite lane may be necessary if the adjacent lane to the right is occupied. On a 2+1 road, the subject vehicle driving in the right lane of the wider side of the roadway must ensure that no overtaking vehicle is oncoming before performing a lane change into the left lane.
6. *Respond to vehicles crossing in front*: If cross traffic is present, same consideration as for lane maintenance apply, but the subject vehicle must proceed carefully if passing a front vehicle that obstructs the view of the cross traffic; thus, in particular, the subject vehicle may need to delay passing the other vehicle after changing lane around it until it is clear that there is no cross traffic.
7. *Passing a parked vehicle where there is not enough space to remain in traveled lane*: The parked vehicle triggers the lane change. Similar caution as in LM8.10 applies.
8. *Responding to pedestrians intending to enter the roadway (individuals and groups)*: Same considerations as for lane maintenance apply here.
9. *Responding to pedestrians in the roadway (individuals and groups)*: Same considerations as for lane maintenance apply here.
10. *Responding to cyclists*: Same considerations as for lane maintenance apply here.
11. *Responding to motorcycles performing lane splitting*: Same considerations as for lane maintenance apply here. Also, the subject vehicle should anticipate the possibility of a lane-splitting motorcycle filling the gap left after the subject vehicle makes a lane change, which may make a lane change abort difficult.
12. *Responding to emergency vehicles*. Same considerations as for lane maintenance apply here. If the vehicle has started the lane change maneuver but has not yet moved across the lane boundary, it should abort the lane change; otherwise it should complete the lane change. It then should proceed same as for lane maintenance.

LC9 *Animals on the roadway or the roadside*

Same considerations as for lane maintenance apply here.

LC10 *Other obstacles in the roadway*

Same considerations as for lane maintenance apply here. An obstacle in the travelled lane may trigger a lane change. Obstacles may also require modifying the typical lane change trajectory.

LC11 *Visibility conditions*

Same considerations as for lane maintenance apply here.

LC12 *Lighting conditions*

Same considerations as for lane maintenance apply here.

LC13 *Wind*

Same considerations as for lane maintenance apply here.

LC14 *Road surface conditions*

Same considerations as for lane maintenance apply here.

5.3 Swerving out of a same-direction traffic lane (SO)

The subject vehicle must signal all swerve maneuvers using directional signal light sufficiently ahead of time, but not too early.

5.3.1 Swerving out of a same-direction traffic lane across directional dividing line (SOD)

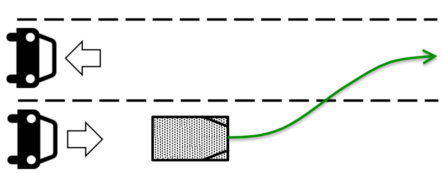

Figure 20 Swerving out of a same-direction traffic lane across directional dividing line

Objective: The task is to swerve forward across the boundary of the travelled lane, which is a traffic lane consistent with the direction of travel, into the opposite traffic lane (Figure 20).

This primary maneuver is typically performed as part of overtaking, possibly combined with leaving traffic into a driveway access at the left edge of the roadway. The main concern in performing this maneuver is ensuring sufficient oncoming gap when performing the encompassing overtaking maneuver. Therefore, this maneuver is analyzed as part of the overtaking maneuver.

5.3.2 Swerving out of a same-direction traffic lane into a non-traffic lane or shoulder (SON)

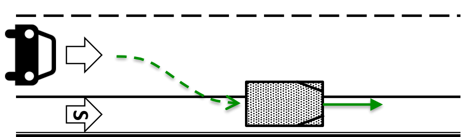

Figure 21 Swerving out of a same-direction traffic lane into a non-traffic lane or shoulder

Objective: The task is to swerve forward across the boundary of the travelled lane, which is a traffic lane consistent with the direction of travel, into a roadway part that is not a traffic lane, such as parking lane, turnout, bicycle lane, or shoulder (Figure 21).

Non-traffic lanes and shoulder are not intended for through vehicular travel. Swerving into these areas is temporary.

Parameters:

1. Target lateral location for the swerve.

Entry condition: The subject vehicle is set-up for forward movement. The vehicle is located within a traffic lane with position and heading such that the vehicle can execute the swerve maneuver. Most commonly, the vehicle will enter this maneuver from lane maintenance, but it could also follow a lane change or turn or swerve into a traffic lane, or an emergency maneuver.

Trigger: The following conditions or events may trigger this maneuver:

1. Moving towards or into a lane required for a planned turn or exit that requires crossing a bike lane (Figure 22);
2. Swerving out of the travelled lane to avoid an obstacle in the travelled lane;

3. Swerving into a parking stall in a parking lane; and
4. Swerving into onto the shoulder to park at the curb.

This maneuver should not be used to pass a vehicle, as passing on the right using non-traffic lanes or shoulder is against traffic rules.

Exit condition: Same as for a lane change.

Duration: Typically up to a few seconds.

Perception: Same as for a lane change.

Procedure: Same as for a lane change; however, in contrast to a traffic lane, which is intended for the movement of a single line of vehicles, the non-traffic lane or shoulder is mainly occupied by bicycle traffic, pedestrian traffic, and parked vehicles. Merging into a line of bicycle traffic by swerving out of the travelled lane into the bicycle lane is preferred to turning into and across the bicycle lane (Figure 22). In particular, a right turn out of the travelled traffic lane and across a bicycle lane, for example, into a driveway, is hazardous for the bicycle traffic along the bike lane.

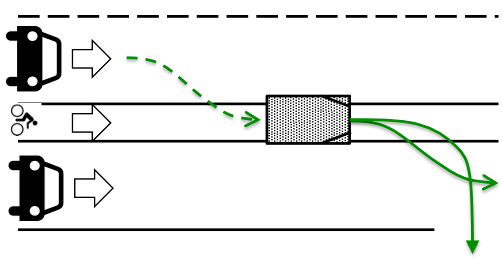

Figure 22 Swerving out of a same-direction traffic lane into a bicycle lane before swerving or turning out into another lane

Control: Same as for a lane change.

SO0. *Base case analysis*

The base case is analogous to a lane change.

Analysis in the presence of behavior modifiers:

The main impact of the behavior modifiers on swerving out of a same-direction traffic lane behavior, including their interactions, is as follows.

SO1. *Horizontal curves*

Same as consideration as for a lane change apply.

Extra caution needed if there is a possibility of vehicles parked on the shoulder just behind a curve. This case should be handled by the ACDA rule.

SO2. *Vertical curves*

Same considerations as for a lane change apply.

SO3. *Cross-section design (lane and road-side structure)*

Same considerations as for lane maintenance apply.

The cross-section design must include the non-traffic lane or shoulder to execute this maneuver. Further, the boundary between the traffic lane and non-traffic lane or shoulder must be drivable along the length of the maneuver

Shoulder and bicycle lanes are typically narrower than a passenger vehicle, so the subject vehicle driving along them will likely be driving partly in a traffic lane and partly on the shoulder or bike lane (lane splitting).

The shoulder may be *hard* or *soft shoulder*. Soft shoulder may create a split-μ situation; therefore a swerve onto a soft shoulder at higher speeds should be avoided. Also, some shoulders, especially soft ones, may be lower then the roadway surface (*low shoulder*), also creating potential stability challenges.

SO4. *Regulatory traffic signs and signals and other traffic control devices*

Same as considerations as for a lane maintenance apply.

SO5. *Intersecting vehicular lanes, rail tracks, and pedestrian and cyclist facilities*

Same as considerations as for a lane change apply.

SO6. *Temporary structure*

Same as considerations as for a lane change apply.

Shoulders in constructions zones are more likely to be obstructed by equipment and debris.

SO7. *Bridges and tunnels*

Same as considerations as for lane maintenance apply.

SO8. *Road users*

Same as considerations as for lane maintenance apply.

Cyclists and pedestrians are more likely to be encountered on bike lanes, parking lanes and shoulders.

SO9 *Animals on the roadway or the roadside*

Same as considerations as for lane maintenance apply.

Swerving onto the shoulder carries a higher risk of striking animals, especially on rural roads with roadside vegetation at night.

SO10 *Other obstacles in the roadway*

Same as considerations as for lane maintenance apply.

Shoulders have a higher probability of containing other obstacles than traffic lanes, such as blown tires, debris, and rocks.

SO11 *Visibility conditions*

Same as considerations as for lane maintenance apply.

SO12 *Lighting conditions*

Same as considerations as for lane maintenance apply.

Shoulders may be occupied by pedestrians, who may be poorly visible at night.

SO13 *Wind*

Same as considerations as for lane maintenance apply.

SO14 *Road surface conditions*

Same as considerations as for lane maintenance apply.

Split-μ conditions are more likely when swerving onto the shoulder.

5.4 Swerving into a same-direction traffic lane (SI)

The subject vehicle must signal all swerve maneuvers using directional signal light sufficiently ahead of time, but not too early.

5.4.1 Swerving into a same-direction traffic lane across directional dividing line (SID)

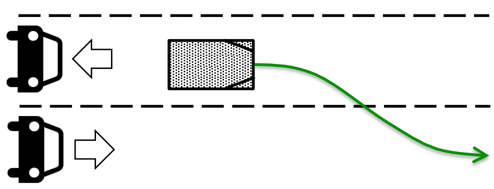

Figure 23 Swerving into of a same-direction traffic lane across directional dividing line

Objective: The task is to swerve forward from a traffic lane that is opposite to the direction of travel into an adjacent traffic lane that is consistent with the direction of travel (Figure 23).

This primary maneuver is typically performed as part of overtaking in order to return to the original lane. It may also be used to join traffic into the desired direction.

This maneuver is similar to a lane change, except that oncoming traffic is a special concern. The maneuver is analyzed as part of the overtaking and traffic joining maneuvers.

5.4.2 Swerving into a same-direction traffic lane from a non-traffic lane or shoulder (SIN)

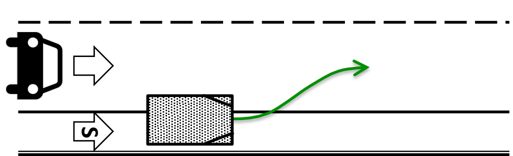

Figure 24 Swerving into a same-direction traffic lane from a non-traffic lane or shoulder

Objective: The task is to swerve forward from a non-traffic lane or shoulder into a traffic lane that is consistent with the direction of travel (Figure 24).

The maneuver may be executed following a swerve into the non-traffic lane or shoulder to avoid an obstacle in the traffic lane. It could also be executed as part of joining traffic from a curb parking location.

This maneuver is similar to a lane change and same considerations apply. Additional analysis is performed as part of secondary maneuvers, such as joining traffic.

5.5 Turning out of a same-direction traffic lane (TO)

The subject vehicle must signal all turn maneuvers using directional signal light sufficiently ahead of time, but not too early.

5.5.1 Turning out of a same-direction traffic lane across directional dividing line (TOD)

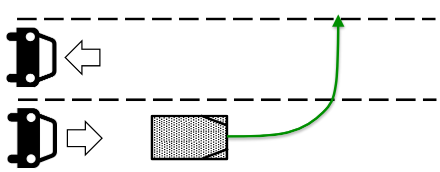

Figure 25 Turning out of a same-direction traffic lane across directional dividing line

Objective: The task is to turn forward left across the boundary of the travelled lane, which is a traffic lane consistent with the direction of travel, into the opposite traffic lane (see Figure 25).

The turn is normally executed as part of leaving traffic by turning into a driveway on the left or parking in a parking stall that is perpendicular or at angle to the curb and located in a parking lane, or as part of a turnabout maneuver. The maneuver is analyzed as part of these secondary maneuvers.

The main behavioral modifier for this maneuver is presence of oncoming traffic, to which the subject vehicle must yield (Figure 26).

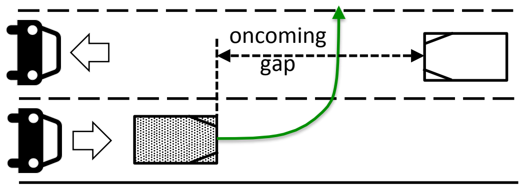

Figure 26 Turning out of a same-direction traffic lane across directional dividing line with oncoming traffic

This maneuver is similar to the intersection turn known as *left turn across path / opposite direction* (LTAP/OD), but executed not at an intersection.

5.5.2 Turning out of a same-direction traffic lane into a non-traffic lane or shoulder (TON)

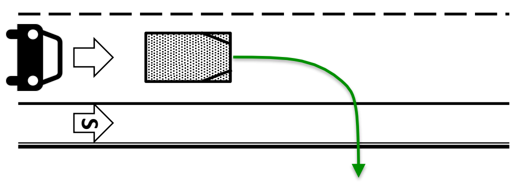

Figure 27 Turn out of a same-direction traffic lane into a non-traffic lane or shoulder

Objective: The task is to turn forward across the boundary of the travelled lane, which is a traffic lane consistent with the direction of travel, into and across a roadway part that is not a traffic lane, such as parking lane, turnout, bicycle lane, or shoulder (Figure 27).

The turn is normally executed as part of leaving traffic by turning into a driveway or parking in a parking stall that is perpendicular or at angle to the curb and located in a parking lane on the right, or as part of a turnabout maneuver. The maneuver is analyzed as part of these secondary maneuvers.

The main behavioral modifier for this maneuver is presence of parallel traffic, such as bicycles along the shoulder, to which the subject vehicle must yield.

5.5.3 Turning out of a same-direction traffic lane into another same-direction traffic lane (TOS)

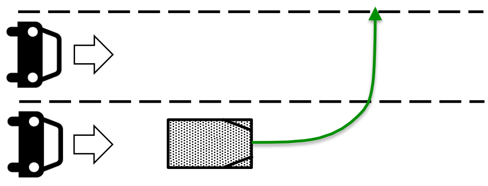

Figure 28 Turn out of a same-direction traffic lane into another same-direction traffic lane

<TBD>

5.6 Turning into a same-direction traffic lane (TI)

The subject vehicle must signal all turn maneuvers using directional signal light sufficiently ahead of time, but not too early.

5.6.1 Turning into a same-direction traffic lane across directional dividing line (TID)

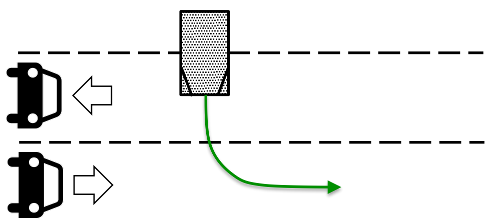

Figure 29 Turning into a same-direction traffic lane across directional dividing line

<TBD>

5.6.2 Turning into a same-direction traffic lane from a non-traffic lane or shoulder (TIN)

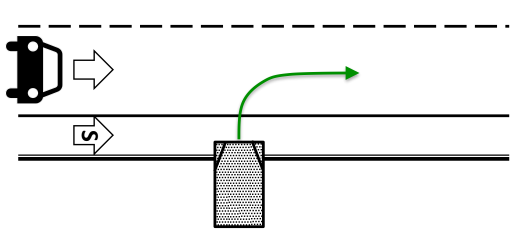

Figure 30 Turn into a same-direction traffic lane from a non-traffic lane or shoulder

<TBD>

5.6.3 Turning into a same-direction traffic lane from another same-direction traffic lane (TIS)

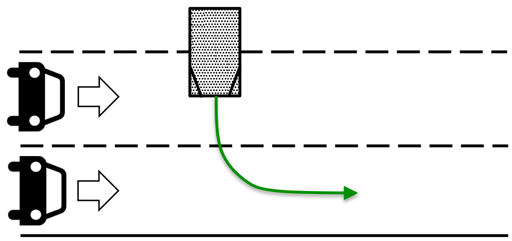

Figure 31 Turn into a same-direction traffic lane from another same-direction traffic lane

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5.7 Crossing a lane (CL)

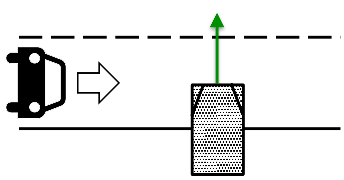

Figure 32 Crossing a lane

<TBD>

5.8 Turning, swerving, and longitudinal movements outside a same-direction traffic lane (OL)

<TBD>

5.9 Reverse driving maneuvers (RD)

<TBD>

6. Secondary Maneuvers in Normal Driving on Structured Roads

6.1 Overtaking (OT)

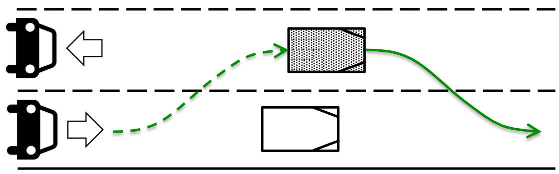

Figure 33 Overtaking

<TBD>

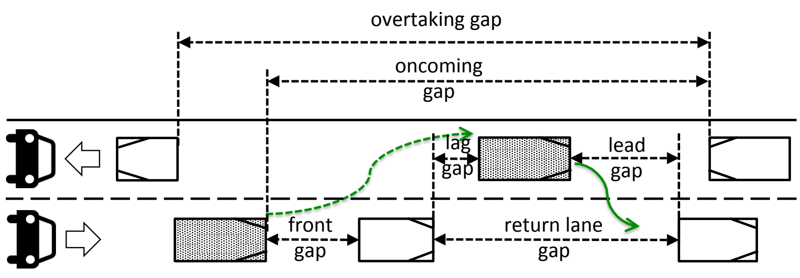

Figure 34 Gaps during overtaking [DP15] (note that the figure in [DP15] refers to overtaking gap as passing gap)

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6.2 Passing (PS)

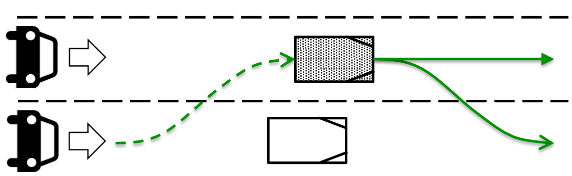

Figure 35 Passing

<TBD>

6.3 Intersection handling (IH)

Maneuver: Intersection handling

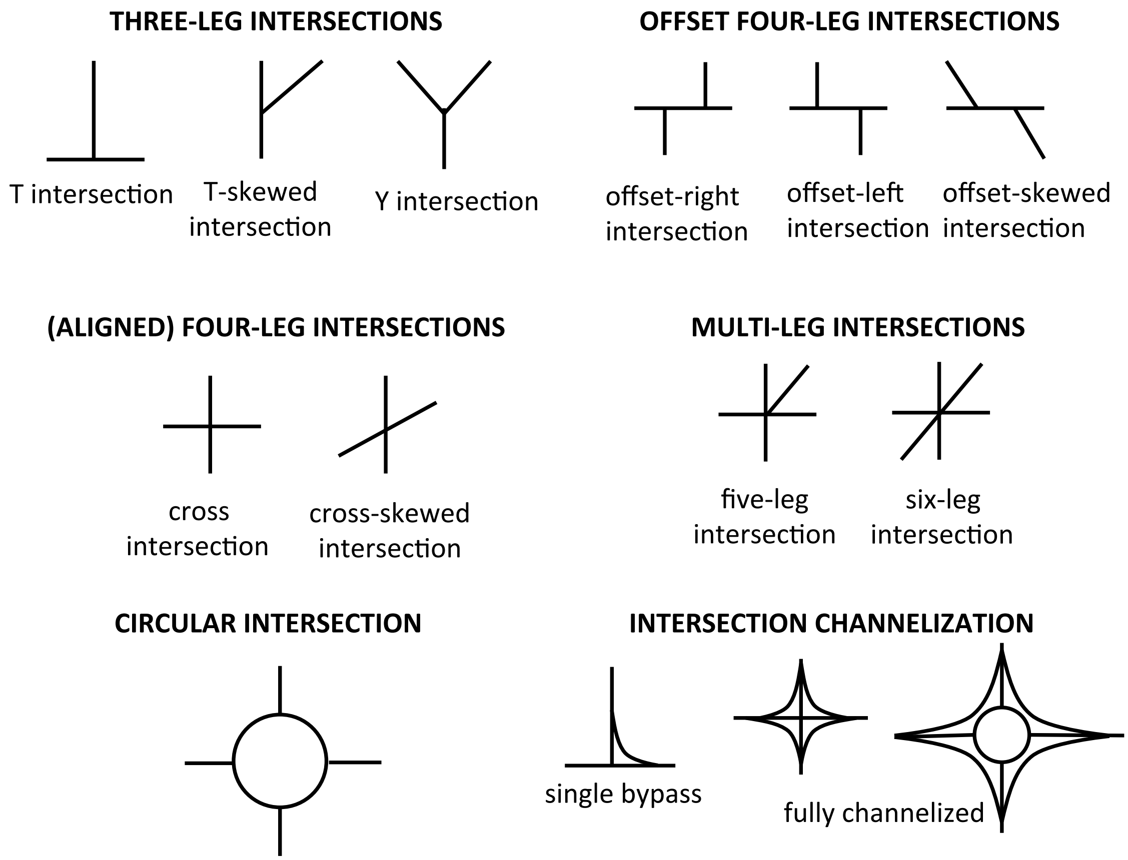

Figure 36 Basic intersection forms (Figure E2-2 adapted from [GDS85])

<TBD>

6.4 Interchange handling (IH)

Maneuver: Intersection handling

<TBD>

6.5 Pedestrian crossing handling (PC)

Maneuver: Pedestrian crossing handling

<TBD>

6.6 Cycle crossing handling (CC)

Maneuver: Cycle crossing handling

<TBD>

6.7 Railway crossing handling (RC)

Maneuver: Railway crossing handling

<TBD>

6.8 Turnabouts (TA)

Maneuver: Turnabout

<TBD>

6.9 Joining traffic (JT)

Maneuver: Joining traffic

<TBD>

6.10 Leaving traffic (LT)

Maneuver: Leaving traffic

<TBD>

7. Emergency Maneuvers

<TBD>

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