WISE Requirements Analysis Framework for Automated Driving Systems

Automated Driving System (ADS) Task Analysis

Part 1: Basic Motion Control Tasks

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Abstract

This document defines a catalog of basic motion control tasks for ADS. These tasks reside at operational level and comprise (i) longitudinal control, including acceleration, deceleration, and speed maintenance, and (ii) lateral control, including straight driving, cornering, and swerving. Each task is analyzed in terms of factors impacting its execution, physical parameters from naturalistic driving data, and scoring criteria to evaluate the task performance.

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1. Scope

The objective of *basic motion control tasks* is to achieve deliberate movement of the subject vehicle while maintaining vehicle stability and occupant comfort due to the motion. These tasks occur at the operational level of Michon's hierarchy of driving tasks [Mic85], and are performed continuously during driving. Issues such as road structure, obstacles, traffic regulations, or interaction with other road users are not considered within these tasks.

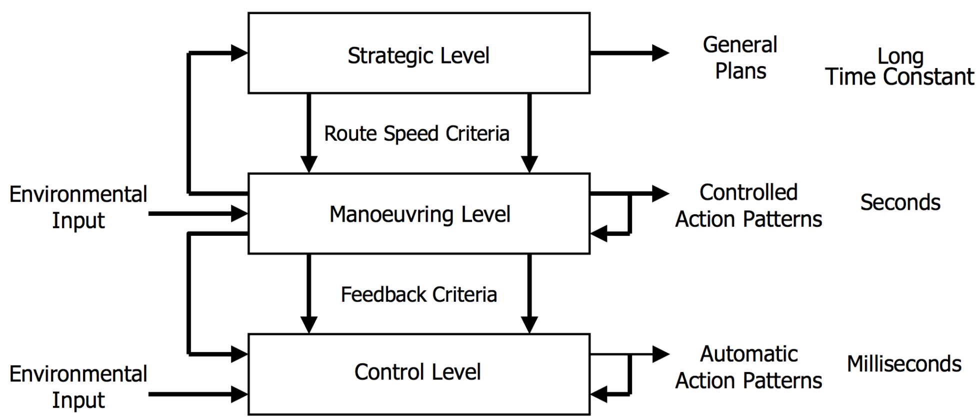

Figure 1 The hierarchical structure of road user task (Figure 2 from [Mic85])

The requirements on basic motion control depend on the current situation being normal driving or emergency. In particular, driving comfort is irrelevant in emergency situations. The ADS maintains a vehicle model, which includes vehicle dynamics and power train behavior, that is sufficiently accurate for planning and executing the dynamic driving task. Emergency maneuvering or driving on very slippery, such as icy, road surface require higher accuracy vehicle model than normal driving on dry road surface. As some parameters of the host vehicle may change during operations, such as passenger and cargo load, they may need to be estimated online for the tasks that require higher model accuracy.

This document targets SAE J3016 Levels 3, 4 and 5 driving automation operating a passenger vehicle similar to a conventional vehicle, but equipped with dire-by-wire capability and an ADS. In particular, the subject vehicle is assumed to have front steering and have much higher operating speed and maneuverability in the forward direction compared to the reverse direction. This is in contrast to some novel vehicle platforms such as those that have similar capabilities in forward and reverse direction.

Further, the document focuses on the vehicle behavior in terms of its actual movements, including position, heading, velocity, and acceleration, rather than the

ADS behavior in terms of vehicle control inputs, such as the commanded steering, braking, and throttle inputs.

2. Basic Motion Control Perception Requirements

The basic motion control, as defined in this document, is concerned with the stability and comfort of the movements performed by the vehicle. Consequently, it does not involve any Object Detection, Evaluation, and Response (OEDR) functions. However, the basic motion control requires sensing of vehicle state, which includes steering angle, position, heading, and liner and angular velocity and acceleration. Additional state variables may be required vehicle dynamic model of higher fidelity is used. The state has to be sensed with sufficient accuracy and update rate and freshness (low latency) to enable accurate control. The minimum necessary rate depends on the speed of the vehicle and the type of controller used. Some amount of delay can be compensated with predictions.

3. Basic Motion Control Tasks

Table 1 summarizes the basic motion control tasks. They are categorized by longitudinal and lateral motion, and forward and reverse direction. Longitudinal control and lateral control occur simultaneously. Longitudinal control corresponds to speed regulation, and lateral control corresponds to steering. The separation of the two types of control facilitates requirements analysis and specification, as the requirements can be stated, to some degree, independently. For example, some maneuvers, such as yielding to another vehicle at an intersection can be accomplished mostly by speed control while the vehicle travels on a fixed path through the intersection. Other maneuvers, such as lane changes in intense traffic, require simultaneous and coordinated planning of longitudinal and lateral motion, however (see the discussion of this maneuver in Section 3.2.1).

Table 1 Summary of basic motion control tasks

Task Category	**Task Subcategory**	**Task**
Longitudinal Control	Forward Longitudinal Control	SetUpForward
		Accelerate
		Decelerate
		MaintainSpeed
	Reverse Longitudinal Control	SetUpReverse
		AccelerateInReverse
		DecelerateInReverse
		MaintainSpeedInReverse
Lateral Control	Forward Lateral Control	StraightSteer
		CurvedSteer
	Reverse Lateral Control	StraightSteerInReverse
		CurvedSteerInReverse
Stability Recovery		RecoverFromSkid

The following subsections specify each task by stating its

1. objective
2. entry condition,
3. exit condition,
4. expected duration,
5. task scoring, and
6. test condition variations.

Task scoring assesses the task performance with respect to driving quality requirements; in the case of basic motion tasks, these are

1. safety requirements in terms of vehicle stability (see [HLSR]) and
2. motion-related occupant comfort requirements (see [HLCR]).

3.1 Longitudinal Control

Longitudinal control is divided into forward longitudinal control and reverse longitudinal control. Each of them is divided, in turn, in to acceleration, deceleration, and maintaining speed. Any forward or reverse movement can be composed from a sequence of these three tasks.

3.1.1 Forward Longitudinal Control

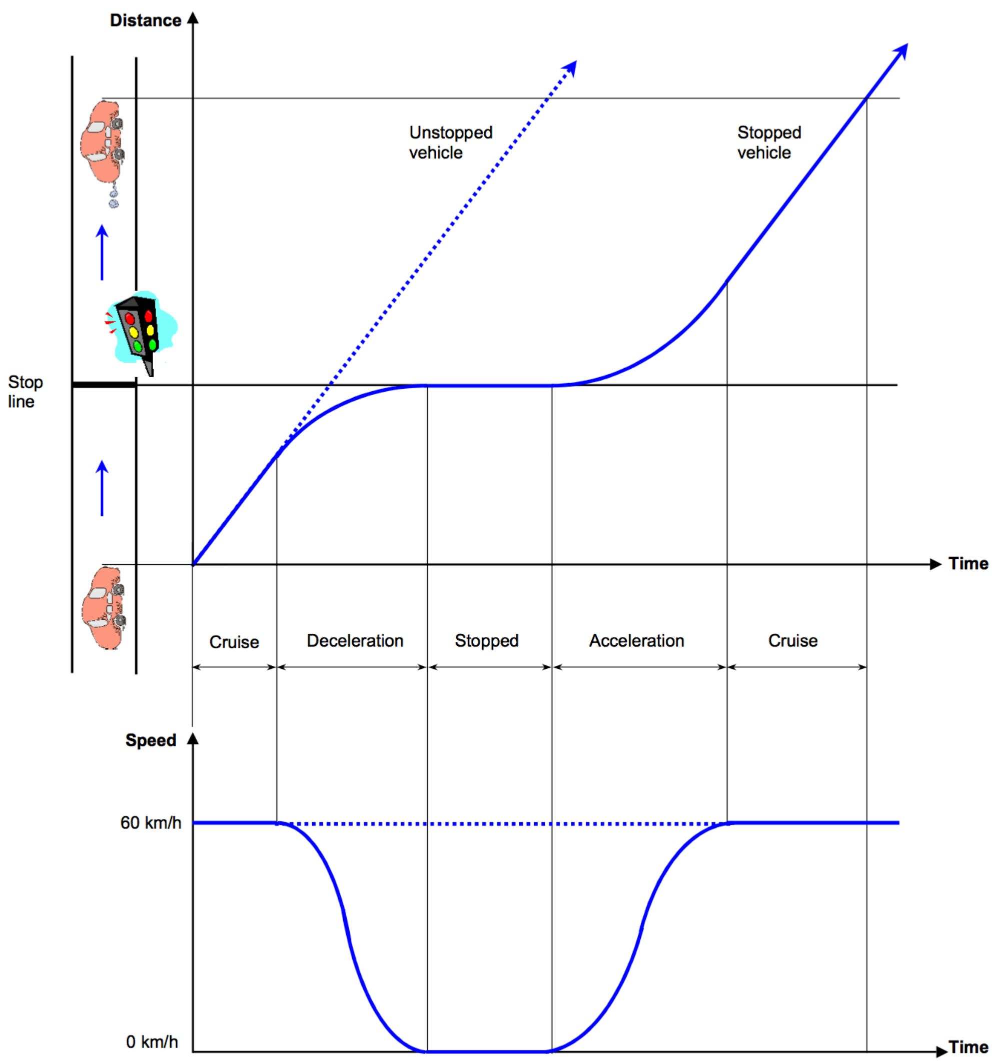

Figure 1 Forward longitudinal control consisting of acceleration, maintaining speed, and deceleration

SetUpForward is required before the subject vehicle can drive forward. Any subsequent forward longitudinal control consists of acceleration, maintaining speed, or deceleration (see Figure 1).

Task: SetUpForward
Objective: The task sets up the subject vehicle for forward driving. This task normally includes starting the propulsion system if not already started and shifting into drive.
Entry condition: The subject vehicle is stopped. [or is already moving forward, such as coasting forward or rolling forward down a grade. In particular, vehicle that is moving in reverse must come to a complete stop before SetUpForward is executed.]
Exit condition: The subject vehicle is set-up for forward movement, that is, propulsion system is ready and gear is in drive, and the vehicle is stopped.
Duration: The task has normally a fixed duration of up to a few seconds, depending on the propulsion system.

Task: Accelerate
Objective: The task is to increase vehicle speed.
Parameters:
1. Target speed to be achieved at a future target point in time or location;
2. Acceleration profile type to follow;

Entry condition: The subject vehicle is set-up for forward movement.
Exit condition: Successful exit condition is when the vehicle speed is close to target at the target point in time or location. The task can be aborted at any time by switching to another longitudinal task.
Duration: The duration depends on initial and target speed difference and acceleration level. A typical acceleration profile in normal driving from 0 to 100 km/h with maximum acceleration of 2.4 m/s^2 lasts approximately 20 seconds [Sna02].
Task scoring:
1. Sufficient stability margin for normal driving kept; that is, combined slip on each tire is sufficiently below the value corresponding to the peak friction coefficient for the given conditions;
2. Effective use of available stability in near crash or crash situation;
3. Comfort of the acceleration profile; measures include maximum acceleration and jerk, and also durative measures such as root mean square of acceleration or jerk over their duration; and
4. Closeness to the specified acceleration profile.

Test condition variations:
1. Variation in initial and final speed and acceleration profile to follow;
2. Variation in vehicle acceleration performance;
3. Variations in road friction;
4. Variation in tire inflation;
5. Variation in road grade;
6. Head or tail wind; and
7. Variations in vehicle loading (occupants, cargo).

Acceleration profiles are strongly limited by vehicle performance, much more so than deceleration profiles, which are more driver-dependent. Figure 2 shows typical maximum performance acceleration profiles for passenger vehicles; the model has been validated on 13 different vehicles from 6 different manufacturers [Sna02].

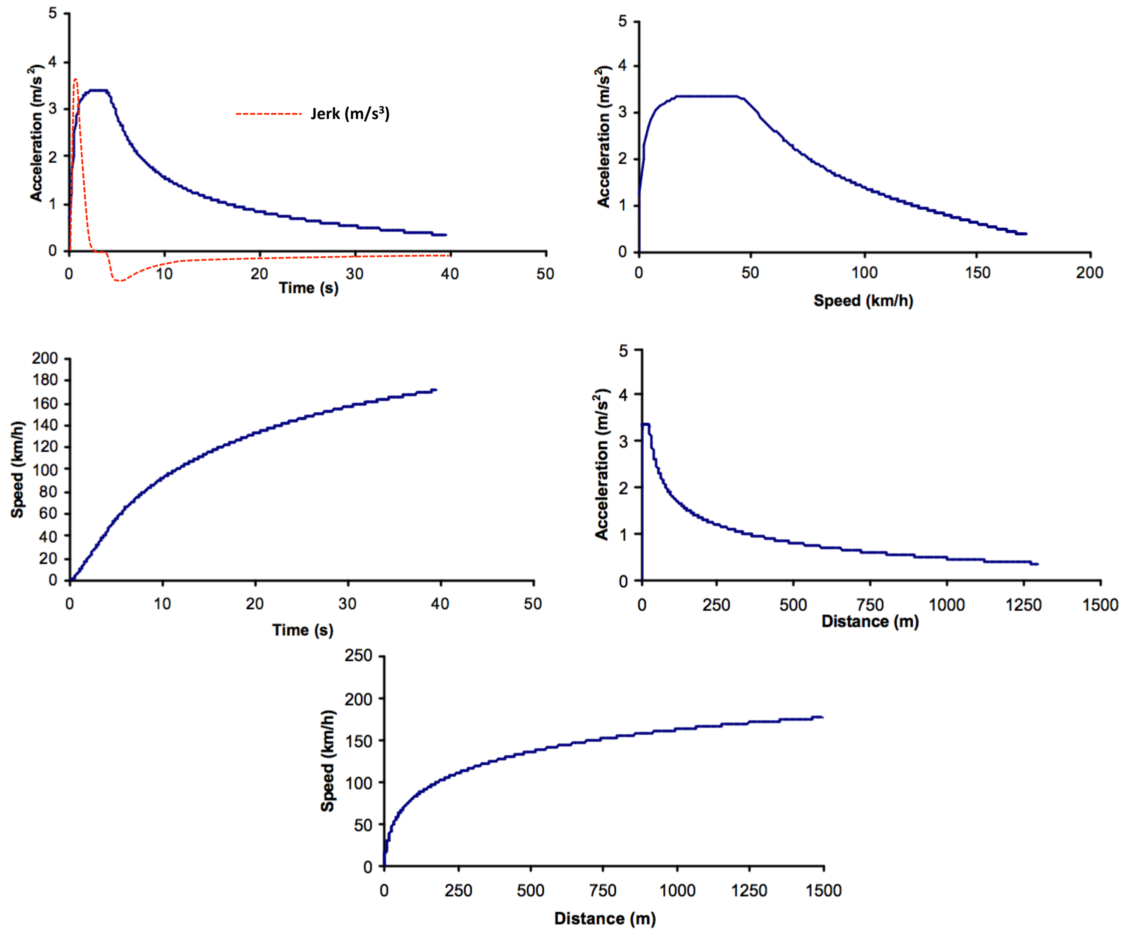

Figure 2 Acceleration profiles representing maximum vehicle performance from stopped state [Sna02]

Acceleration profiles in normal driving tend to follow the natural acceleration profile of a vehicle, but only scaled down by a factor to use less of the available power [Sna02]. The study defines three types of acceleration profiles in naturalistic driving (Figure 3):

1. *Standard accelerator*: Drivers in this category will tend to follow the shape of the maximum acceleration profile of a vehicle, with the model simply shifted by a constant reduction factor throughout the run;
2. *Gradual accelerator*: These drivers are primarily concerned with passenger comfort, and accelerate at a relatively constant and moderate rate throughout the period of acceleration, despite the ability of the vehicle to accelerate more aggressively at low speeds; the corresponding acceleration vs. time diagram is similar to that in Figure 2, except that the initial peak is lower and flatter;

3. *Hard accelerator*: These drivers tend to accelerate from a stop at a high initial rate that is close to the maximum value and then decrease their acceleration rate as they approach their desired speed.

The study analyzed normal acceleration of 20 human drivers, such as starting from a red signal and accelerating to highway speed. The study confirmed that drivers tend to follow the natural acceleration profile of a vehicle, but only scaled down to use less of the available power. Fourteen of the twenty drivers (70%) fell into the standard accelerator category; the other two categories, gradual and hard accelerator, had three drivers (15%) each. The reduction factor ranged between 40% and 70% of the available power. A reduction factor of 70% corresponds to maximum acceleration of 2.4 m/s^2 and maximum jerk of 2.6 m/s^3.

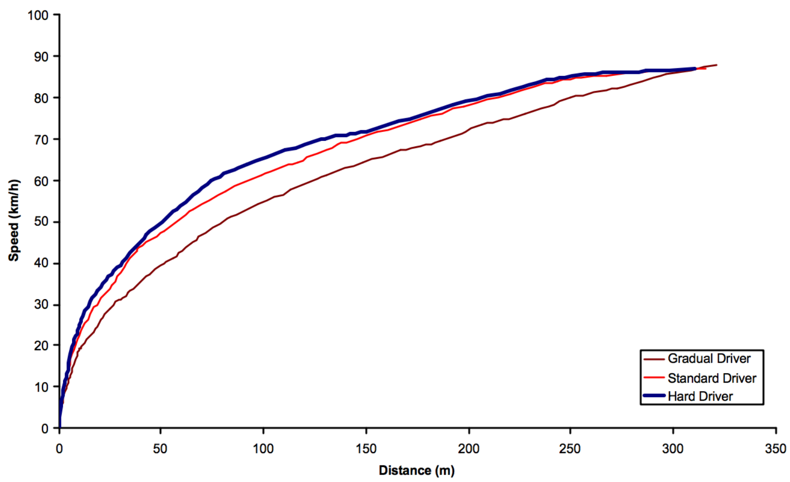

Figure 3 Three types of human driver acceleration profiles [Sna02]

Akçelik and Biggs [AB01] defined a polynomial model of the acceleration and deceleration profiles based on extensive observations of naturalistic driving:

$$a(t) = r\, a_m\, \theta\, (1 - \theta^m)^2$$

$a(t)$ is acceleration or deceleration at time t (m/s^2) ($a > 0$ for acceleration, $a < 0$ for deceleration);
a_m is maximum acceleration or deceleration (m/s^2) ($a_{ma} > 0$ for acceleration, $a_{md} < 0$ for deceleration);
θ is time ratio($\theta=t/t_{a/d}$, i.e., $\theta=t/t_a$ or $\theta=t/t_d$);
t is time since the start of acceleration (seconds);
$t_{a/d}$ is acceleration or deceleration time (t_a or t_d) (seconds);
m is model calibration parameter; and
r is model parameter given by:

$$r = [(1+2\,m)^{2+1/m}] / 4\,m^2$$

Figure 4 shows an example of this model for the case of accelerating from zero to 60 km/h, with a maximum acceleration a_{ma} = 2.69 m/s^2, average acceleration of 1.53 m/s^2, acceleration distance of 106.4 m, acceleration time t_a = 10.9 s, and model calibration parameter m = 0.587.

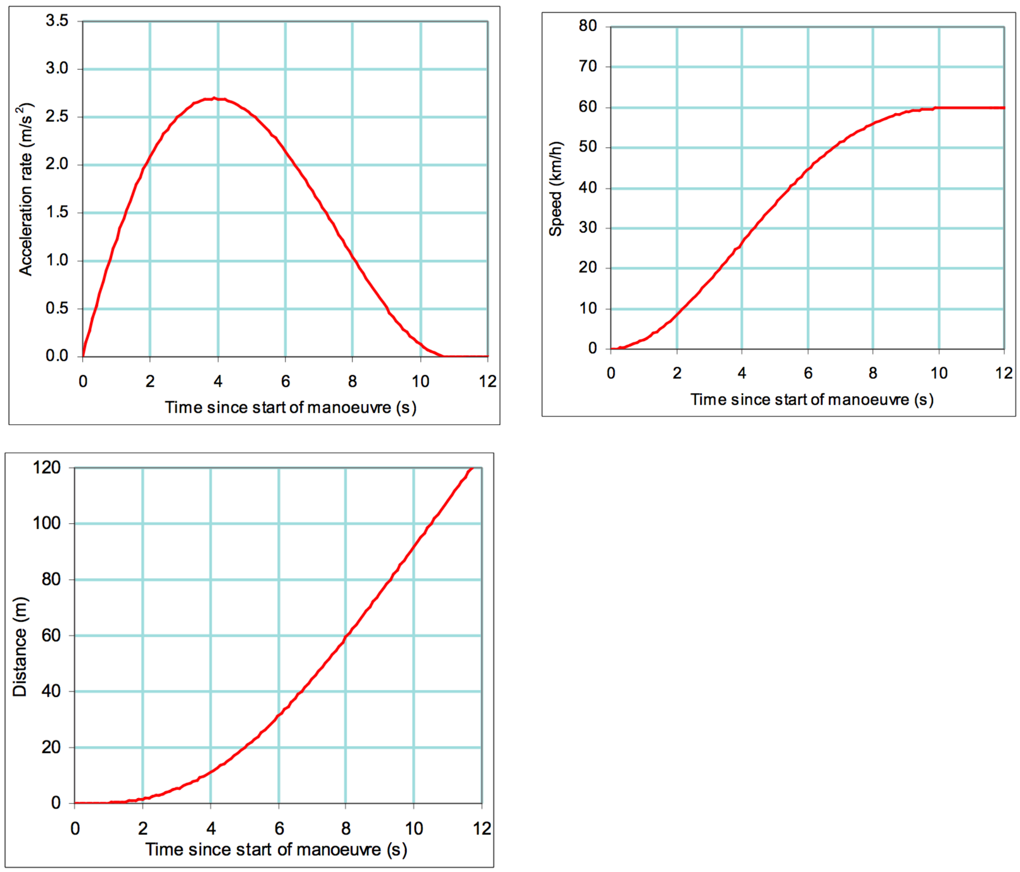

Figure 4 Sample instance of a polynomial model of acceleration [AB01]

The acceleration profiles discussed so far are mostly for free driving case. Acceleration profiles may be further constrained by the movement of a front vehicle.

When starting on snow or icy road, the steering angle should be zero, and the acceleration should be very gradual, while maintaining little slip.

Maximum acceleration available in emergency situations is also limited by the maximum available power, which is speed-depended (Figure 2).

Task: Decelerate
Objective: The task is to decrease vehicle speed.
Parameters:

1. Target speed to be achieved at a future target point in time or location;
2. Deceleration profile type to follow;

Entry condition: The subject vehicle is set-up for forward movement.

Exit condition: Successful exit condition is when the vehicle speed is close to target at the target point in time or location. The task can be aborted at any time by switching to another longitudinal task.

Duration: The duration depends on initial and target speed difference and deceleration level. A typical deceleration profile in normal driving from 60 to 0 km/h with maximum acceleration of 3 m/s^2 lasts approximately 9.5 seconds [AB01];

Task scoring:

1. Sufficient stability margin for normal driving kept; that is, combined slip on each tire is sufficiently below the value corresponding to the peak friction coefficient for the given conditions;
2. Effective use of available stability in near crash or crash situation;
3. Comfort of the deceleration profile; measures include maximum deceleration and jerk, and also durative measures such as root mean square of deceleration or jerk over their duration; and
4. Closeness to the specified deceleration profile.

Test condition variations:

1. Variation in initial and final speed and deceleration profile to follow;
2. Variation in vehicle bake system performance;
3. Variations in road friction;
4. Variation in tire inflation;
5. Variation in road grade;
6. Head or tail wind; and
7. Variations in vehicle loading (occupants, cargo).

Figure 5 shows a sample deceleration profile in normal driving according to the previously discussed model of Akçelik and Biggs [AB01]. The sample profile corresponds to deceleration from the initial speed of 60 km/h to zero final speed, with a maximum deceleration of 3.09 m/s^2, average deceleration of 1.78 m/s^2, deceleration of 88.5 m, deceleration time t_d = 9.4 s, and model calibration parameter m = 0.566.

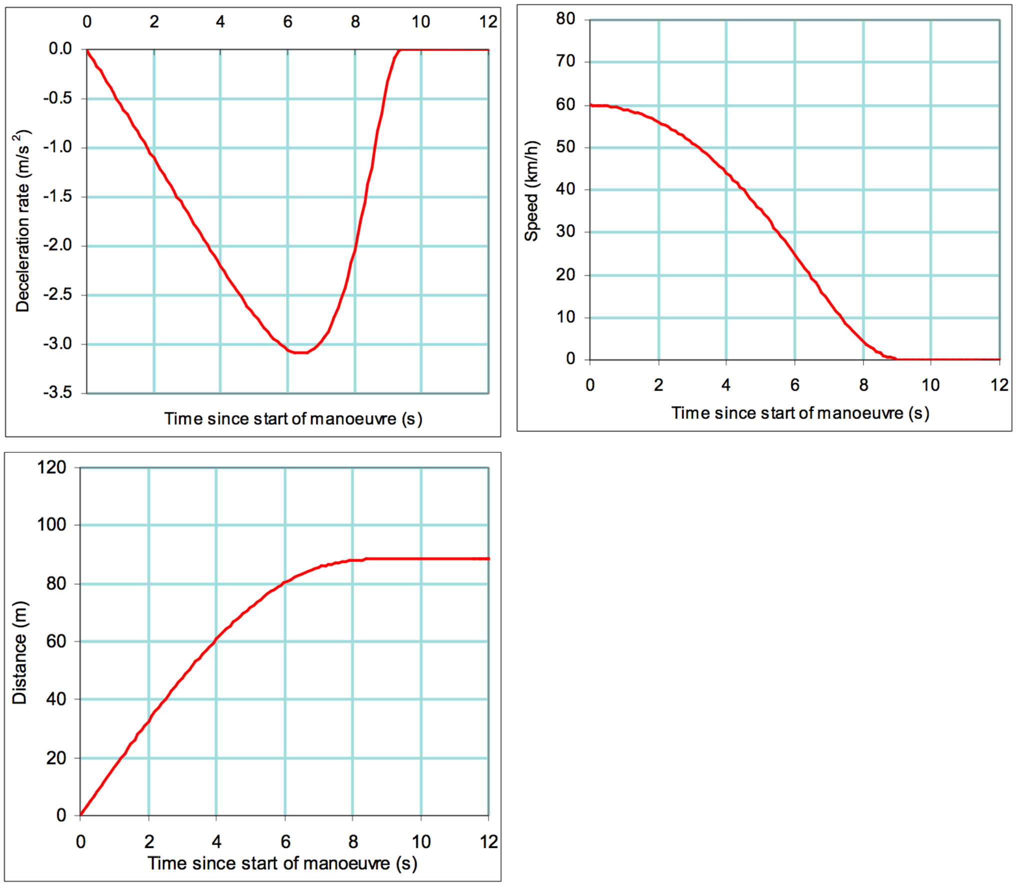

Figure 5 Sample instance of a polynomial model of deceleration [AB01]

Deliganni et al. [DQM17] observed 16 drivers over a route of 16.5 km, recording 11 million observations to identify the profile, value, and duration of deceleration events. They classified deceleration profiles in normal driving into three classes (Figure 6):

1. *Gradual deceleration*: The gradual deceleration profile is characterized by a linear relationship between deceleration value (d) and elapsed deceleration time (t), i.e., $d = a_1 t$. In real traffic, this reflects the driver's braking gradually (blue line in Figure 6). This profile is similar to that in Figure 5.
2. *Early braking*: The early braking profile is a parabola $d^2 = 2 a_2 t$ (red dashed curve in Figure 6). In real traffic, it represents the situation where the driver brakes firmly at the beginning of the event owing to a sudden obstacle appearing, followed by a gradually smoother braking, since there is plenty of space to stop.
3. *Late braking*: The early braking profile is a parabola $t^2 = 2 a_3 d$ (green curve in Figure 6). In real traffic, this profile corresponds to a wrong judgment of the driver, who brakes smoothly at the beginning considering enough space to stop the vehicle, though this is followed with a hard brake because of a lack of space and time.

The study of the naturalistic deceleration showed that in a majority of cases drivers were braking hard early and then smoothly: 488 out of 574 deceleration profiles had the early braking, parabolic shape. Only 51 profiles fitted the linear equation, and 35 the late braking, parabolic profile.

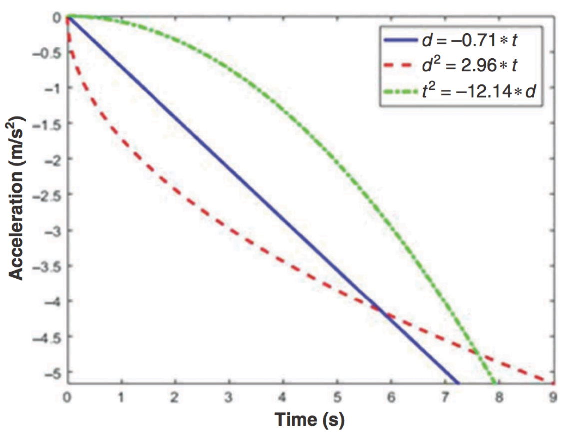

Figure 6 Best fit of naturalistic deceleration data into gradual (blue), early (green), and late braking (red and dashed) [DQM17]

In emergency situations when approaching an obstacle in front, early and hard braking is desired. The German Automobile Club (ADAC) published a detailed test report comparing the performance of advanced emergency braking (AEB) of vehicles from six manufacturers [AEB]. Figure 7 shows the deceleration profile of the test winner, Volvo V60 D5 AWD Geartronic 2013, which initiates full braking of the subject vehicle travelling at 100 km/h and approaching a slower vehicle traveling at 60 km/h. In this scenario, the driver of the subject vehicle fails to brake. The maximum deceleration applied is 10 m/s^2, which implies a dry road surface. The maximum jerk is 12 m/s^3. The profile is initially linear and then becoming gradual.

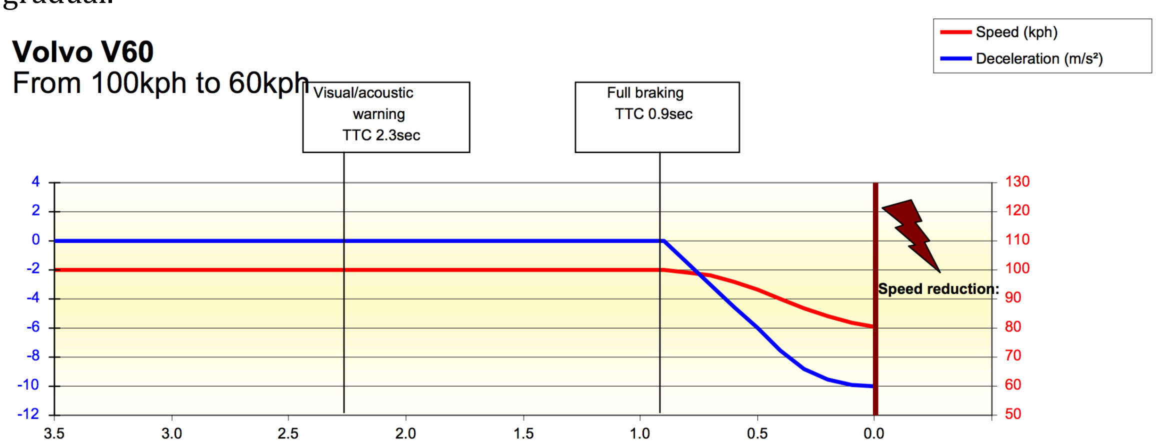

Figure 7 Deceleration profile of Volvo V60 D5 AWD Geartronic 2013 advanced emergency braking (AEB) decelerating from 100 km/h to 60 km/h to avoid a collision with a slower vehicle in front

Figure 8 shows a recorded sample emergency deceleration profile executed by a professional driver [Gre07]. The sample comes from an emergency braking test with 6 professional drivers and 16 non-professional drivers. In Figure 8, the vehicle is decelerating from 108 km/h to a stop, with maximum deceleration of 9 m^2/s. The time from the initiation of the pedal movement to when the deceleration commences is referred to as *braking initiation time*. A typical range for braking initiation time is 0.1 to 0.4 seconds, depending on the car's braking system and the speed at which the brake pedal is depressed [Gre07]. In Figure 8, the brake initiation time is approximately 0.3 seconds. Afterwards it takes another 0.2 seconds to reach the maximum deceleration. In the study, professional drivers typically achieve 20-25% shorter braking distances than non-professional drivers; however, the variation is large and some non-professional drivers need twice the stopping distance compared to professional drivers.

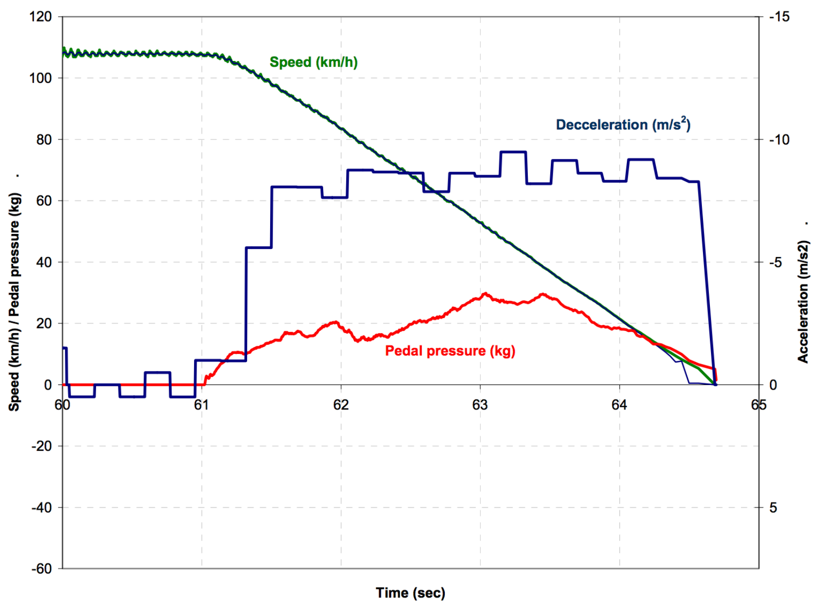

Figure 8 Sample emergency deceleration profile executed by a professional driver [Gre07]

Figure 9 shows two sample naturalistic deceleration events in near-crash situation recorded during a week of driving of an elderly driver [CCC16]. Both profiles show clearly a late braking pattern. The rapid deceleration event (RDE) 1 has an initial phase of 4 seconds with a deceleration of up to approximately 4 m^2/s, followed by sharp deceleration with a peak of 8.6 m^2/s.

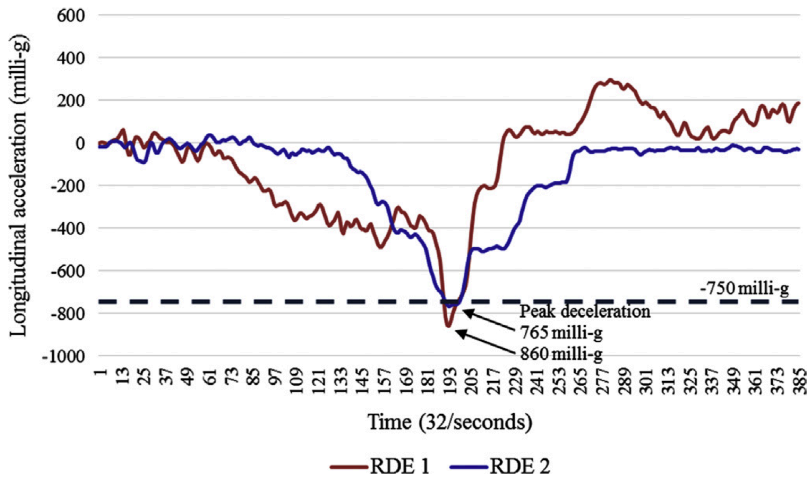

Figure 9 Two sample naturalistic rapid deceleration events (RDEs) in near-crash situations recorded during a week of one elderly driver's driving [CCC16]

Task: MaintainSpeed

Objective: The task is to maintain the current vehicle speed; this task includes *cursing*, that is, maintaining positive speed, or being *stopped*, i.e., maintaining zero speed.

Entry condition: The subject vehicle is set-up for forward movement.

Exit condition: Successful exit condition is when the vehicle has been maintained throughout. The task can be aborted at any time by switching to another longitudinal task.

Task scoring:

1. Amount of deviation from the speed to be maintained. The deviation may be measured using maximum, average, or root mean square error for the entire task or some window.

Test condition variations:

1. Variation in the target speed to maintain;
2. Variation in road grade; and
3. Head or tail wind.

3.1.2 Reverse Longitudinal Control

SetUpReverse is required before the subject vehicle can drive in reverse. Any subsequent revers longitudinal control consists of acceleration, maintaining speed, or deceleration. Reversing often involves low-speed maneuvering in tight spaces, such as reverse parking. Low-speed maneuvering normally relies on the vehicle creep with no accelerator pedal depressed and the use of brakes for speed control. Acceleration to higher speeds in reverse typically occurs in the case of turning around using a three-point turn or when backing out of a driveway.

1. SetUpReverse
2. AccelerateInReverse
3. DecelerateInReverse
4. MaintainSpeedInReverse

Note: Reverse longitudinal control tasks are outside the scope of the current version of this document.

3.2 Lateral Control

Lateral control is divided into forward lateral control and reverse lateral control. Each of them is divided, in turn, in to straight or curved driving. Curved driving may be cornering, such as following a circular arc, a clothoid, or some other type of drivable "bend"; or swerving, such as in a lane change or obstacle avoidance. Lateral and longitudinal movements are composed in parallel.

3.2.1 Forward Lateral Control

Lateral control consists of steering the subject vehicle on a horizontal tangent or a curve.

Task: StraightSteer
Objective: The task is to keep the subject vehicle on a horizontal tangent.
Entry condition: The steering angle is 0 and the heading is aligned with the desired direction.
Exit condition: Successful exit condition is when the vehicle remains on the tangent with the same heading.
Task scoring:
1. Closeness to the prescribed horizontal tangent; deviations measured as cross-track error and heading error.

Test condition variations:
1. Variations in road bank; and
2. Variations in cross wind.

Task: CurvedSteer
Description: The task is to keep the subject vehicle on a horizontal curve of a given shape.
Parameters:
1. Horizontal curve to be followed; the curve must be feasible for the subject vehicle under the speed profile that is executed concurrently. Horizontal profiles that are common in road driving are cornering and swerving.

Entry condition: The steering angle and the heading are aligned with the required heading and curvature at the beginning of the curve.
Exit condition: Successful exit condition is when the vehicle closely traces the curve.
Task scoring:
1. Sufficient stability margin for normal driving kept; that is, combined slip on each tire is sufficiently below the value corresponding to the peak friction coefficient for the given conditions;
2. Effective use of available stability in near crash or crash situation;
3. Comfort of the trajectory; measures include maximum lateral acceleration and jerk, and also durative measures such as root mean square of lateral acceleration or jerk over their duration; and

4. Closeness to the specified curve.

Test condition variations:

1. Variation in vehicle speed profile;
2. Variation in the horizontal curve to trace;
3. Variations in road friction;
4. Variation in tire inflation;
5. Variation in road bank (superelevation, sideslope);
6. Variation in road grade;
7. Variations in cross wind;
8. Head or tail wind; and
9. Variations in vehicle loading (occupants, cargo).

The specific curve to follow depends on the maneuver the subject vehicle is performing. In general, the requirement of smooth steering leads to the requirement of smooth curvature, and thus the paths traversed by vehicles are desirably geometrically continuous in the second order, which is also known as G^2 [PB00a].

Two common curves that a vehicle must be able to trace are determined by horizontal road alignment (see Section 4.3.1 in [O18a]):

1. circular arcs and
2. clothoids.

Another requirement is executing swerves, such as lane change trajectories.

A study of naturalistic lane change trajectories revealed two major types of trajectories: *continuous lane change execution (CLCE)* and *discontinuous lane change execution (DLCE)* [YZY15]. CLCE is characterized by a continuous lateral movement of the subject vehicle from the current lane to the target lane; in contrast, DLCE involves a pause in the lateral movement before the subject vehicle enters the target lane. CLCE normally occurs in free driving or in low traffic, that is, when the lane change is (largely) unconstrained by other vehicles. DLCE occurs in more intense traffic conditions, such as at higher traffic density, higher differential speeds between the lanes, and when the target gap is closing. Figure 10 shows three sample recorded CLCE scenarios. In all three scenarios, the subject vehicle, represented by a black curve, is laterally moving from its current lane into a gap on the target lane in between a front vehicle, represented by a red curve (with circles), and a rear vehicle, represented by a blue curve (with crosses). In two scenarios, Figure 10(a),(c), there is an ample front and rear gap around the subject vehicle in the target lane; in one scenario, Figure 10(b), the gap is smaller but the front vehicle is driving significantly faster than the subject vehicle when the subject vehicle enters the target lane: vehicle number 1914 is about 3 m/s faster than the subject vehicle number 1926.

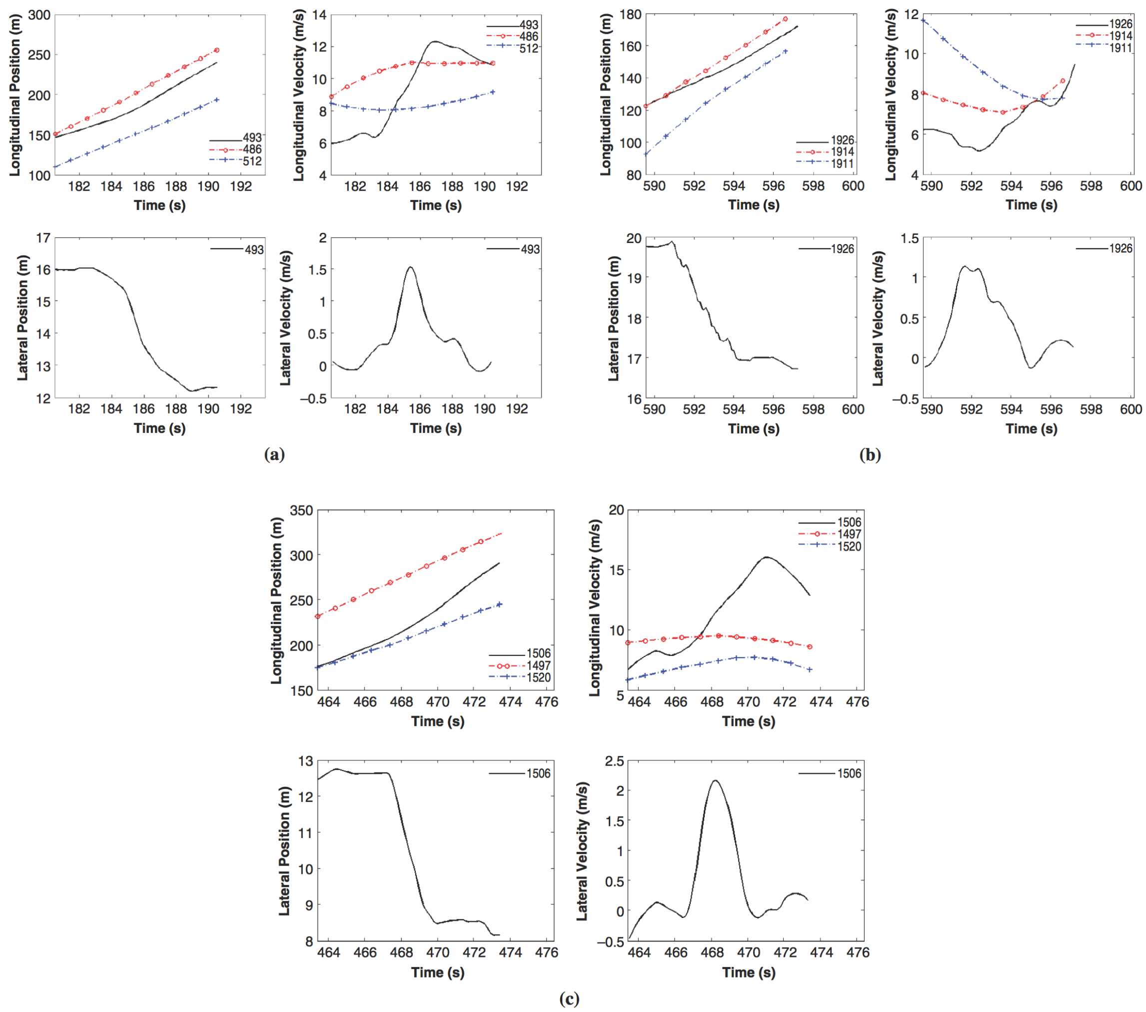

Figure 10 Three continuous lane change execution (CLCE) scenarios [YZY15]

Figure 9 shows four sample recorded DLCE scenarios. In the first two scenarios, Figures 9 (a) and (b), the subject vehicle pauses briefly before entering in a relatively tight gap on the target lane. The third and fourth scenario, Figures (c) and (d), show the case where the subject vehicle has to accelerate or decelerate significantly in order to enter the gap on the target lane, respectively. The subject vehicle pauses briefly to make sure that the lane change is safe after the acceleration or deceleration maneuver. Note that the initial acceleration or deceleration on the current lane may also be constrained by a front or rear vehicle in the current lane.

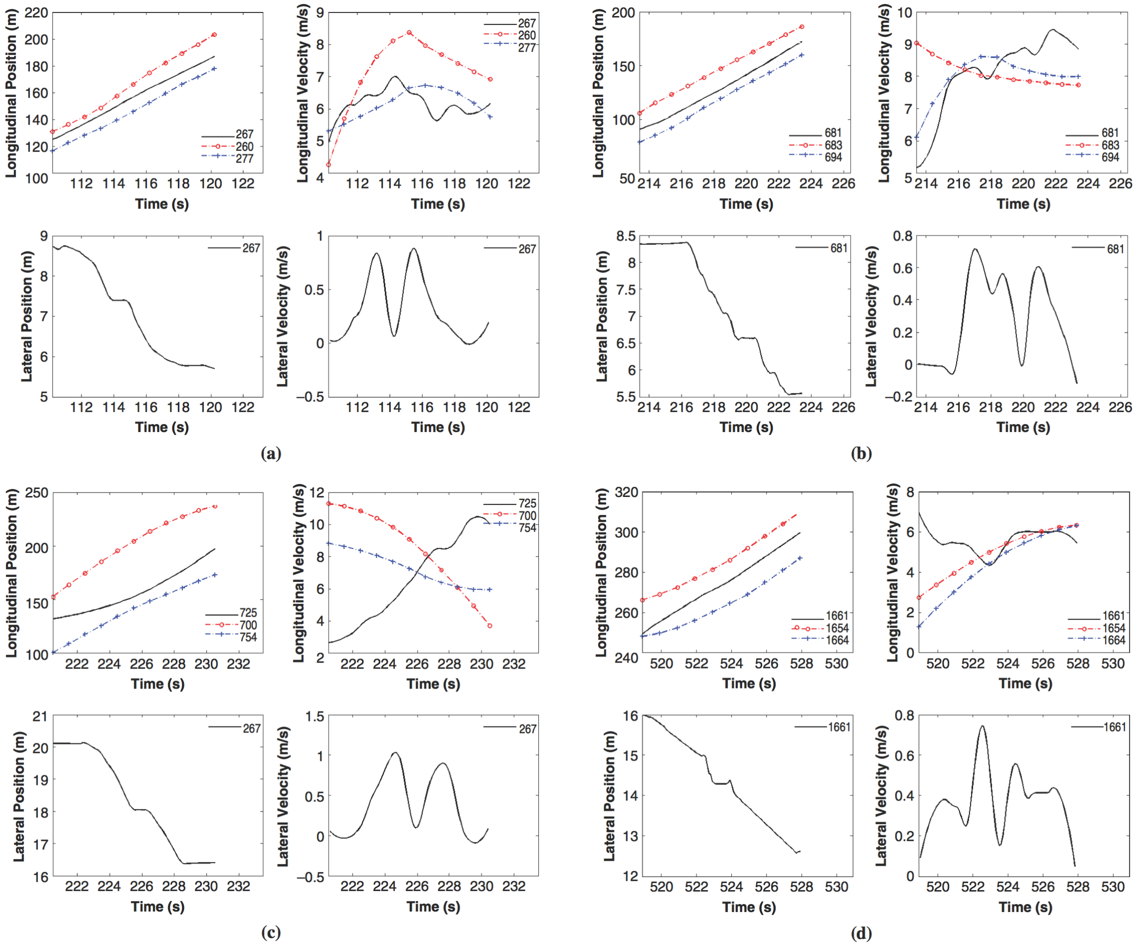

Figure 11 Four discontinuous lane change execution (DLCE) scenarios [YZY15]

The study used the NGSIM dataset, which is a recording of all vehicle trajectories in rush hour traffic over a 640 m stretch of the Hollywood Freeway (US-101) and a 503 m stretch of the Berkeley Highway (I-80) in California. In that dataset, 74% of lane changes were of CLCE type and 26% fitted the DLCE type.

The authors of the study also propose a parametric model to represent the analyzed CLCEs (Figure 10). The model uses linear lateral acceleration profile $a(t) = -(12S/T^3)\, t + 6S/T^2$ (Figure 12), which results in a parabolic lateral speed profile $v(t) = -(6S/T^3)\, t^2 + (6S/T^2)\, t$ and a S-shaped lateral position profile represented by a third-degree polynomial $s(t) = -(2S/T^3)\, t^3 + (3S/T^2)\, t^2$. The authors also present a model of DLCEs, which depends on the front and rear gaps and speeds of the front and rear vehicles on the target lane.

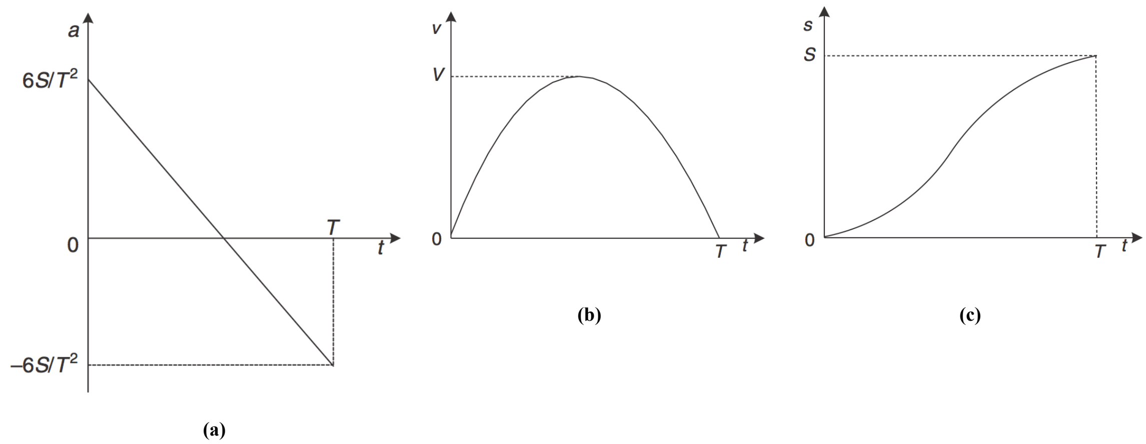

Figure 12 A polynomial model of continuous lane change execution (CLCE) [YZY15]

The model in Figure 12 only covers the main lateral movement of the subject vehicle where the lateral acceleration changes linearly. Within the entire maneuver, the lateral acceleration starts off and ends smoothly, as shown in Figure 13. The swiftness of the lane change depends on the driving style (Figure 14). The scenario in the top of Figure 14 has higher maximum lateral acceleration and jerk than the scenario in the bottom of the figure (cf. Table "Comfort assessment of three dynamic profiles for a lane-change maneuver and three passenger activities" [HLCR]). Further, the CLCE might not be symmetric (see Figure 15); in particular, it may be desirable to execute the initial approach to the target lane swifter than the settling in the target lane in order to make the lane change amply visible to other road users [LAS15]. In this case, the increased maximum lateral jerk is traded off for improved visual communication and thus improved safety, assuming good road surface conditions.

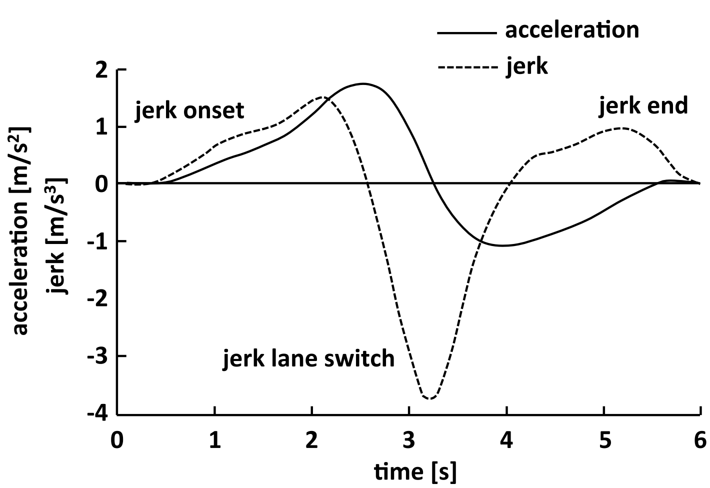

Figure 13 Lateral acceleration and jerk during a continuous lane change execution (adapted from [BSK16])

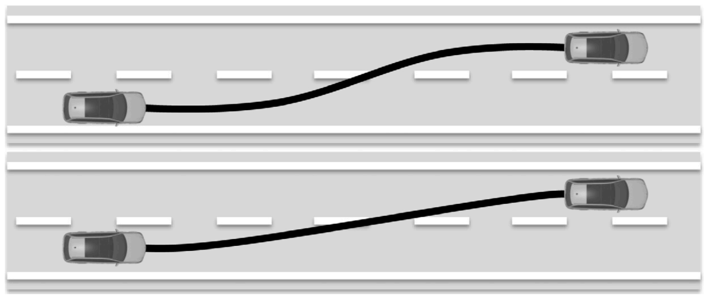

Figure 14 Two continuous lane change executions with varying dynamisms [BSK16]

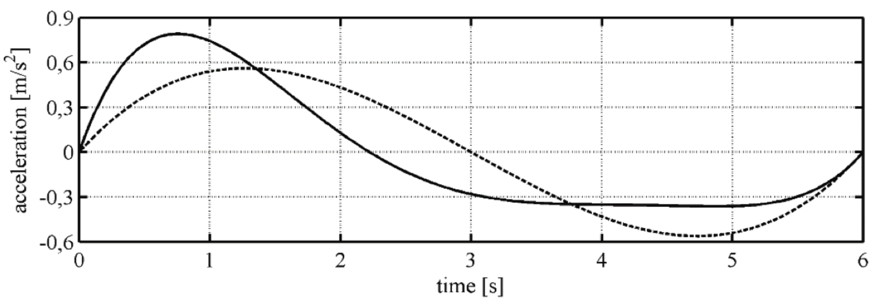

Figure 15 Modification of the lateral acceleration profile during a lane change for timely feedback [LAS15]

Obstacle avoidance, such as avoiding a pothole or debris on the roadway, typically results in a maneuver whose path is similar to a continuous lane change or double lane change, but with a smaller maximal lateral displacement.

Existing work on trajectory planning has used a range of curves to represent continuous lane change execution [KS16], including quintic polynomials [PBB02], polynomial spirals [KN03], and sinusoids [CT94,Wie06]. Inspecting the shape of lateral acceleration in Figure 13, it is obvious that the shape can be approximated well by a third degree polynomial, which leads to a quintic polynomial for representing the lateral displacement profile. Quintic polynomials have been also shown to approximate closely circular arcs and clothoids [PB00b].

In contrast to a continuous lane change in free driving, a lane change in dense traffic, which is likely but not necessarily a discontinuous lance change, is constrained by the front and rear vehicles in the current and target lanes. Such a maneuver is less about following a particularly shaped path, and more about ensuring safe gaps and speed differences from the front and rear vehicles, with the gaps and speed differences only partly controlled by the subject vehicle through its longitudinal speed, and executing a lateral movement, possibly with a pause, into the target gap on the target lane when it is safe to do so or aborting the maneuver if the movement of the vehicles on the target lane prevents the safe completion of the maneuver. The resulting path and trajectory is a result of the composition of these highly variable longitudinal speed and lateral displacement profiles.

While maneuvers in normal driving often lead to certain typical classes of paths or trajectories, such as horizontal road alignment curves or the different types of lane change trajectories, emergency maneuvering should ideally have access to the complete set of feasible trajectories within the stability envelope. Nevertheless, typical evasive steering (swerving) maneuvers resemble lane change or double lane change maneuvers [GDL16].

3.2.2 Reverse Lateral Control

Reverse lateral control consists of steering the subject vehicle on a horizontal tangent or a curve in reverse:

1. StraightSteerInReverse
2. CurvedSteerInReverse

Note: Reverse lateral control tasks are outside the scope of the current version of this document.

3.3 Recovery from Instability

The previously discussed tasks consider normal driving and emergency situations where the subject vehicle remains within its stability envelope. This section considers tasks that attempt to recover lost stability. These tasks are executed exclusively rather than in combination with the previously discussed longitudinal and lateral control tasks.

3.3.1 Skid Recovery

In the case of skidding, recovery is achieved by reducing tire forces, such as by disengaging brakes and reducing the sideslip angle, that is, aligning the wheels with the direction of the travel. When stability is recovered, previously discussed longitudinal and lateral control can be resumed.

3.3.2 Excessive Roll Recovery

Excessive lateral force may lead to an untripped rollover for some vehicles, such as vans and trucks, and reducing lateral force may be required to avoid an imminent rollover. Passenger vehicles tend to skid before reaching the critical rollover lateral force, however, and thus no rollover-specific recovery task is applicable. Tripped rollovers are avoided by avoiding the tripping event; once the rollover is tripped, the control is lost and a rollover cannot be avoided.

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