WISE Requirements Analysis Framework for Automated Driving Systems

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

Driving Behavior Comfort

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Abstract

This document analyzes how the driving behavior of an ADS-operated vehicle impacts road user comfort. The main focus is occupant comfort related to acceleration and jerk; however, the analysis also considers other physical parameters, such as speed and gaps, and links them to comfort using the concept of a comfort zone. While much research on driving behavior comfort remains to be done, this document summarizes existing studies and data on acceleration and jerk in naturalistic driving and the impact of different levels of acceleration and jerk on occupant comfort. This data can be used to inform driving behavior design for occupied trips.

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1 Scope

Comfort is the subjective state of wellbeing of a human road user. This analysis focuses on the comfort of road users, including vehicle occupants, cyclists, and pedestrians, in relation to behavioral choices of an ADS-operated vehicle.

The analysis covers
1. occupant comfort related to the vehicle motion and the driving style, and
2. comfort of human road users outside the vehicle related to the interactions between the vehicle and the other road users.

Motion-related occupant comfort is mainly impacted by acceleration and jerk. This document summarizes value ranges of acceleration and jerk in naturalistic driving and the impact of different levels of acceleration and jerk on occupant comfort based on existing research.

2. Occupant Comfort

Occupant comfort is the subjective state of wellbeing of an occupant. Traditionally, vehicle occupant comfort has been studied with respect to the following factors [Col87, Sil02]
1. *dynamic factors*, which include vibration, shocks, and acceleration levels;
2. *ambient factors*, which include thermal comfort, air quality, noise, pressure gradients; and
3. *spatial factors*, which relate to the ergonomics of the passenger's position.

Another set of factors relates to the outside of the vehicle, such as closeness to other road users and objects and the subjective assessment of driving style and the resulting perceived safety.

Occupant comfort is relevant for trips with occupants. ADS may perform trips with no occupant on board, such as package delivery or bringing the vehicle to a passenger pick-up location. For such trips, motion control is unconstrained by comfort factors discussed in this section.

2.1 Noise, Vibration, and Harshness

In traditional vehicle engineering, the comfort factors related to vehicle motion include *noise*, *vibration*, and *harshness* (NVH). Noise and vibration come from the mechanical devices inside the vehicle and from the vehicle motion on a road that is not perfectly smooth. The ability of the tires and the suspensions to filter out this external vibration is critical. Noise and vibration are classified based on their frequencies [GG16]:

1. *Ride*: low frequency (up to 5 Hz) vibration of the vehicle body;
2. *Shake*: vibration at intermediate frequency (between 5 and 25 Hz), at which some natural frequencies of subsystems of the vehicle occur;
3. *Harshness*: high frequency vibration (between 25 and 100 Hz) of the structure and its components, felt primarily as noise; and
4. *Noise*: acoustic phenomena occurring between 100 Hz and 22 kHz, i.e., up to the threshold of human hearing.

The effects of vibration on human beings can be stated by defining the following frequency ranges [GG16] (also see ISO 2631):

- $\omega < 1$Hz. The low frequencies produce sensations that may be associated with motion sickness. "They depend on many parameters other than acceleration and vary among individuals."
- $1 < \omega < 4$ Hz. "The ability of humans to tolerate acceleration decreases with the frequency increase in this range." Jerk is the main cause of discomfort in this range.
- $4 < \omega < 8$ Hz. "The ability of humans to tolerate acceleration reaches a minimum in this range, and the acceleration causing discomfort is constant with the frequency." The thorax-abdomen system, including vital organs in the abdominal cavity, has a resonant frequency at about 3–6 Hz, although all resonant frequency values depend strongly upon individual characteristics.
- $8 < \omega < 80$ Hz. "The tolerance to vibration increases again with a practically linear law with frequency. In practice, what creates discomfort in that range is not so much acceleration but the velocity." The head-neck-shoulder system resonates at about 20–30 Hz, and the eyeball resonates at 60–90 Hz.
- $\omega > 80$ Hz. "The effect of vibration depends upon the part of the body involved, as local vibrations become the governing factor, making it impossible to give general guidelines." For example, the lower jaw-skull system resonates at 100–220 Hz. It is also challenging to grip a steering wheel if it is moving at 50-200 Hz.

In summary, frequencies between 4 Hz and 8 Hz are most uncomfortable to humans.

Traditionally, ride comfort has focused on engineering suspensions to filter effectively vibrations due to road roughness. Acceleration and jerk due to driver controls were not addressed since the driver was outside the control of vehicle engineering. However, acceleration and jerk levels due to control inputs are the main determinants of ride comfort for an ADS-controlled vehicle (see next section).

Noise, vibration, and harshness are less relevant to ADS performance, but may still impact ADS driving decisions, such as choice of the travelled lane based on road surface quality, or adjusting the vehicle speed to the surface roughness to avoid certain frequencies

2.2 Acceleration and Jerk

Large acceleration and jerk values cause passenger discomfort. Acceleration and jerk that act on a human body uniformly, such as in a free fall, are not felt. It is the force transmitted between the seat of an accelerating vehicle and the side of the human body contacting the seat that causes compression and discomfort. Another effect comes from jerk, that is, the rate of change of acceleration. Human muscles, which are responsible for maintaining body pose, have limited reaction time. When acceleration changes at a high rate, muscles do not have enough time to adjust their tension to match the changed forces. As a result, the body pose changes involuntarily. Seated passengers can tolerate much higher jerk levels than standing ones. Jerk impacts negatively occupant activities, such as consuming a drink or writing using a pen.

The level of discomfort caused by specific acceleration and jerk depends on the maneuver being performed, personal characteristics of the occupant, and the activity the occupant is engaged in [FED17]. Traditionally, vehicle response to control inputs has been tuned to a human driver, both to allow feedback and to enhance driver comfort and enjoyment of driving. For ADS-controlled vehicles, the focus is on the *comfort of passengers*, who may engage in different activities, such as looking out the window, reading, eating, sleeping, etc. The specific ranges of accelerations and jerk that are comfortable depend on these activities.

Table 1 summarizes motion-related comfort metrics [BSK16], which include longitudinal and lateral acceleration and jerk, and their value ranges in different maneuvers. The values are mainly based on naturalistic driving studies, that is, they represent accelerations and jerks that occupants are exposed to in driving performed by human drivers.

Table 1 Comfort-related acceleration and jerk value ranges for common maneuvers

Maneuver	Metric	Value Ranges
Expected braking, such as for an expected curve or intersection	Maximum longitudinal deceleration (the maximum occurs typically early during braking [DQM17])	For seated passengers, slight discomfort starts with decelerations of 1 m/s^2, but deceleration up to 2 m/s^2 are assumed as still relatively comfortable for seated passengers [SE15]. Average maximum deceleration in naturalistic driving is 2.42 m/s^2; the average maximum varies depending on traffic situation and initial speed

		between 2.35 and 2.7 m/s^2 [DQM17]. Another study found average maximum deceleration of 1.3 / 2.2 / 3.3 m/s^2 for 10%, 50%, and 90% percentile of drivers [HN03].
	Maximum longitudinal jerk (the maximum occurs typically at the beginning and end of braking)	Jerk of up to 0.9 m/s^3 is assumed comfortable for seated occupants [SE15]. Average maximum longitudinal jerk in naturalistic driving is 3.6 m/s^3, but values up to 8.0 m/s^3 still occur in normal driving situations for some drivers [Nyg99].
Emergency braking (for near-collisions)	Maximum longitudinal acceleration	Maximum longitudinal deceleration observed in near-collisions in naturalistic driving is between 4.0 and 7.7 m/s^2 [Hor90].
	Maximum longitudinal jerk (typically at the beginning and end of braking)	Maximum longitudinal jerk observed in near-collisions in naturalistic driving is between 9.9 and 12.6 m/s^3 [Nyg99]
Acceleration	Maximum value of longitudinal acceleration (typically at the beginning of the acceleration)	Average maximum acceleration when leaving an intersection or a turn in naturalistic driving is 0.9 / 1.6 / 2.6 m/s^2 for 10%, 50%, and 90% percentile of the driver sample [HN03].
	Maximum longitudinal jerk (typically at the beginning and end of acceleration)	Maximum longitudinal jerk rages between 2 and 3.7 m/s^3
Cornering	Maximum lateral acceleration (the highest lateral acceleration occurs in the entrance of a curve; regardless of radius, the lateral acceleration decreases towards the same value at the end point of a curve [Oth11,IP15]).	Drivers choose maximum lateral acceleration depending on curvature (see Tables 2 and 3); maximum values in sharp curves go up to 5.3 m/s^2; also see [BDS14]
	Maximum lateral jerk, typically at the beginning and end of the turn	The GDS assumes jerk of under 0.6 m/s^3 in curves to be comfortable [GDS85].

Lane change	Maximum lateral acceleration	Maximum lateral acceleration of 1 m/s^2 for "normal" and 2.2 m/s^2 for "sharp" lane changes in naturalistic driving [SN85]. See Table 4 for comfort-related ranges.
	Average lateral jerk, typically at the beginning and end and the middle of the lane change	See Table 4 for comfort-related ranges.
	Maximum lateral jerk, typically at the beginning and end and the middle of the lane change	See Table 4 for comfort-related ranges.

Table 2 Lateral acceleration values in naturalistic driving recorded on curves of different radii. Count refers to number of curves on the experimental route within a given radius range. Acceleration values are given for 10%, 50%, and 90% percentile of the driver sample [HN03]

Radii [m]	Mean [m]	Count	10% [m/s²]	50% [m/s²]	90% [m/s²]
20 – 40	34	6	3.1	4.1	5.3
40 – 70	51	11	2.5	3.6	4.9
70 – 100	83	2	2.2	2.9	3.4
100 – 200	151	7	1.1	1.7	2.7
150 – 300	267	2	0.6	1.1	1.9

Table 3 Lateral acceleration values in naturalistic driving recorded on sharp curves. Very sharp corners (10 m radius) lead to lower lateral acceleration; possible explanation is that the discomfort caused by higher acceleration does not offer significant time advantage on very short curves [HN03]

Radius [m]	10% [m/s²]	50% [m/s²]	90% [m/s²]
10	2.6	3.2	4.3
20 – 40	3.1	4.1	5.3

Data on the comfort of different levels of acceleration and jerk is lacking. As an exception, Table 4 shows the lateral acceleration and jerk levels for three lane-change profiles of increasing dynamism (D1-3), and the corresponding passenger comfort rating depending on passenger activity (A1-3) [FED17]. Each dynamic profile specifies the absolute mean $|\bar{x}|$, minimum |min|, and maximum |max| value of the maximum lateral acceleration during the maneuver and maximum lateral jerk during the beginning and the end of the maneuver, and the middle, when crossing the lane line. The lane-change maneuver was performed with the different lateral dynamic profiles on a test track with the subject vehicle driving at 110 km/h and approaching a front vehicle driving at 80 km/h and with human subjects as passengers performing one of the three tasks. Each of the 38 human subjects scored profiles D1 and D3 on a Likert comfort scale -2, -1, 0, 1, 2. Profile D2 was used as a reference, i.e., it has score 0 by definition. The table shows the mean scores and the standard deviations for profiles D1 and D3. The results show that the dynamic profile D3 interferes with all three activities, but most strongly with reading and playing on a tablet.

Table 4 Comfort assessment of three dynamic profiles for a lane-change maneuver and three passenger activities [FED17]

Dynamic profile	**Maximum lateral acceleration (m/s2)**			**Maximum lateral jerk at the beginning and end (m/s3)**			**Maximum lateral jerk in the middle (m/s3)**			**A1: Watching traffic**		**A2: Reading an article**		**A3: Playing on a tablet**	
	$\|\bar{x}\|$	|min|	|max|	$\|\bar{x}\|$	|min|	|max|	$\|\bar{x}\|$	|min|	|max|	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
D1	0.8	0.5	1.1	1.2	0.8	1.8	1.2	0.8	1.8	0.7	1	0.9	1	0.9	0.7
D2	1.1	1	1.3	1.6	1.2	2	1.7	1.4	2.2						
D3	1.5	1.4	1.9	2.2	1.8	2.7	2.6	2.1	3.2	-0.6	0.9	-0.8	0.8	-0.9	0.5

In a different research, Huang and Wang study the comfort of *transient jerk* and *durative jerk* and propose using a combination of maximum jerk value and root mean square of jerk over its duration as metric [HW04].

In general, longitudinal or lateral acceleration and jerk up to the following limits are considered comfortable for seated passengers:

1. longitudinal or lateral acceleration of up to 2 m/s^2 ;
2. longitudinal or lateral jerk of up to 0.9 m/s^3 .

Longitudinal or lateral acceleration and jerk above the following limits are indicative of intense maneuvers, such as in emergencies:

1. longitudinal or lateral acceleration above 5 m/s^2 ;
2. longitudinal or lateral jerk above 8 m/s^3.

2.3 Perceived Safety and Progress

Apart form the dynamic factors impacting passenger comfort through physical forces, the subjective assessment of driving behavior by the occupants and the resulting perceived safety and progress also impact their comfort. The relationship between choices of driving behavior parameters such as speed and gaps and occupant comfort could be explained using the zero-risk theory [NS76, Sum88]. The theory was proposed to explain driver behavior, but its basic idea can be applied to passenger comfort too. The theory hypothesizes that the driver's adaptive behavior is the result of a balance of excitatory and inhibitory motives, as illustrated in Figure 1. Excitatory motives animate the driver to participate actively in the environment, such as by increasing speed and reducing the front gap. Inhibitory motives push towards the reduction of the perceived risk, causing the driver to decrease speed and increase the front gap. According to the zero-risk theory, drivers tend to avoid perceived risk in order to feel comfortable. At the same time, they will also want avoid too slow speed and too large of a front gap, as they may feel to make insufficient progress otherwise. Applying this concept to occupant comfort, the diving behavior should target the *comfort zone* of the occupants, assuming that the comfort zone is within the safety zone (Figure 1).

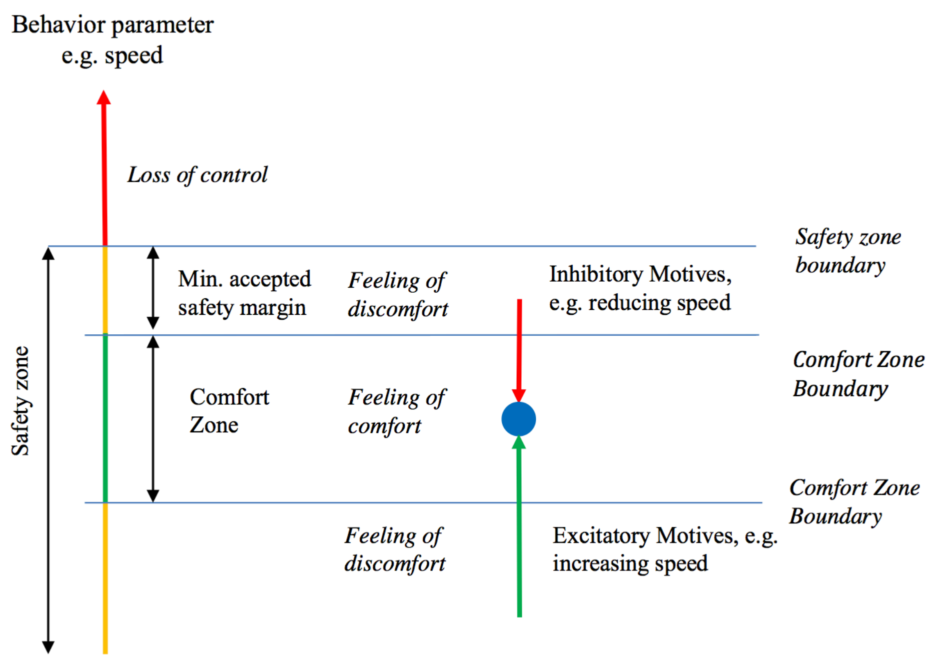

Figure 1 Safety zone versus comfort zone (reproduced from [SB15])

In general, the perceived risk may be higher or lower than the actual risk. The perceived risk is impacted by many factors, including type of object or user being approached, maneuver, speed, and personal characteristics and experience of the occupants. For example, when the subject vehicle passes a large truck while observing safe minimum lateral clearance, some occupants may still perceive the clearance as too small. Another example relates to the front gap in vehicle following. Even though an ADS-operated vehicle may have substantially faster reaction time than a human, and thus can follow safely another vehicle more closely than a human driver could, the shorter front gap could be perceived as risky and lead to occupant discomfort. The perceived risk being lower than the actual risk is a serious issue when a human driver operates a vehicle, but an ADS must maintain safe speed and gaps even if the occupants desired higher speeds and lower gaps.

3. Comfort of External Human Road Users

The subject vehicle behavior impacts the comfort of human road users outside the vehicle both at the physical level, e.g., through gaps and speed, and at interaction and communication level, such as through courtesy in yielding and clarity of intention.

The tradeoff between perceived risk and progress from Figure 1 also applies to road users that are external to the subject vehicle. For example, a vehicle that passes a pedestrian waiting at a crosswalk will make the pedestrian feel uncomfortable above a certain speed; on the other hand, a vehicle that slows down too much may also make the pedestrian uncomfortable—feeling to be unnecessarily delayed to cross.

Similarly, some road users may find gaps that are just larger than the safe minimum uncomfortable. In particular, an ADS-operated vehicle may follow safely another vehicle at a closer distance than a human-operated vehicle; however, if a human driver operates the followed vehicle, the driver may interpret the close following as tailgating and feel uncomfortable. Another example is the lateral clearance when overtaking a bicycle. A study found the perceived risk to be correlated with a combination of lateral clearance and vehicle speed that is proportional to the aerodynamic force generated by the passing vehicle and affecting the cyclist [LA14]. Assuming maximum speed of 120 km/h, the aerodynamic force drops to zero at a lateral clearance of 3 m. The study found that lateral clearance of 1.5 m at 50 km/h and 2.75 m at 120 km/h resulted in very low perceived risk.

At the physical level, there is also the possibility of splash and spray on a wet road surface, which may require slowing down and keeping an extra distance from cyclists and pedestrians.

Another aspect is the interaction between the subject vehicle and other road users. Human drivers follow social norms, which supplement formal traffic rules. For example, a Swedish study found that drivers arriving on a narrower roadway at uncontrolled intersections tend to yield to drivers who arrive on a wider roadway, even though formally the crossing road have equal priority [BA05]. A vehicle respecting these norms will interact with human drivers more smoothly and likely make them feel more comfortable. An ADS-operated electric vehicle optimizing for fuel consumption may have a different braking pattern than a human-operated vehicle powered by an internal combustion engine. If the ADS-operated vehicle is followed by the human-operated one, it may need to adjust its braking pattern to reduce the potential of annoying the driver.

Finally, the vehicle behavior needs to be designed such that the vehicle’s intention is clear to the other road users. Lack of clarity negatively impacts both safety and comfort.

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