Driver Influence on Vehicle Track-Ability on Floating Bridges

TME180 Automotive Engineering Project

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Cover: Image shows the E39 across Bjørnafjorden. Concept: straight, side-anchored pontoon bridge. Illustration: Norwegian Public Roads Administration

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Abstract

Thinking from a traveler's perspective, it can be said that it is important to reduce travel time. The Norwegian Public Roads Administration (NPRA) is working on a long term project to extend the coastal highway route E39 as a continuous stretch of road between Kristiansand and Trondheim. The road has a number of ferry crossings over fjords. Due to the depth in the fjords, it is not possible to build conventional bridges. Thus, the objective is to reduce the travel time by implementing a series of connections (e.g.submerged floating tunnels, subsea road tunnels and floating bridges). One such fjord crossing is the Bjørnafjorden bridge which spans for a length of over 5000 m.

The floating bridge will be exposed to a number of varied weather conditions of different intensities. It is important to assess the vehicle handling and how the driver is experiencing the moving road surface in these conditions. The bachelor thesis which was proposed on the same topic, established a method to simulate the weather conditions in the CASTER driving simulator at Chalmers. The Automotive Engineering project (AEP) aims at evaluating the driving comfort and handling, when driving over the bridge in different weather conditions. The main approach adopted is to simulate the driving conditions in CASTER driving simulator, using the weather data provided by NPRA. Further, driving trials are conducted for a combination of different weather conditions and vehicle speeds for car and bus models. The results obtained from the trials are analyzed both subjectively using the driver feedback and objectively using the data obtained from the driving simulator, to make suitable conclusions and recommendations regarding the safe operating conditions of the bridge.

The project further concludes the correlation between the weather conditions and drivability through both subjective and objective data analysis. The weather conditions were varied from no wind condition to a 100-year storm condition. Also, the most frequently occurring 1-year storm condition was studied in detail with only wind on the vehicle, sea swell and wind due to the wave conditions. A total of 157 driving trials were conducted with different vehicle speeds (70 kmph, 90 kmph and 110kmph) and different maneuvers like lane change and overtaking were performed to analyze the handling and stability of the car and bus. Straight line driving is also simulated to determine the operating conditions of bridge, to check the safe speed limit and ability of the driver to stay in lane.

Another deliverable of the project is to develop a driver model to perform a greater number driving trials to test more conditions. Due to the lack of time and complexity of the weather data, a basic driver model has been developed and a thorough literature survey has been done to make suitable suggestions for the existing basic driver model as a future scope of the project.

To sum it up, the vertical and lateral dynamics of the vehicles driving over the bridge are assessed in a virtual environment. A detailed analysis is done with the help of the data obtained in order to make suitable recommendations for safe driving on the bridge at different weather conditions.

Keywords: Floating bridge, Driving trials, Simulation, Driver comfort, Lane change, Overtake, Staying in lane, Driver model.

Acknowledgements

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Abbreviations

NPRA	Norwegian Public Roads Administration
AEP	Automotive Engineering Project
VEAS	Vehicle Engineering and Autonomous Systems
STI	Standard Tyre Interface model
RMS	Root Mean Square
FFT	Fast Fourier Transform
CoG	Center of Gravity
MF	Magic Formula
PID	Proportional Integral Derivative
MPC	Model Predictive Control
LIDAR	Light Detection and Ranging
ADAS	Advanced Driver Assistance System

Contents

Chapter 1

Introduction

1.1 Background

A good infrastructure system plays a vital role in shaping up an efficient mobility system. The Norwegian Public Roads Administration (NPRA) is working on a long term project to extend the coastal highway route E39 as a continuous stretch of road between Kristiansand and Trondheim. The route is roughly 1100 km long and travel time is approximately 21 hours at low average vehicle speed of 50kmph. The time required to cover the distance between Kristiansand and Trondheim is very high because of 7 different ferry routes. By implementing a series of connections without ferries (e.g.submerged floating tunnels, subsea road tunnels and floating bridges) the NPRA aims to bring down the travel time to 11 hours with reduction in the total distance by 50 km. NPRA is also collaborating with different universities to work on this huge project. The current project at Chalmers University of Technology deals with the crossing at Bjørnafjorden which has a width of 5 km and a depth of 550 m. This project in the Automotive Engineering Project course is a continuation of the bachelor thesis project. During the bachelor thesis, primary scope was to establish a methodology for understanding the driver influence on vehicle track ability on floating bridges [1]. The vehicle models for the car and bus were also selected and driving trials were conducted in the CASTER driving simulator. Different scenarios were considered and subjective and objective assessments were done to evaluate the driving on the bridge.

Figure 1.1: E39 highway route

1.2 Project tasks and deliverables

The main objective of this project is to conduct driving trials in order to draw suitable recommendations and conclusions for safe driving on the bridge. In order to improve the trials, the existing vehicle models were improved and bridge roll motion was implemented. The below list shows the tasks planned in the current AEP project:

- Literature study and to get an understanding for existing simulation models and control model for driving simulator
- Currently, the bridge model comprises of sway and heave motion. The Roll motion can be added to the existing bridge model to analyze it's effects on the driver and the vehicle.
- To enhance the Simulink model of the bus by refining a few parameters of suspension, drive-line and tire model.
- To perform driving trials of the vehicles at different speeds, different weather conditions and several drivers. Selection of suitable weather conditions based on NPRA inputs to test different levels in driving trials.
- To test the stability of the vehicle by subjecting it to various driving maneuvers.
- To compile results from different driving trials and understand the effect of different weather conditions on the driving.
- To evaluate different design approaches for the driver model.

1.3 Limitations

The project has the following limitations to consider-

- The vehicle model used is an existing generic sedan model and a similar model has been used to model the bus by using relevant parameters.
- All assessments are made without considering the traffic on the road.
- Simplified suspension models have been used.
- Dry road conditions will be considered

1.4 Stakeholder(s)

The Norwegian Public Roads Administration (NPRA), is a government organization responsible to improve the E39 coastal highway and, is the primary stakeholder. Vehicle Engineering and Autonomous Systems (VEAS), at Chalmers has collaborated with NPRA to work on this project.

Chapter 2

Literature Survey

2.1 Floating Bridge

To obtain one part of the theoretical basis for the Bjornafjorden project it was fundamental to setup a driving simulator model and understand the effects of the weather on the selected vehicles. The thesis report 'Driver Influence on Vehicle Track-Ability on Floating Bridges' [1] explains how a method was developed to evaluate the concept of the bridge in the driving simulator. The report further describes the bridge model along with the car and bus models that were developed as the foundation to analyse the effect of weather conditions while driving on the bridge. Also, the developed model was put in use to collect subjective and objective data for three weather conditions; one year storm, hundred year storm and no storm conditions. Finally, the report proposes the possible developments to the vehicle models to improve reliability and the methods to collect subjective data.

On the similar guidelines as the above discussed literature, the paper titled 'Effect of floating bridge motion on vehicle ride comfort and road grip'[3] provides in depth analysis of the consequences of a floating bridge motion on the drivers ride comfort and road grip. The paper in particular compares the scenario of a floating bridge motion when driving on four different speeds namely 54 kmph, 72 kmph, 90 kmph and 108 kmph and analyses the effects with an ISO standard 2631. The author also establishes that the reason behind the motion sickness which he relates to the low frequency vertical vibrations of the bridge. Further, the paper describes how the dynamic load coefficient is used to study the road grip throughout the bridge span and finds the results to be within the acceptable limits.

2.2 Driver Modelling

The material by Jacobson Bengt, et al., 'Vehicle Dynamics Compendium'[2], provides an insight on how to design a driver and vehicle model. He also mentions the parameters that should be taken into consideration while comparing the results from a driving simulator. The compendium gives us a guidance on how to select driver model based on the requirement of 'verification of vehicle functions' and for implementation in 'driving automation functions' with respect to different vehicle environment.

In context to the above guidelines on how to design a driver model, the document by P.Carlo Cacciabue, et al. 'Modelling Driver Behavior in Automotive Environments'[8], provides the possibility to assess different approaches and considerations in relations to driver behavior modelling and control theory model of driver. Further, each chapter demonstrates a general perspective of the ongoing topics of development for present and future generations of automation and intelligent support systems.

To conclude, the literature provides a strong foundation to further analyse different scenarios and the possible developments to improve the accuracy and reliability of the simulation method. The next section discusses the potential of the established methods in detail.

Chapter 3

Methodology

3.1 Modifications to the car and bus vehicle models

It was decided to carry over the same vehicle models used in the Bachelor thesis project [1] and work on further refining the vehicle models. There were no issues with the car model. However, some room for improvements in the bus model were discussed, eliminating the need for building a bus model from the scratch. Further, the vehicle parameters considered are as listed in the below table.

Parameter	**Bus**	Car
Curb weight	18000 kg	1140 Kg
Frontal area	7.67 m^2	2 m^2
Side area	39.9 m^2	5.1 m^2
Drag Co-efficient	0.39	0.26
Side drag Co-efficient	1.1	0.6
Distance between COG and front axle	3.66 m	1.375 m
Distance between COG and rear axle	2.29 m	1.375 m
Track width front	2.107 m	1.6 m
Track width rear	1.885 m	1.6 m

Table 3.1: Model parameters

3.1.1 Bridge Roll Motion

The wind and bridge motion data received from NPRA was in the form of a space-time matrix where the total distance 5137m of the bridge is divided in the steps of 1m and a time step of 0.2s each. C++ Mex function is used for the interpolation. The implementation of the same is shown below in Figure 3.1. In the figure, In1 corresponds to the suspension position and the Out2 is the deflection sent to the wheel. The Mex file compiled using MATLAB is added to Simulink using the S-function.

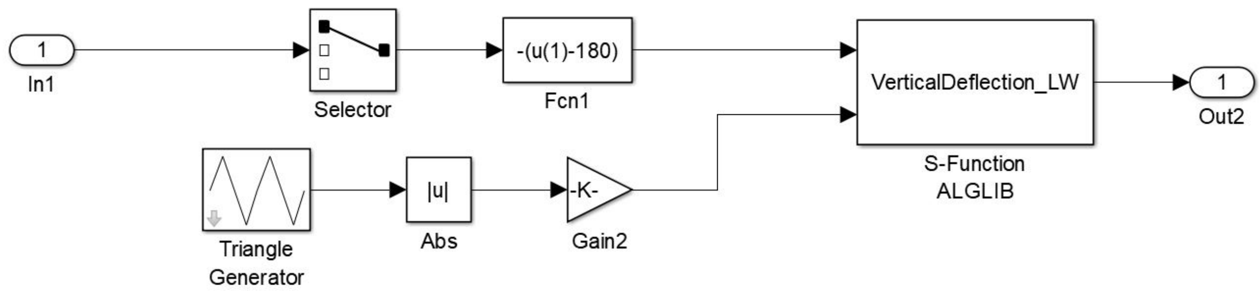

Figure 3.1: Simulink model to obtain bridge deflections

The existing model contains the lateral motion and vertical motion. However, there is one more motion which influences the driving behaviour on the floating bridge. In extreme weather conditions the bridge rolls about its longitudinal axis. It was necessary to add roll motion to the existing model before conducting the driving trials. Figure 3.2 shows the simulink model which was created to add roll motion. This was done by using the same method of longitudinal and lateral motion model. Instead of giving the vertical displacements to the axles, they are given to each wheel.

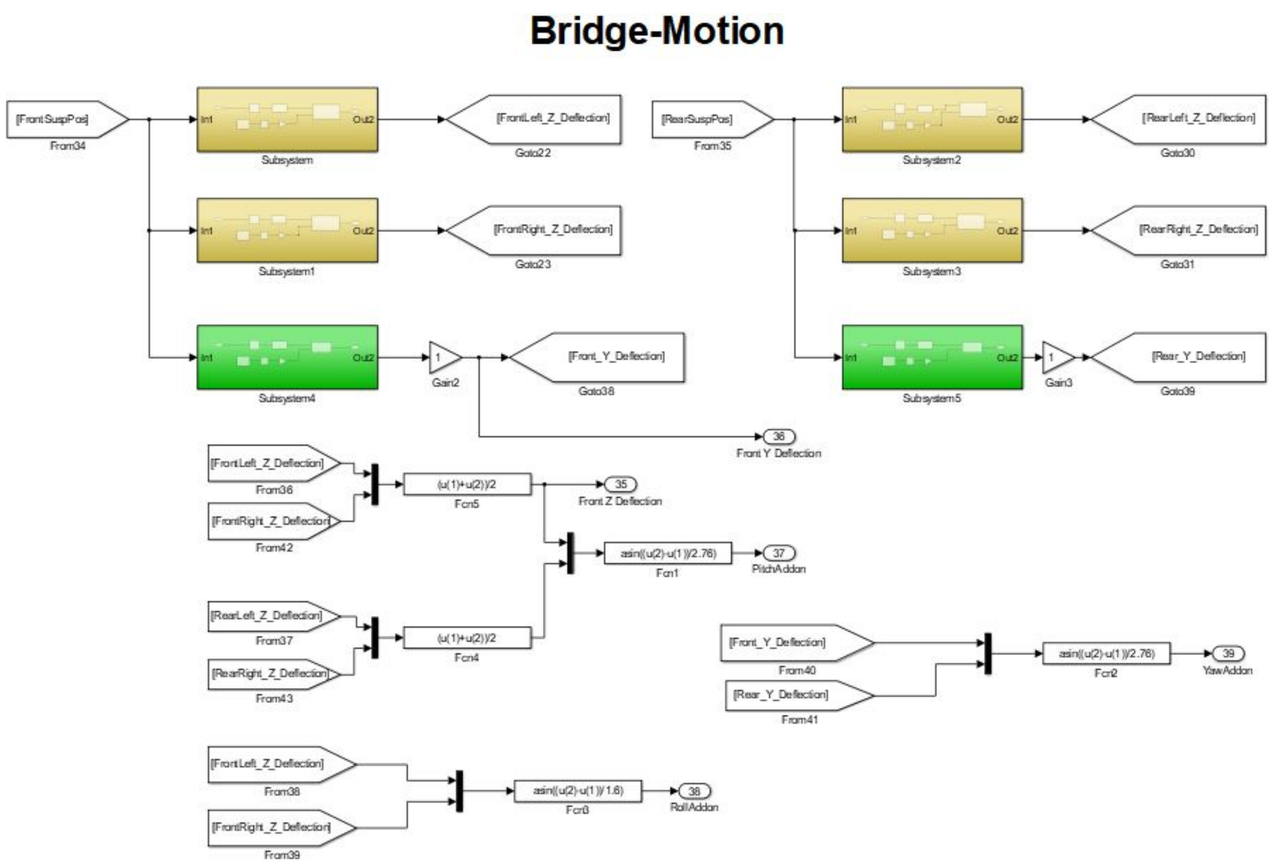

Figure 3.2: Simulink model of bridge roll motion

Vertical displacement of each wheel can be obtained at a particular time on the bridge. Difference in the inputs to the left wheel and right wheel displacements result in the roll motion. Similarly, difference in front and rear wheel displacements give pitch motion. Same method can be repeated to obtain yaw motion by replacing longitudinal displacements with lateral displacements in the model. The output of these blocks is then fed to tyre models to generate tyre forces. The outputs indicated in figure 3.2 as pitch add on, roll add on and yaw add on are sent to the simulator platform block to convert these signals to physical motion.

3.1.2 Bus model

The bus model is a heavily modified version of the car model. The prominent changes were made with tire and suspension model. Tuning the tire model was recommended in order to improve the sudden increase in longitudinal acceleration of the bus due to abrupt increase in longitudinal forces, especially at high slip ratios. In order to reduce the longitudinal forces, the current tire model was replaced with the existing SimMechanics first generation tire model to a Standard tyre interface model (STI) (Refer figure 3.3). The response of bus improved, but there was not significant improvements in the longitudinal forces.

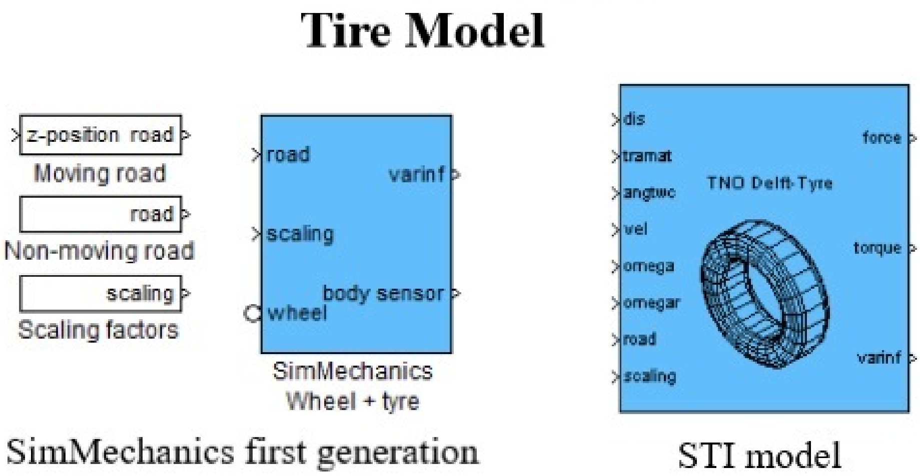

Figure 3.3: Simulink Tire Model

In order to correct the sudden increase in longitudinal forces, the engine model block was modified by varying the velocity and acceleration gain parameters in simdriveline Engine block. A predefined gain value of 1 is changed to 1.6 to fix velocity for each gear change. By changing the gain parameters, improved drivability and rational simulation results were established (Refer figure 3.4).

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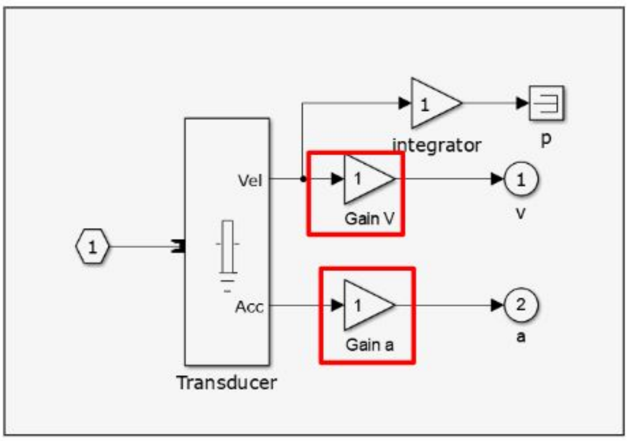


Figure 3.4: Engine Velocity and acceleration gain block

3.1.3 Weather Conditions and Environmental Loads

The weather data provided by NPRA is based on the intensity of the storm condition. The weather varied from the storm that frequently occurs several times in a year to a hundred year storm. In total 10 different weather conditions were considered as explained below.

- Weather 1 to 5 : Less than 1 Year storm condition
- Weather 6 : 1 Year storm condition
- Weather 7 : 2 Year storm condition
- Weather 8 : 10 Year storm condition
- Weather 9 : 50 Year storm condition
- Weather 10 : 100 Year storm condition

Further, weather 6 which is the 1 year storm condition was analysed in detail by considering individual environmental loads at a given time. The environmental loads are as described below.

- Swell : Long periodic sea waves which are generated by storms far away from the site.
- Windsea : Short periodic ocean waves locally generated due to friction between sea surface and wind
- Wind: Response of the bridge due to wind

The effects of these environmental loads are compared with weather 6 and its results are discussed in detail in chapter 5.4.

3.2 Driving Trials

Once the vehicle models were ready and tested, the next step was driving trials in the CASTER driving simulator. The driving trials were conducted for the different weather conditions. This data was obtained from NPRA and trials were conducted based on their inputs. Based on NPRA's suggestions, the driving trials were conducted for all the weather conditions and the impact of environmental loads on driving were also studied. Thus, all of the above were taken into consideration while planning the driving trials.
The first set of driving trials were conducted with the car. 16 trials were conducted with one driver. The driver was asked to fill a questionnaire at the end of each trial in order to understand the driver interaction with the car and the bridge. The driving trials are conducted with the following two scenarios based on different maneuvers.

- A trial with lane change and overtaking maneuver.
- A trial with straight line driving.

3.2.1 Driving trial with lane change and overtaking

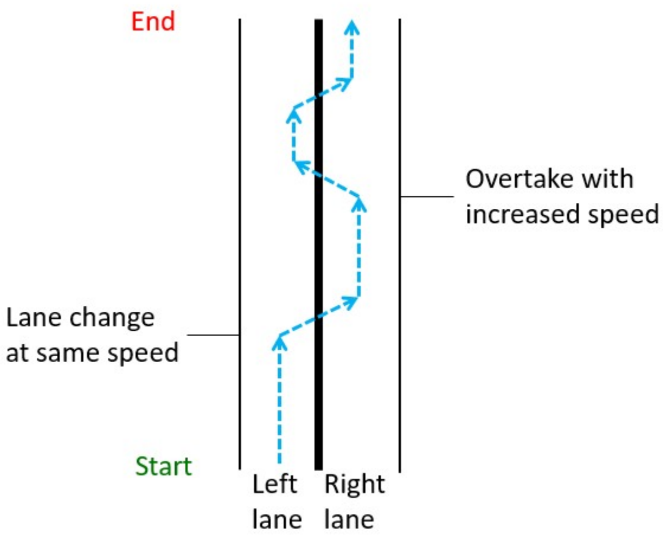


Figure 3.5: Driving trial setup for overtaking and lane change maneuver

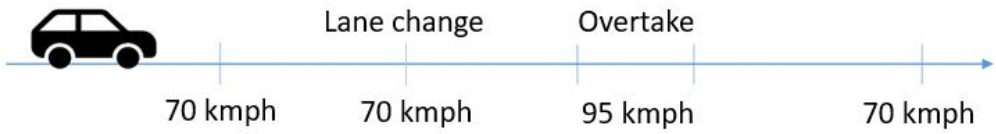


Figure 3.6: Speed profile for the driving trial

As shown in the figures, the vehicle accelerates to 70 kmph in the left lane and performs a lane change maneuver at the same speed after a sign post on the bridge indicates to perform the maneuver. Further, the driver drives in the right lane until another sign post appears indicating the driver to perform the overtaking maneuver by accelerating to a speed of 95 kmph and later returning back to the right lane. Finally, the driver terminates the driving trial while maintaining a speed of 70 kmph at the end of the bridge marked by another sign post.

3.2.2 Driving trial with straight line driving

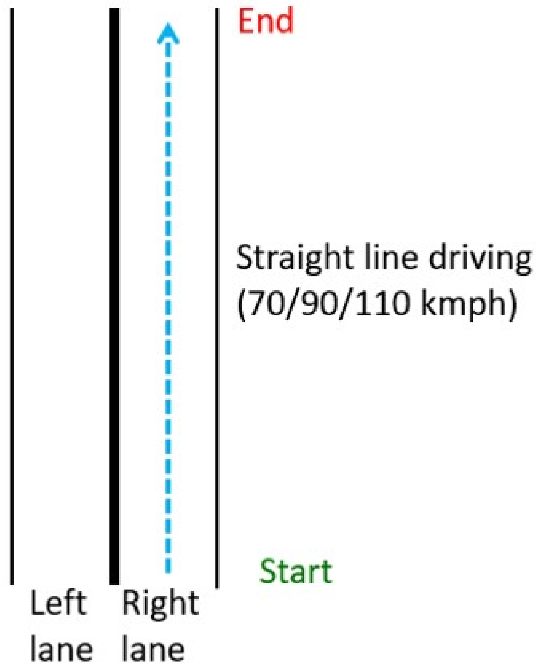


Figure 3.7: Driving trial setup for straight line driving

Figure 3.8: Speed profile for the driving trial

As shown in the above figure, the driver accelerates to the required speed and drives till the end of the bridge in the right lane of the bridge. These driving trials are helpful in determining the difficulty in maintaining the lane and the magnitude of counter-steer required to do so.

3.2.3 Iterations of Driving trials

In order to collect sufficient data to analyse and understand the drivability of the car and the bus across the bridge, several driving trials were performed with different drivers for the scenarios as explained above. The detailed planning of the driving trials is as described below.

Weather	Overtaking and lane change		Straight line driving				
	Car	Bus	Car			Bus	
	70 kph	70 kph	70kph	90kph	110kph	70kph	90kph
Weather 0	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather 1	Yes	Yes	Yes	No	No	Yes	No
Weather 2	Yes	Yes	Yes	No	No	Yes	No
Weather 3	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather 4	Yes	Yes	Yes	No	No	Yes	No
Weather 5	Yes	Yes	Yes	No	No	Yes	No
Weather 6	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather 7	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather 8	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather 9	Yes	Yes	No	No	No	No	No
Weather 10	Yes	Yes	No	No	No	No	No
Environmental loads (weather 6)							
Sea swell	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Wind sea	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Wind on Vehicle	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Wind	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Figure 3.9: Driving trials plan for different speeds

Due to the project time constraints only certain weather conditions were chosen for straight line driving as shown in the above table. However, all the trials were performed for a set of two different drivers. The advantage of testing with multiple drivers is that the comfort level can be assessed and the model can be checked for different driving styles.

Further, the subjective data or the driver feedback was collected after every trial using a questionnaire which can be found below in the appendix section of this report.

3.2.4 Bridge environment

Floating bridge motions depend on the location and time when the vehicle wheel contacts the bridge deck. Figures 3.10, 3.11, 3.12 show one example of the vertical, lateral and roll-angle bridge motions intensities for different weather conditions with respect to rotational center. Examples of bridge motion intensities have been presented in function of distance for one instance of simulation time t=1000s.

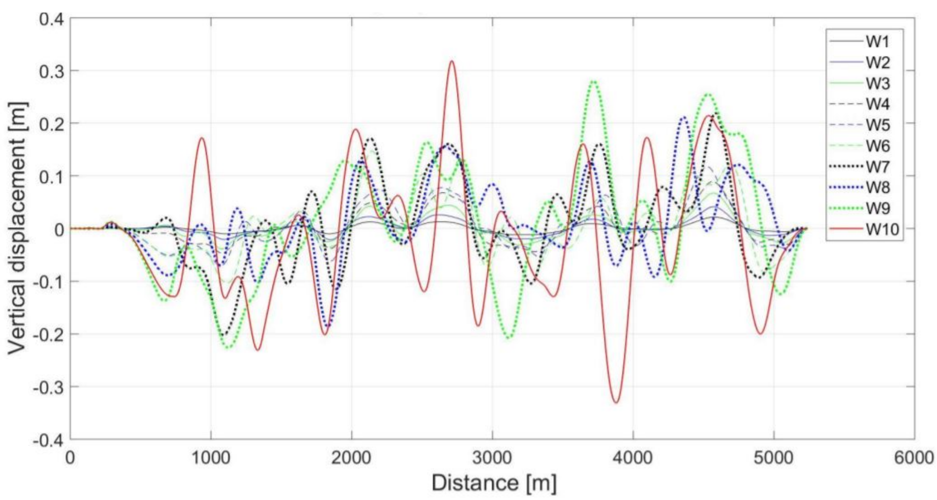


Figure 3.10: Vertical bridge displacement

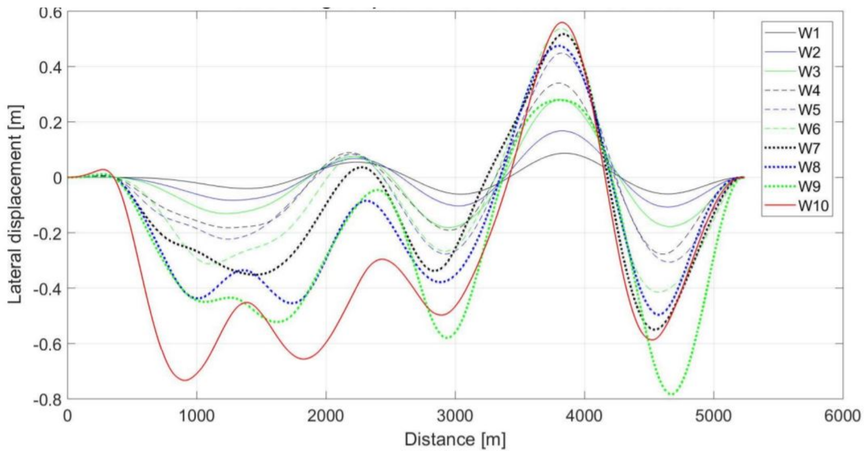


Figure 3.11: Lateral bridge displacement

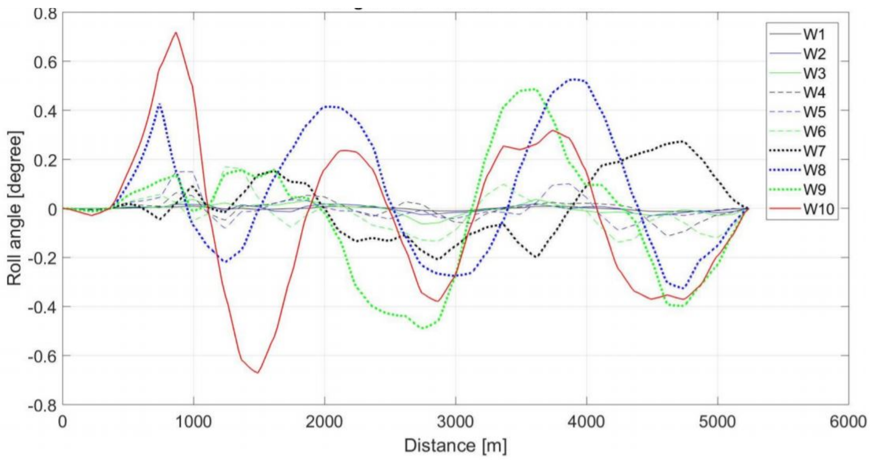


Figure 3.12: Bridge roll motion

It could be noticed that bridge motions intensities increase with the severity of weather conditions. However, floating bridge roll motions for all weather conditions are small values, within ± 0.8 degree (Figure 3.12). The vertical displacements under left/right vehicle track are almost identical. Figure 3.13 presents example of vertical bridge displacements in function of time for both left/right track when vehicle is passing over the bridge at 90 km/h.

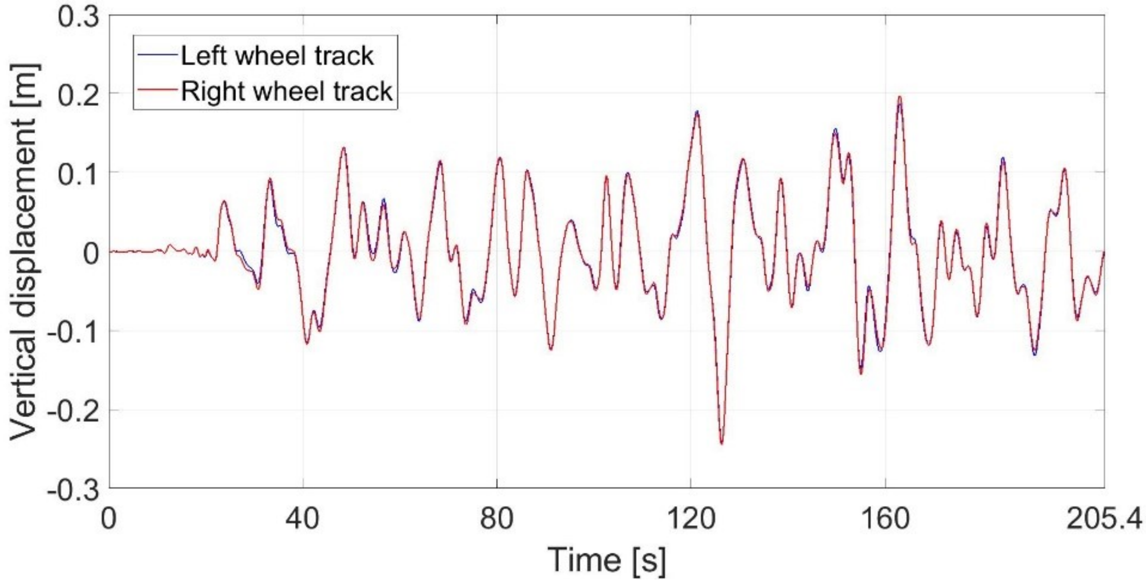


Figure 3.13: Vertical movements of Left and Right wheels to estimate the roll motion of the vehicle

3.2.5 Study of effect of road roughness on driver response

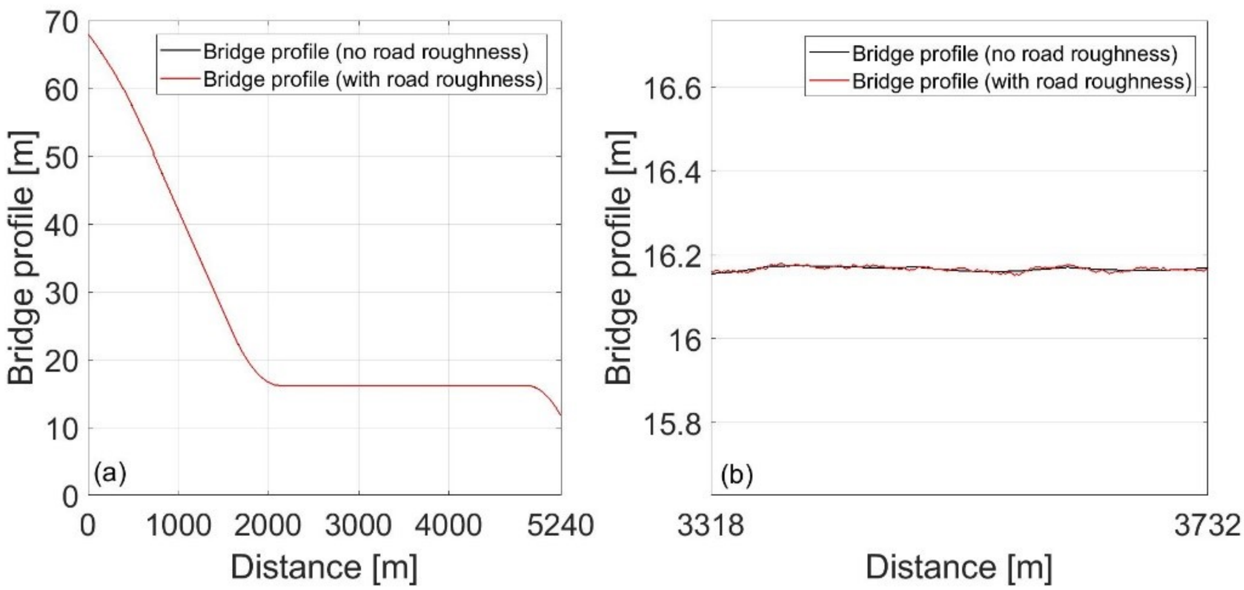


Figure 3.14: Bridge profile with and without road roughness

As we see from the above graphs, a comparison in bridge profile was done in order to check the effect of road roughness on driving. It was observed that driving on the bridge 'with' or 'without roughness' conditions had no significant differences. Based on this understanding it was decided to choose the data set based on 'without roughness' conditions.

3.3 Driver Model

To study how different vehicle designs work in a vehicle operation, a driver model is needed. The driver interacts with vehicle mainly through steering wheel, accelerator pedal and brake pedal. Driver's control is the ability to maintain a defined path while driving and can be evaluated by assessing the longitudinal and lateral dynamics.

The electronic vehicle controllers are designed to support the driver in mastering difficult driving maneuvers, typically caused by driving errors. To test these support functions, critical driving situations must be realized. For reasonable testing of controller behavior in the vehicle environment, a desirable virtual driver environment is required. The driver model also exhibits non-perfect driving behavior like ordinary human drivers do.

The driver model is realized as a technical controller considering some human characteristics. Different from technical controllers, a human driver does not simply follow a given trajectory but sets the target course within given constraints. This is reflected in a two-level structure of the driver model consisting of guidance and stabilization. This is highlighted by the blue rectangular box which can be seen in Figure 3.15.[8]

At the guidance level, it determines time dependent target position, target speed, target direction and target path curvature. These values serve as nominal values for the stabilization level which is basically a position controller and control supplement by the model for perception of vehicle state information. The position controller at the stabilization level keeps the vehicle as close as possible to the target moving along the given track [8].

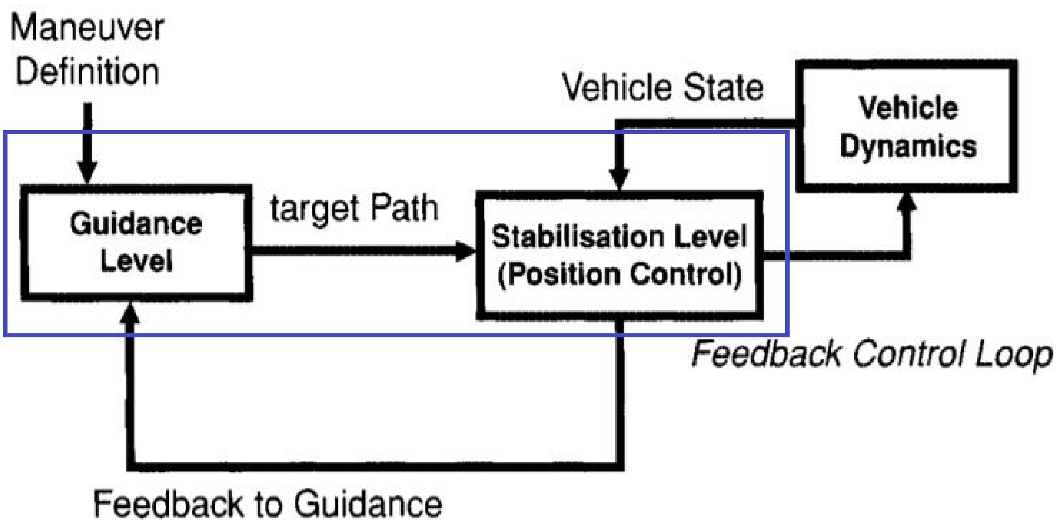


Figure 3.15: Structure of the advanced driver

In guidance to the above context, an example of driver model is the Salvucci and Gray (Fig:3.16). In this model, the desired steering angle is calculated using the below equation (3.1), which is motivated from human biological cognition. The three gain (k) parameters are considered and tuned for certain driver, vehicle and operation. The distance to aim-point also needs to be tuned, such that there should be extra margins on top of W/2, where W can be width of the vehicle, road or lane. This is a simplified driver model referred to as "look ahead" where each time any variations in vehicle and environment states are observed, the gain values have to be re-tuned to achieve the desired steering input. However, a more advanced driver model uses a dynamic model for prediction [2].

$$\dot{\delta_{stw}} = k_f \cdot \dot{\theta}_f + k_n \cdot \dot{\theta}_n + \cdot k_I \,\dot{*}\, \theta_n \Leftrightarrow \delta_{stw}(t) = \delta_{stw}(t_0) + k_f \cdot \theta_f\dot{(t)} + k_n \cdot \theta_n\dot{(t)} + k_I \cdot \int_{t_0}^{t} \theta_n(t_0 ... t)dt \quad (3.1)$$

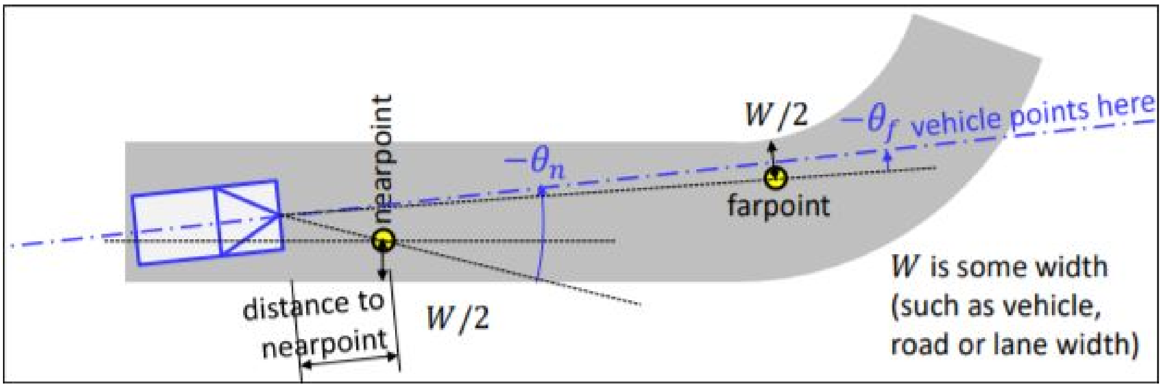


Figure 3.16: Salvucci and Gray model for how driver steers

In reference to the above information, a predictive model approach was found to be quite suitable because the controller model identifies the deviations in the lateral position of the vehicle with respect to the required lane position (aiming to stay in center of the lane) and immediately makes the required steering correction autonomously. With the concept for driver model, two approaches were established. The first approach involved using a Predictive Driver Model and the second approach involved a Model Predictive Controller (MPC).

3.3.1 Approach 1: Predictive Driver model

With respect to the above context, a feedback loop control reference system from Simulink vehicle dynamics block-set is used to simulate a full vehicle dynamics model undergoing a reference steering, acceleration and braking input from a predictive driver model (see Figure:3.15).

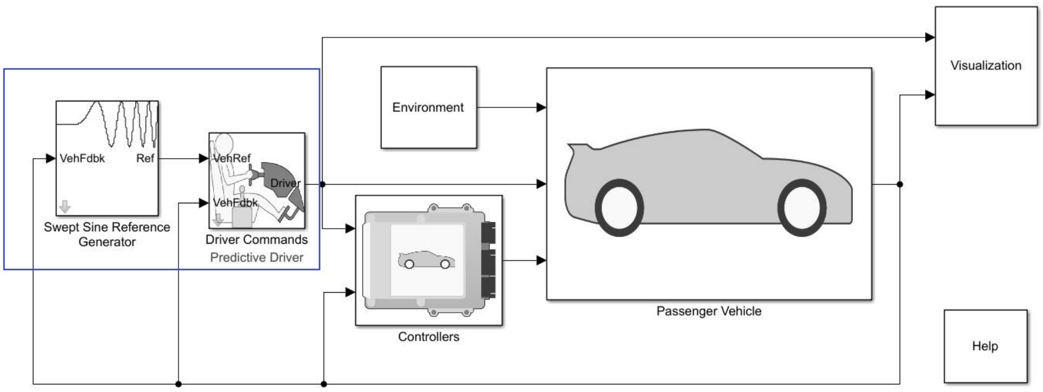


Figure 3.17: Swept Sine Steering Reference Application Simulink model

The above figure shows a swept-sine steering reference application block used to analyze vehicle ride and handling under dynamic steering response. The use of the individual blocks are explained below:

- **Reference Path generator block :** This block refers to guidance level block as per figure 3.15. For the given application, a sinusoidal steering command is generated for a swept-sine maneuver. The steering amplitude and final frequency can be altered based on the requirement and the desired steering angle is generated. Target longitudinal velocity, target path curvature as reference input is fed to the driver model.

- **Driver controller:** This block mainly focuses on the model used for controlling the vehicle path. With the help of different set of configurations such as Proportional-Integral (PI) , Scheduled PI and predictive controllers, it can be implemented to generate normalized steering, acceleration and braking commands to track longitudinal velocity and lateral reference displacement. The normalized commands can vary between -1 to 1 and the controller uses a single-track (bicycle) model for optimal single-point preview control [9]. Based on the above configurations predictive model is selected to study the dynamic behavior of the vehicle.

  The predictive model implements an optimal single-point preview (look ahead) control model developed by C. C. MacAdam1, 2, 3[9]. The model represents driver steering control behavior during path-following and obstacle avoidance maneuvers. Drivers preview (look ahead) to follow a predefined path.

- **Environment:** In this block input signals of wind and ground forces are fed to the tire and suspension model, this is because ground feedback constantly changes for different weather conditions (mainly affected by individual factors like wind, wind on sea and swell).

- **Vehicle model:**In this block 14 Degree's of freedom variant model is selected in order to analyze the lateral and vertical comfort. The Vehicle model subsystem has an engine, controller and a vehicle body with four wheels.

- **Controller:** Controllers subsystem generates engine torque, transmission gear and brake commands.

- **Visualization:** Visualization subsystem provides driver, vehicle and response information. The reference application logs vehicle signals during the maneuver including steering, lateral acceleration, vehicle and engine speed.

3.3.2 Approach 2: Driver Model with MPC Controller

The figure below depicts the Simulink arrangement of blocks for the driver model. It is a feedback loop where the lateral position and yaw angle of the car are continuously monitored and the steering corrections are provided accordingly.

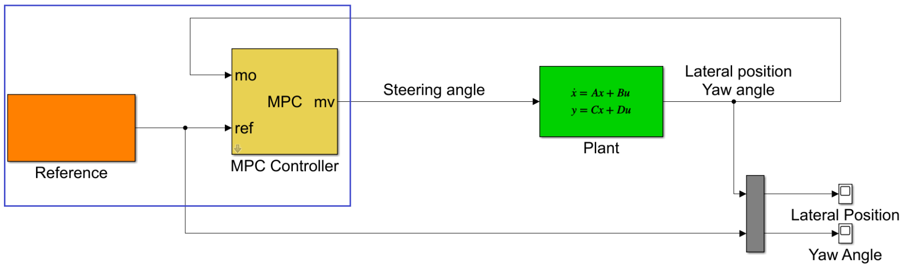


Figure 3.18: Driver Model with MPC Controller

- **Reference**: This block consists of a reference input signal. The lane width is considered to be 3.75 m. Hence, the reference path will be the centre of the lane.
  Vehicle path and the vehicle itself are modeled using Driving Scenario Designer, an application pre-defined from MATLAB. The position co-ordinates of the bridge are defined initially and the road surface is generated as depicted in the figure 3.19. With respect to the road surface, the reference position co-ordinates of the vehicle are defined as depicted in the figure 3.20

- **MPC Controller**: The inputs to the controller are the signals from the **Reference** block and the feedback signal from the **Plant** block. The controller measures the deviation between the input signals and provides necessary steering correction as an output.

- **Plant**: Plant consists of the mathematical expressions for lateral dynamics modeled in a state space nature. The input signal to the Plant is the output signal obtained from the MPC Controller i.e. steering angle. The Plant provides the outputs of the vehicle in terms of its Lateral Position and Yaw Angle.

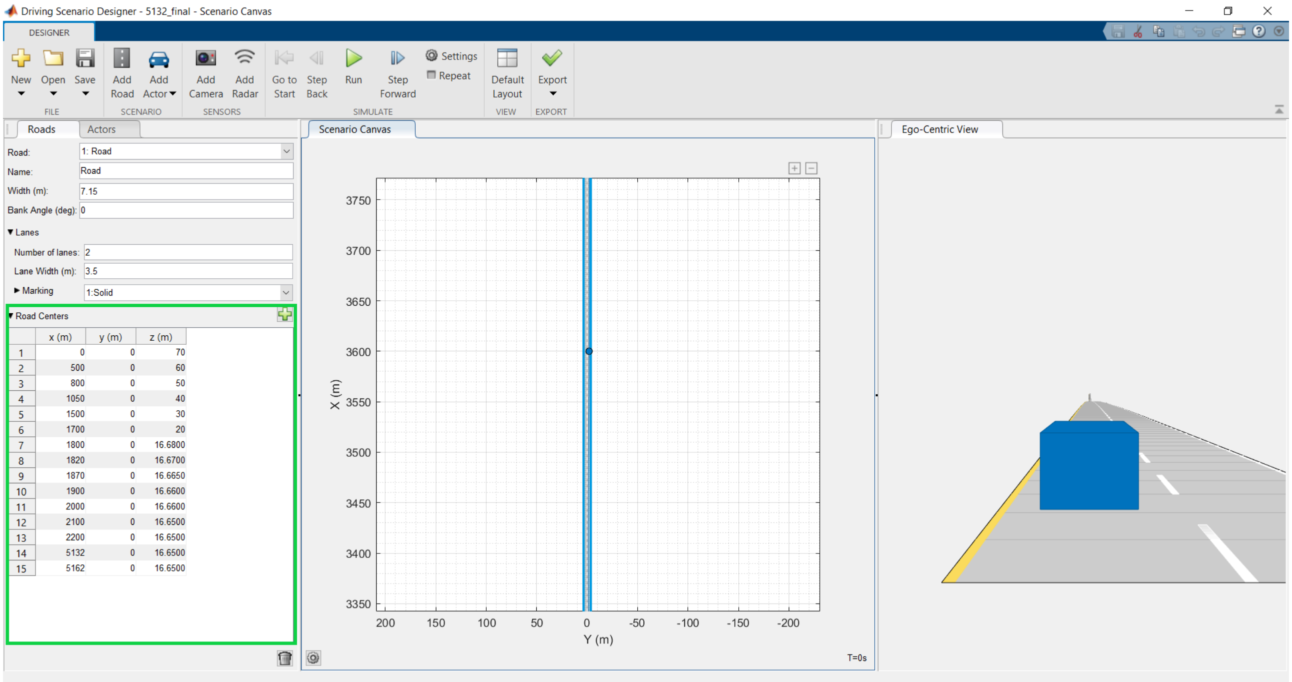


Figure 3.19: Position Co-ordinates of the Bridge

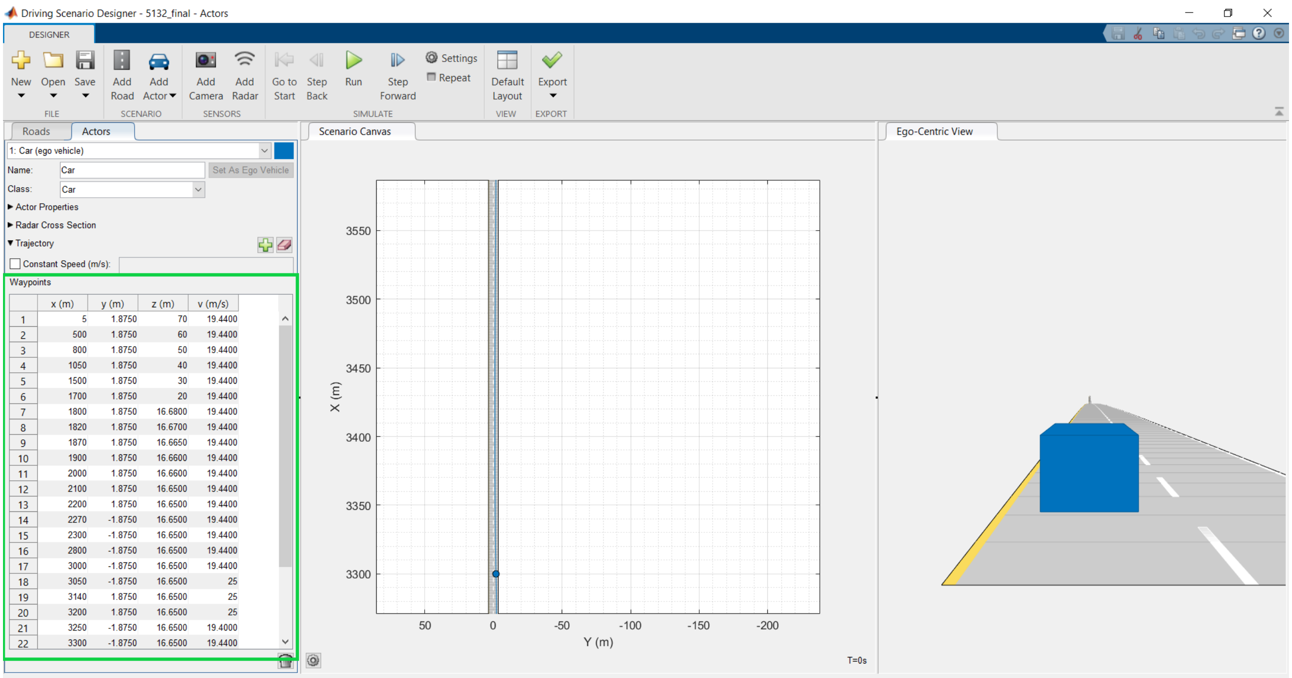


Figure 3.20: Reference Position Co-ordinate of the Vehicle

Chapter 4

Results

Various parameters are studied in order to understand the vehicle trackability. The subjective and objective assessments can be compared to relate the driving behaviour.

In this section the results for the driving trials preformed on the CASTER driving simulator with both the vehicle models are discussed. The first section shows the subjective evaluation based on the questionnaire filled by the driver. Factors like motion sickness experienced while driving in the simulator were taken into consideration by framing the necessary questions in the questionnaire. This can have significant impact on the driver and the response.

4.1 Test Method

Based on discussions within the team and supervisors, it was decided to assess the following parameters:

- In order to understand the ability of the driver to stay in the lane while driving over the bridge, objective parameters like steering angle, lateral deviation from the lane, body roll are evaluated
- Subjective assessment to analyse driver's feedback after the driving trial and to compare it with objective data
- Different data such as steering wheel angle, position of the vehicle, speed accelerations in all three directions were collected from the driving simulator after each driving trial
- Vertical acceleration and lateral acceleration in order to assess the driving comfort during normal driving and overtaking maneuver

4.2 Subjective Assessment

Subjective assessment involves the analysis of results from driver feedback questionnaire. The driver is asked to fill out the questionnaire form after each driving trial. The questionnaire sheet is mentioned in the Appendix section.

The grading scale in the questionnaire ranges from a scale of 1 to 10. Grade 1 corresponds to the driver being unable to grade and grade 10 corresponds to world class comfort. In the analysis, a weather condition is deemed to be permissible for safe driving, if the driver rates his experience above grade 5. Grade 5 is chosen as the limit as it represents uncomfortable driving experience.

4.3 Objective Assessment

Objective assessment involves analysis of data obtained from the driving simulator post driving trials. The parameters for assessment are selected as per the discussions within the team and the supervisors. The test planning document also acts a reference. It is important to correlate the results from subjective and objective assessment as it helps to understand both the drivers experience and driving behaviour under different weather conditions. The first set of driving trials were conducted with no wind and no bridge motion. The results from this trial can be used as a reference for comparison with other trials.

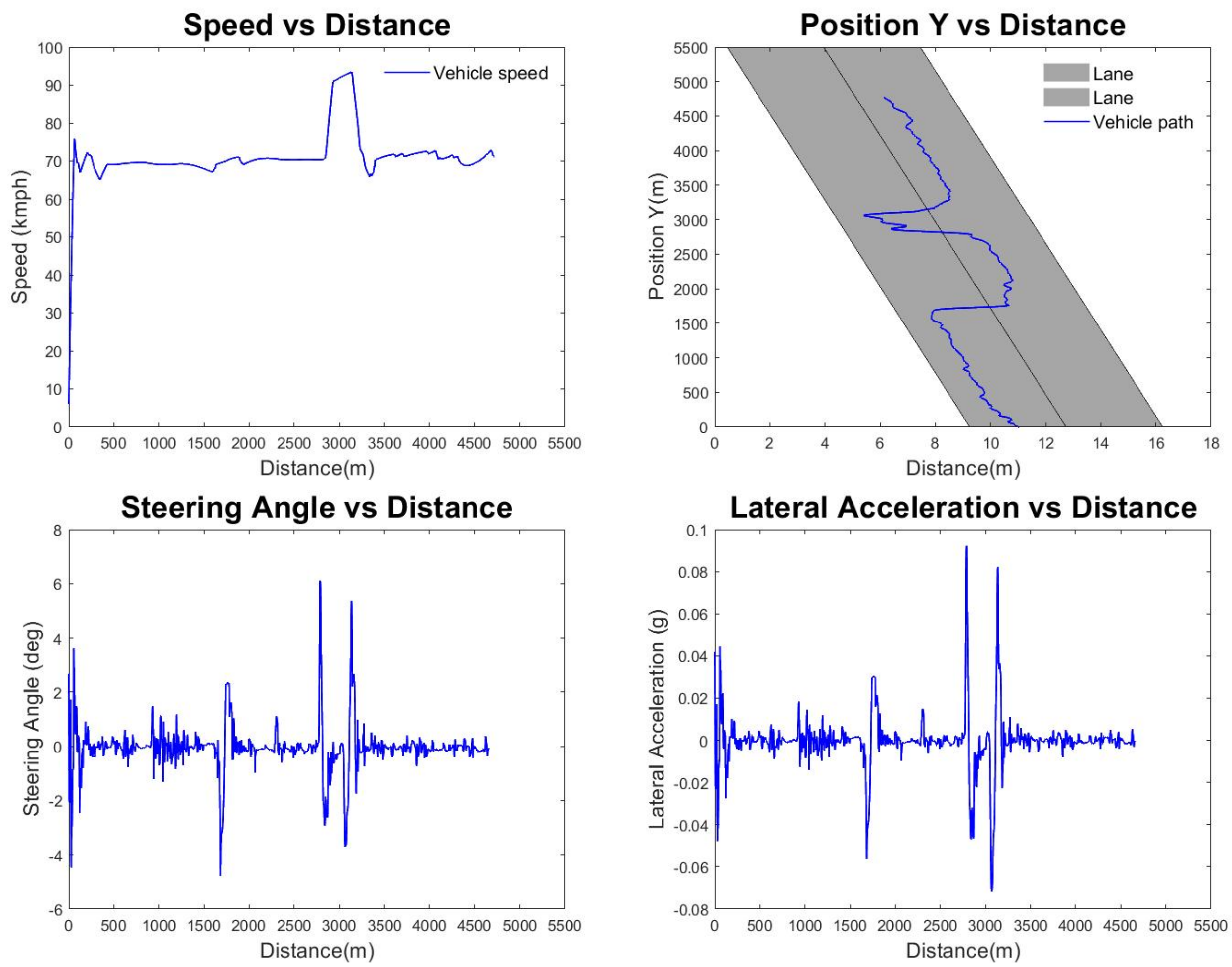


Figure 4.1: Variation of vehicle speed, lateral displacement, steering wheel angle, lateral accelerations for no wind and bridge motion with overtaking and lane change at 70 kmph

4.4 Lane Change and Overtaking - Car

For the first set of driving trials conducted, the car is driven on the bridge at a speed of 70 kmph and the driver performs the lane change and overtaking maneuver. In order to understand the driving pattern, more data from several drivers is required. However, due to time constraints in the project, data between two different drivers for similar driving conditions is compared.

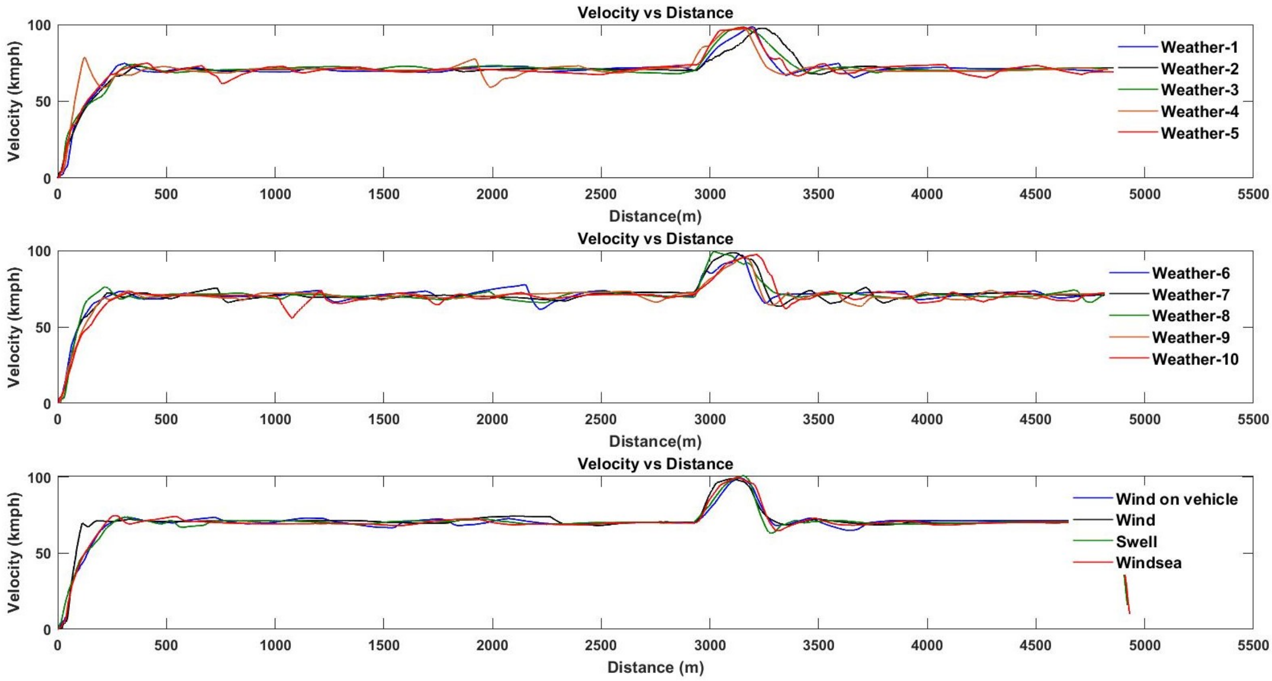


Figure 4.2: Variation in velocity of car throughout the trials, for lane change and overtaking at 70 kmph

As per the driving trial plan mentioned in the methodology, the driver is supposed to drive at a speed of 70 kmph and perform the overtaking maneuver by increasing the speed upto 95 kmph. The above 'speed vs distance' plots show that all the driving trials were conducted according to the above mentioned methodology.

The subjective data analysis was done for two drivers. The drivers had good experience of driving in the driving simulator and this was kept in mind while understanding the results. The assessment for driving comfort, staying in lane, difficulties in lane change and overtaking maneuver is presented below and correlated with the objective data.

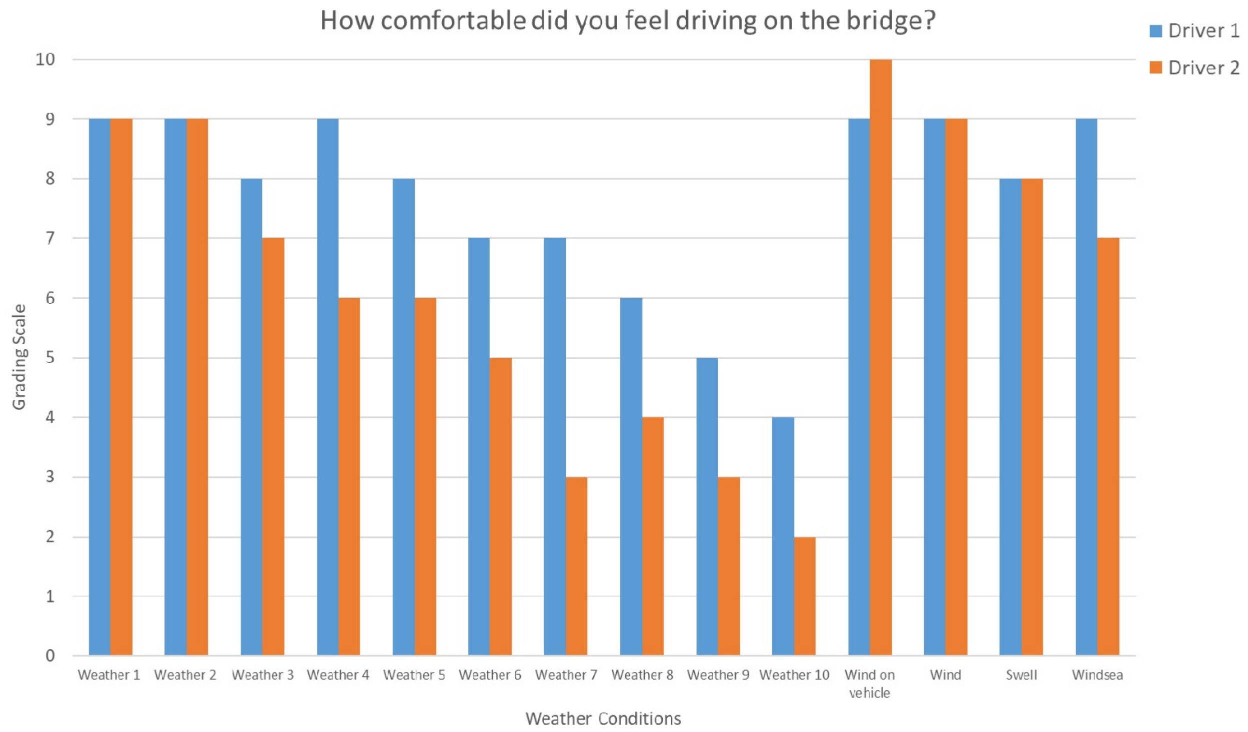


Figure 4.3: Driving comfort in a car for different weather conditions when driven at the speed of 70 kmph

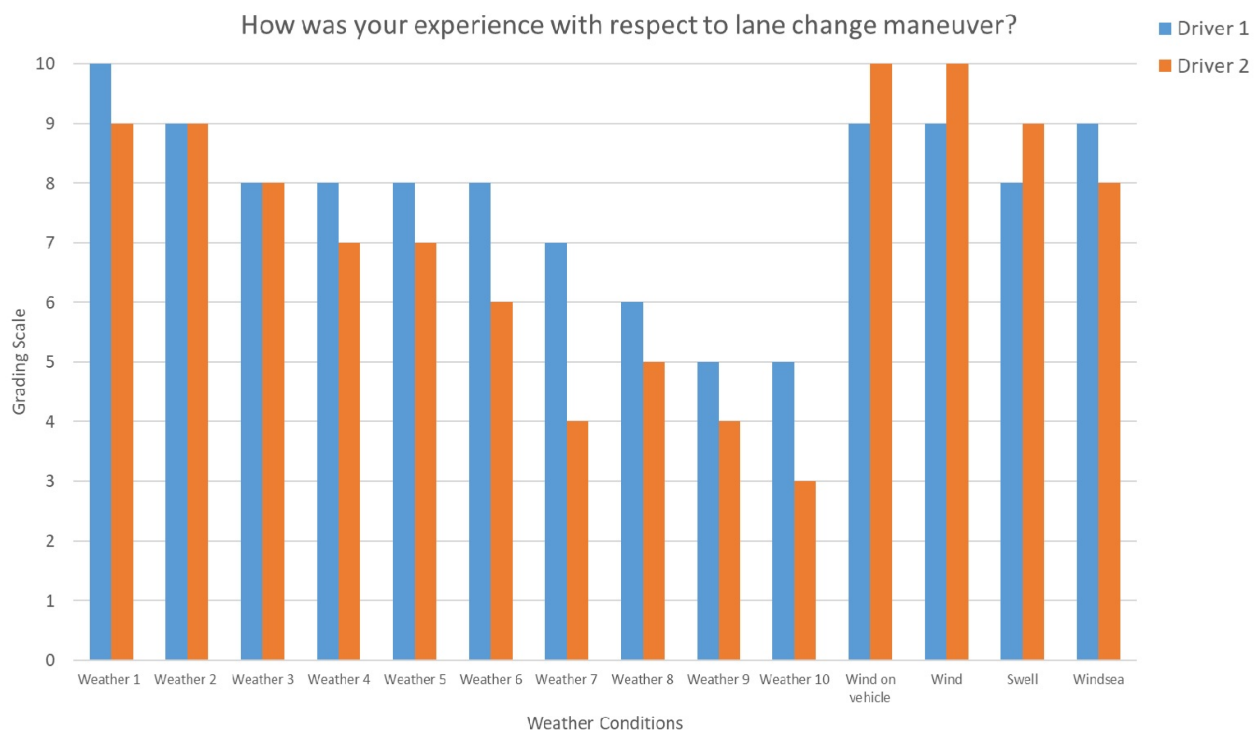


Figure 4.4: Lane change maneuver in a car for different weather conditions when driven at the speed of 70 kmph

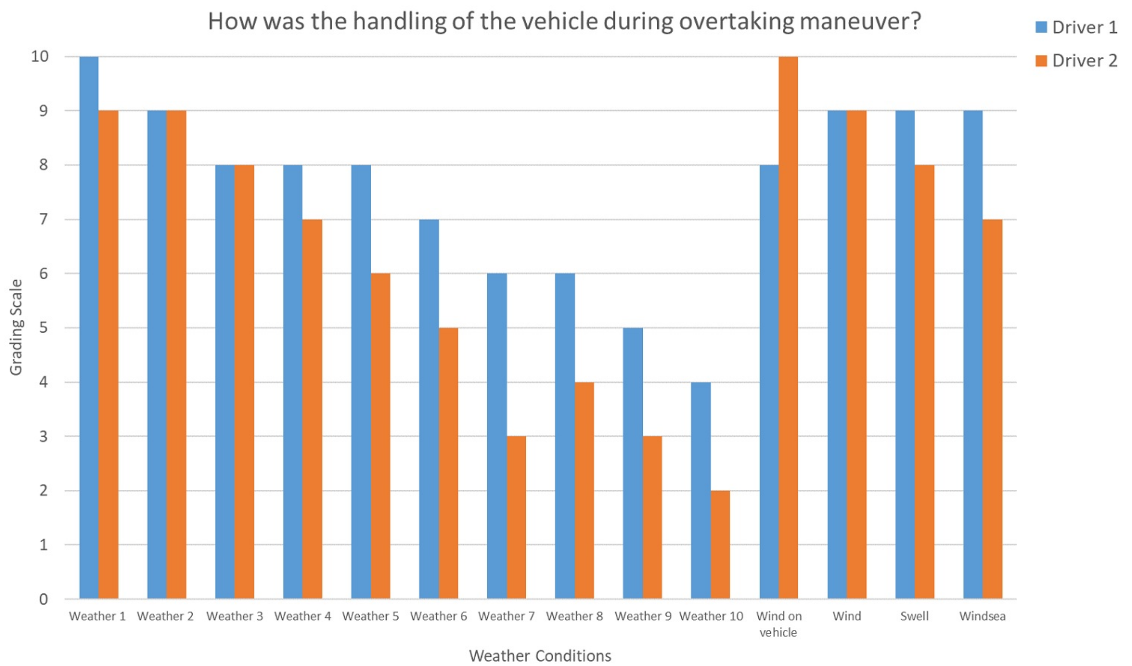


Figure 4.5: Overtaking maneuver in a car for different weather conditions when driven at the speed of 70 kmph

We can see from the above subjective assessment plots that the perceived level of driving comfort varies significantly from one driver to another. A general trend which can be observed is that, the driving comfort reduces with severity in weather conditions. We can also see that the overtaking maneuver is more difficult when compared with lane change. Lane change has higher grades when compared with overtaking maneuver and becomes uncomfortable (grade 5 is uncomfortable) only at weather 7.

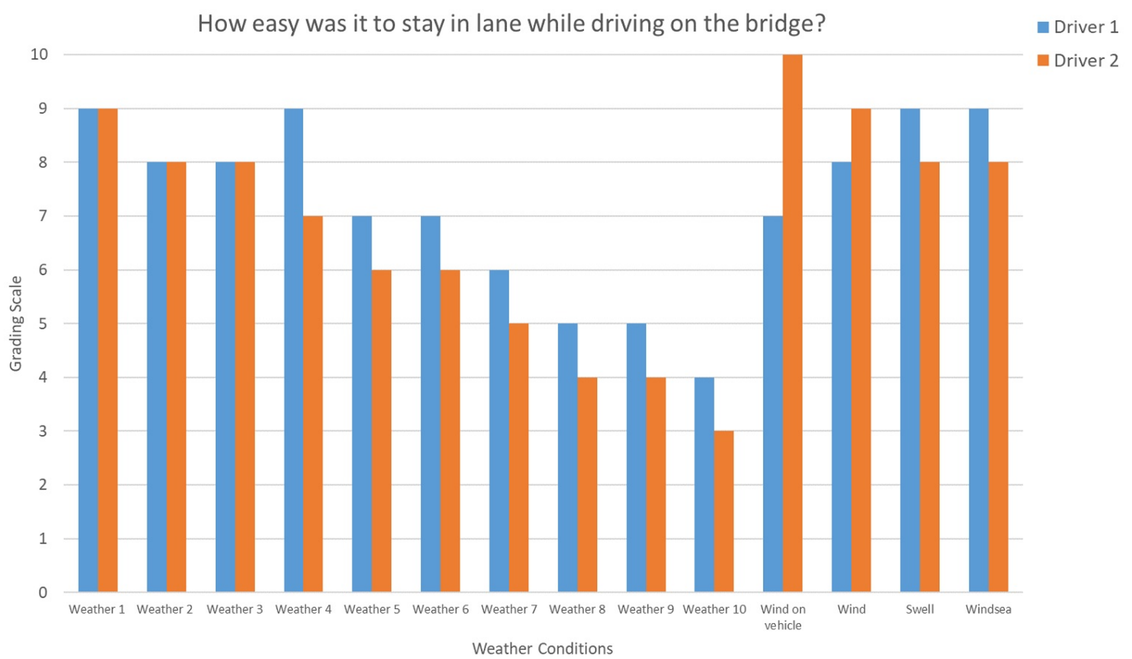


Figure 4.6: Ability to stay in lane when driving in a car at the speed of 70 kmph

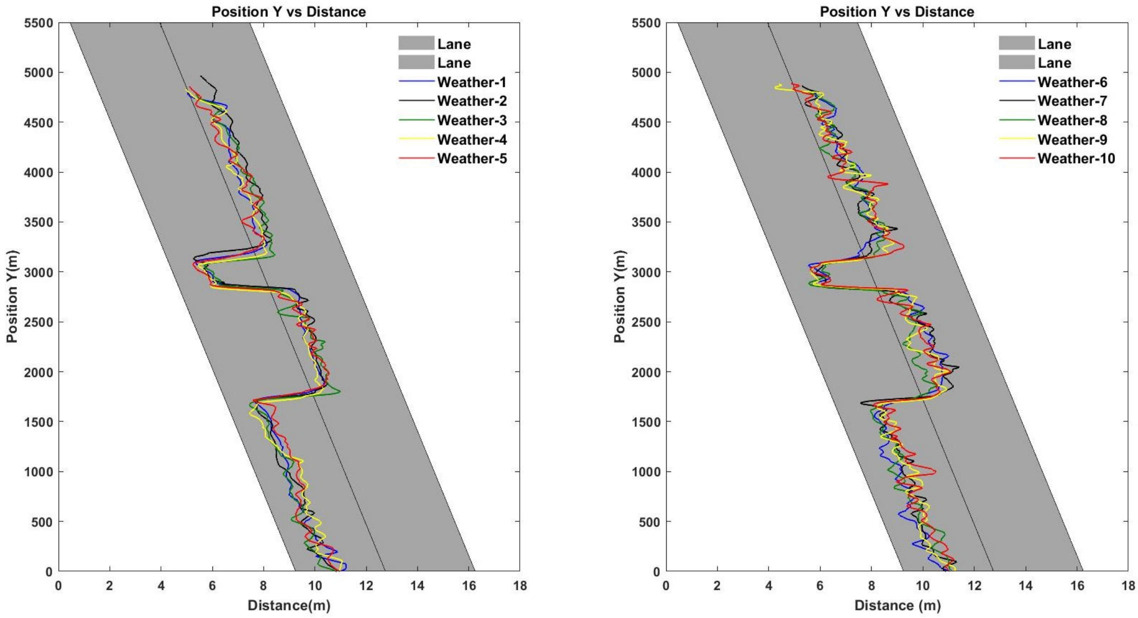


Figure 4.7: Track-ability of the car on the bridge for weather 1-10, when driving at 70 kmph and performing both lane change and overtaking maneuvers

In the above figure, paths travelled by car over the bridge during the driving trials are plotted. Image is divided in two parts, one for lower weathers (left) and second one for higher weather conditions (right) to avoid overlapping of the plots and to maintain clarity. The lane change and overtaking maneuvers can be clearly observed in all weather conditions.

From the plots, it can be seen that in lower weather conditions, the driver could maintain the lane and perform the lane change and overtaking maneuvers without much difficulty. However, when these results are compared with more severe weather conditions, it can be seen that the driver had difficulties staying in the lane. Constant and more frequent deviations can be seen which could be uncomfortable.

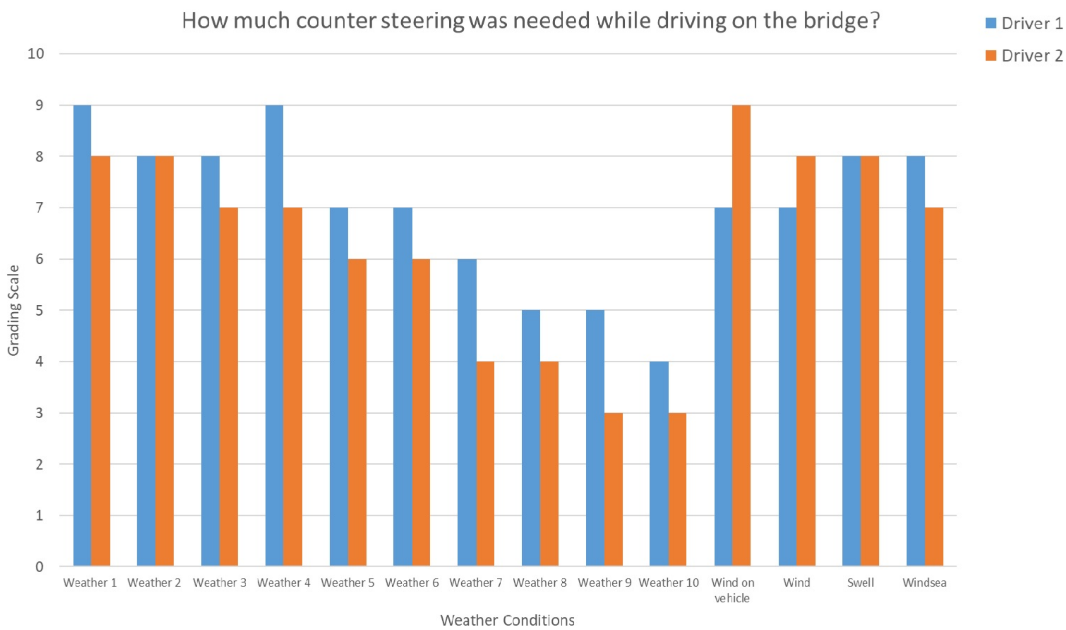


Figure 4.8: Level of counter steering when performing lane change and overtaking at 70 kmph

The amount of counter steering needed gives us an idea on how easy it is to stay in the lane while driving on the bridge. The amount of counter steering needed increases with increase in storm severity. Thus, the driver feels uncomfortable when he goes closer to the railings and the other lane, this results in lower levels of grading.

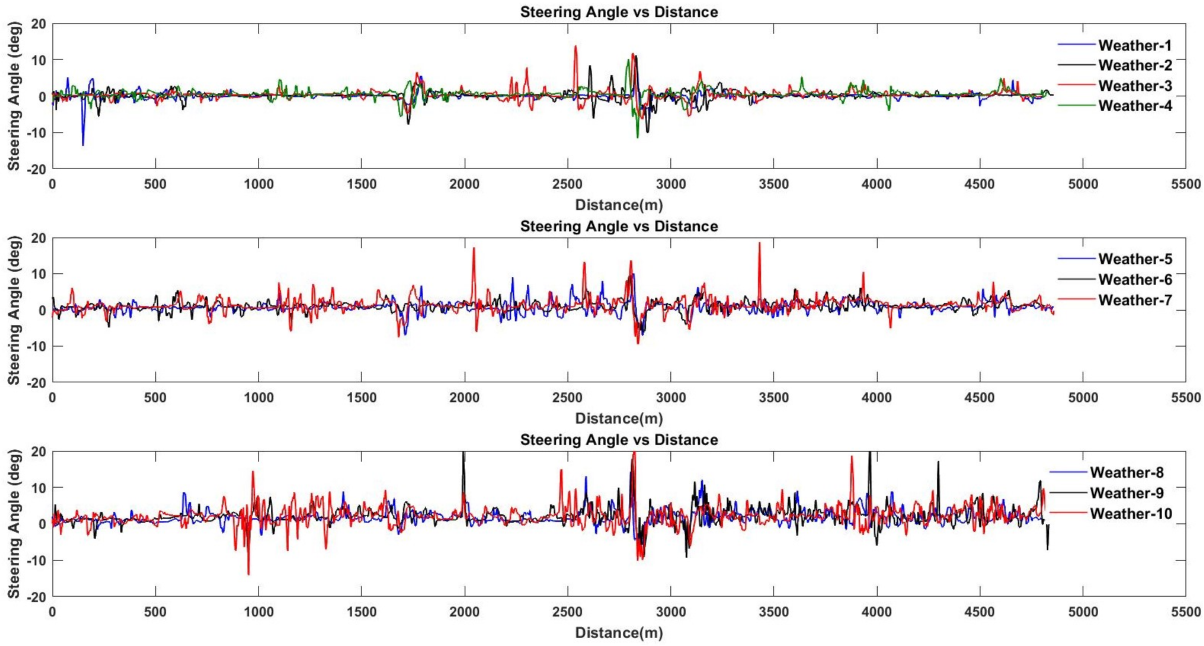


Figure 4.9: Steering wheel inputs of the driver during lane change and overtaking at 70 kmph

The track-ability can be supported with the steering corrections given by the driver. It can be seen that, as the weather becomes worse, it becomes difficult to drive over the bridge. As from the image above, we can see that larger and more frequent steering corrections were needed for weather-8 (10 years), weather-9 (50 years) and weather-10 (100 years storm). Frequent movement in lateral directions with high acceleration could be unbearable for the driver as well as for the passengers.

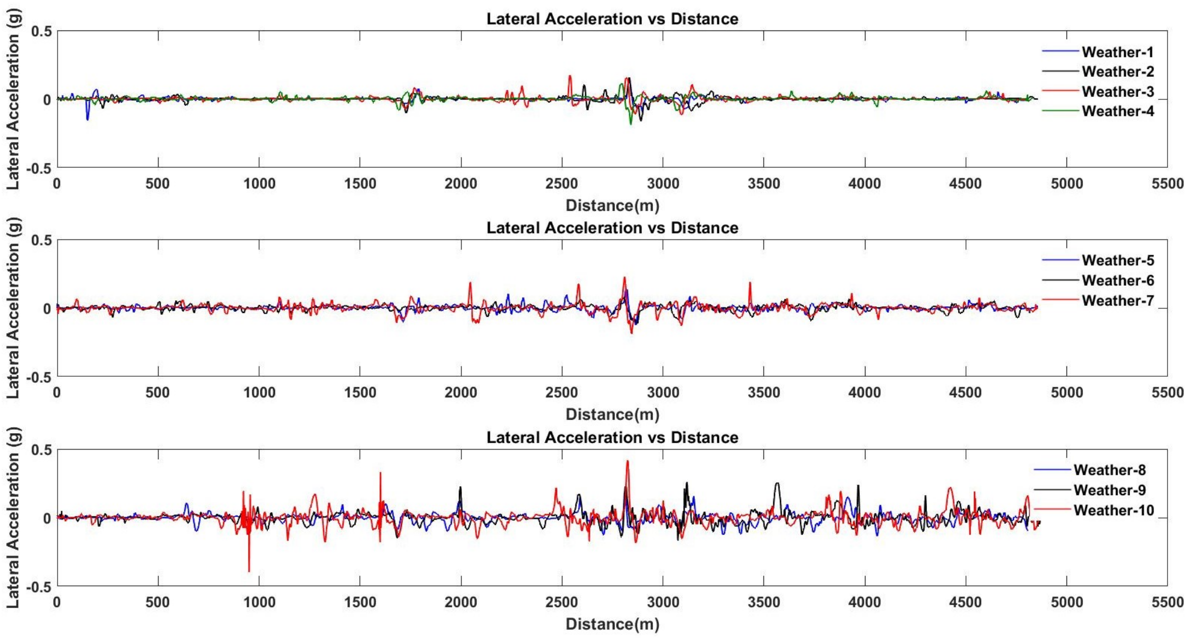


Figure 4.10: Lateral acceleration of the car during lane change and overtaking at 70 kmph

As steering corrections given by the driver increases, the lateral acceleration increases as well. In the above graph for lower weather conditions, the lateral acceleration is high only during lane change and overtaking while for more severe weather conditions, the lateral acceleration is high whenever the driver gives larger steering corrections.

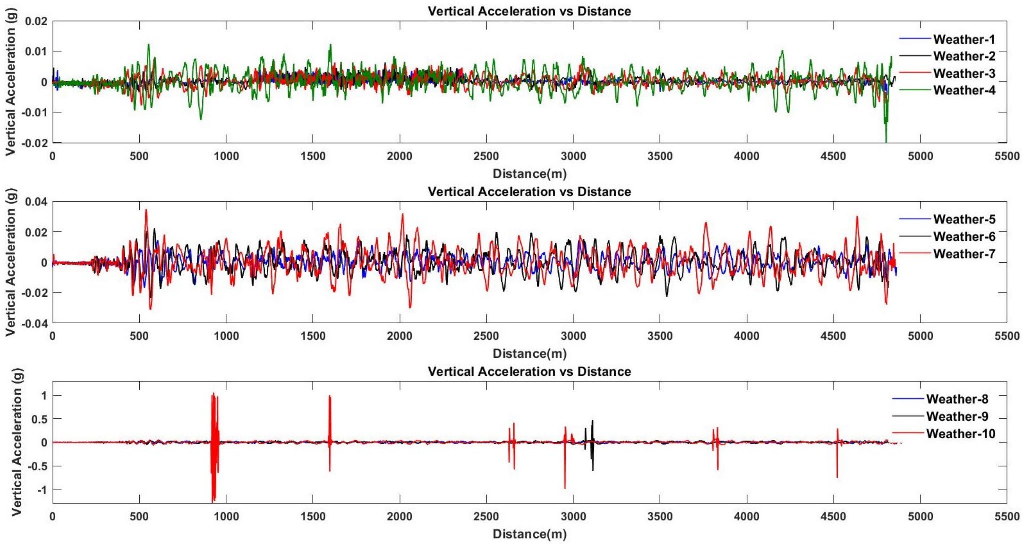


Figure 4.11: Vertical acceleration of the car during lane change and overtaking at 70 kmph

The important factor to be considered when defining driver's comfort is the vertical acceleration. From vertical acceleration plots above, it can be seen that the vertical acceleration is less for all weather conditions which are in the range of -0.03g to 0.03g. This is because road roughness has not been considered for the trials as the road is going to be A-class for the new bridge. However, for weather-9 and weather-10 sudden peaks can be seen at some instances which rises to almost 1g. The reason could be the limitation of the driving simulator which has a fixed stroke length. For weather-9 and 10 the bridge movement is more and the simulator can't go down beyond it's limit even if the simulation output results in lower position which causes the simulator to vibrate (this needs to be further analyzed). This could result is higher peaks of vertical acceleration and not from the road inputs as the road is flat, smooth and has no humps.

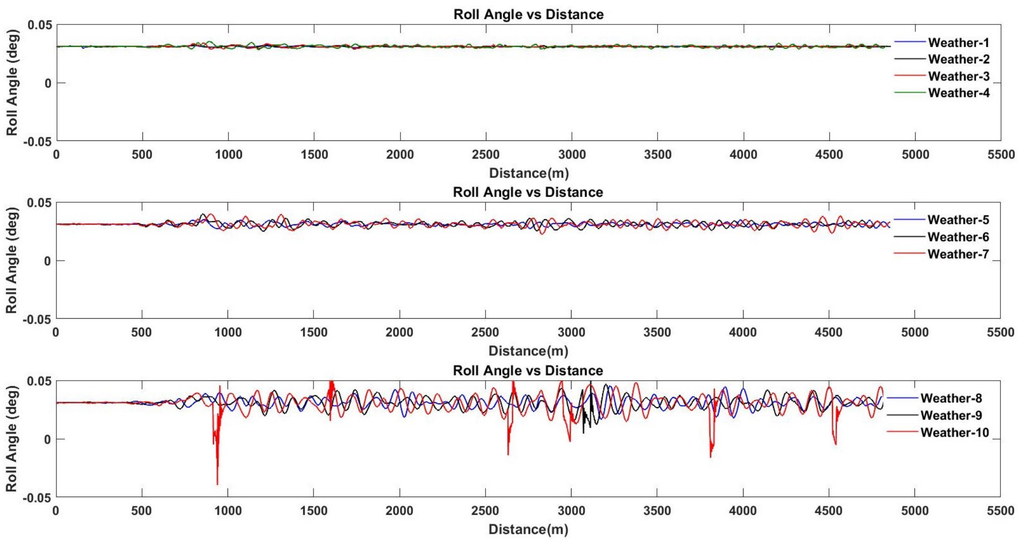


Figure 4.12: Body roll angle of the car during lane change and overtaking at 70 kmph

As mentioned in the methodology section, the roll motion of the vehicle due to the bridge roll motion, side wind forces and lateral load transfer for all weather conditions have been implemented. The image above illustrates the body roll of the car for all weather conditions. The body roll is quite less for the car throughout the distance. However, car rolls more as weather gets worse.

4.5 Straight Line - Car

Lane change and overtaking on the bridge is getting difficult for higher weather conditions. Therefore it becomes necessary to test the vehicles for driving without any lane change maneuvers. This way, a conclusion can be drawn to answer till which storm condition the lane change maneuver can be permitted and until which weather condition the bridge can be kept open for the traffic.

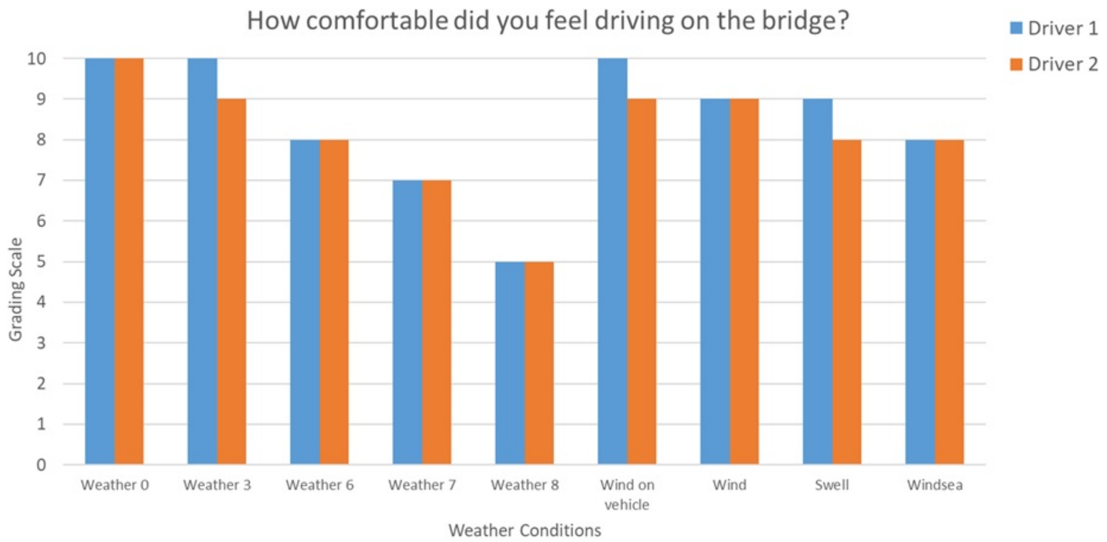


Figure 4.13: Level of comfort in straight line driving in a car at the speed of 70 kmph

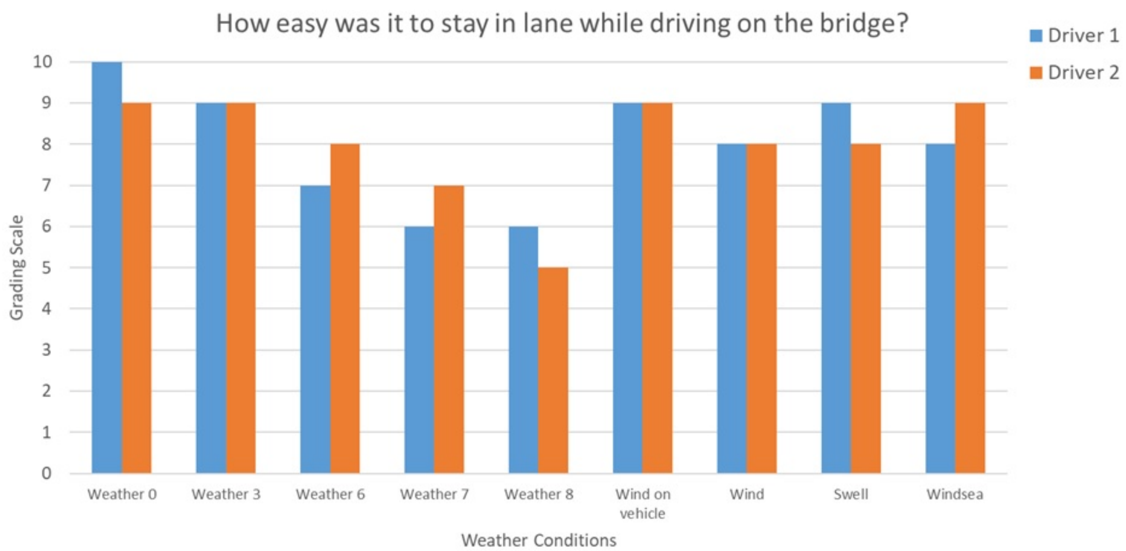


Figure 4.14: Ability to stay in lane in straight line driving in a car at the speed of 70 kmph

The above feedback is again a comparison between two drivers with significant experience driving in the driving simulator. For straight line driving at a speed of 70 kmph in a car, we can already see that the level of comfort is better when compared with the lane change and overtaking maneuvers. The driving becomes uncomfortable (The grade given by one of the driver is 5) only post weather 7. Also, when we look at the major contributing environmental loads for the car, windsea and swell have significant impact when compared to the wind on the vehicle.

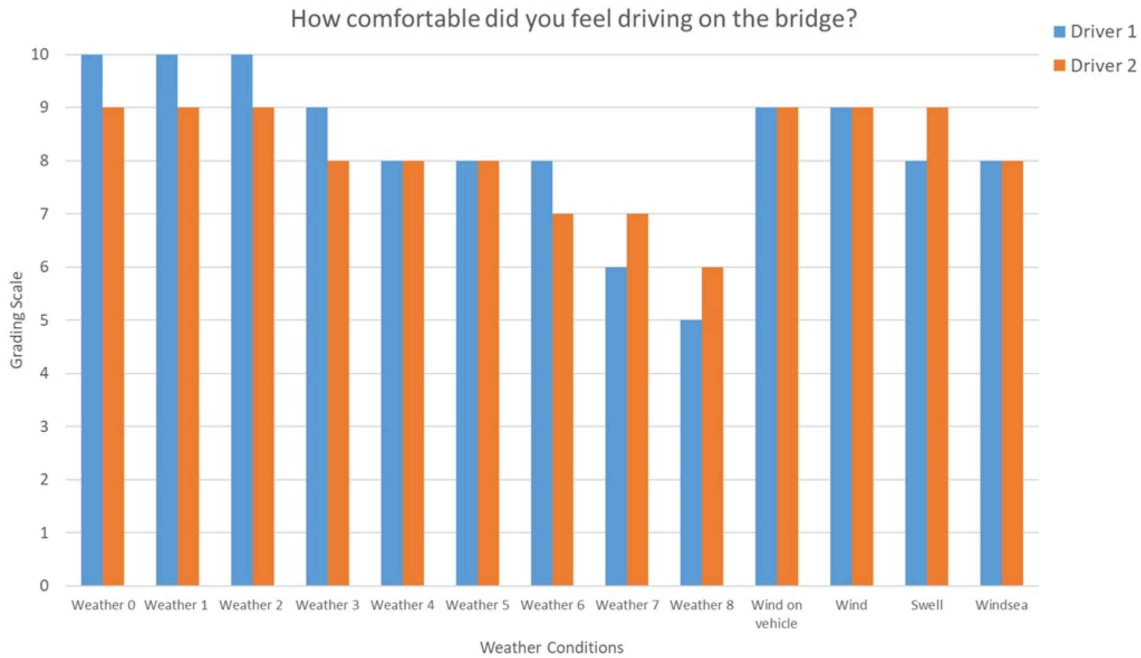


Figure 4.15: Level of comfort in straight line driving in a car at the speed of 110 kmph

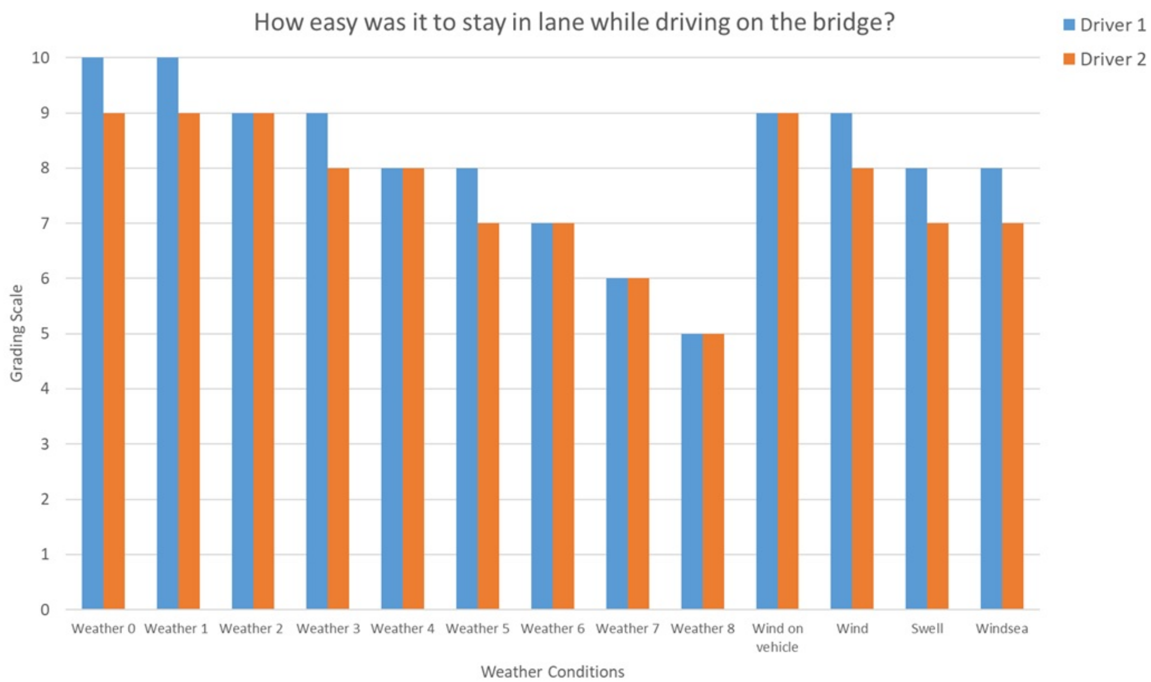


Figure 4.16: Ability to stay in lane in straight line driving in a car at the speed of 110 kmph

In order to see the effect of speed on straight line driving, similar trials were conducted at speeds of 90 and 110 kmph. We can see similar levels of comfort at different speeds. However, this holds good only till weather conditions 6-7. At higher weather conditions (weather 8 and above) we see that driving at a higher speed (110 kmph) has higher deviations in straight line driving, increasing the amount of counter steering needed.

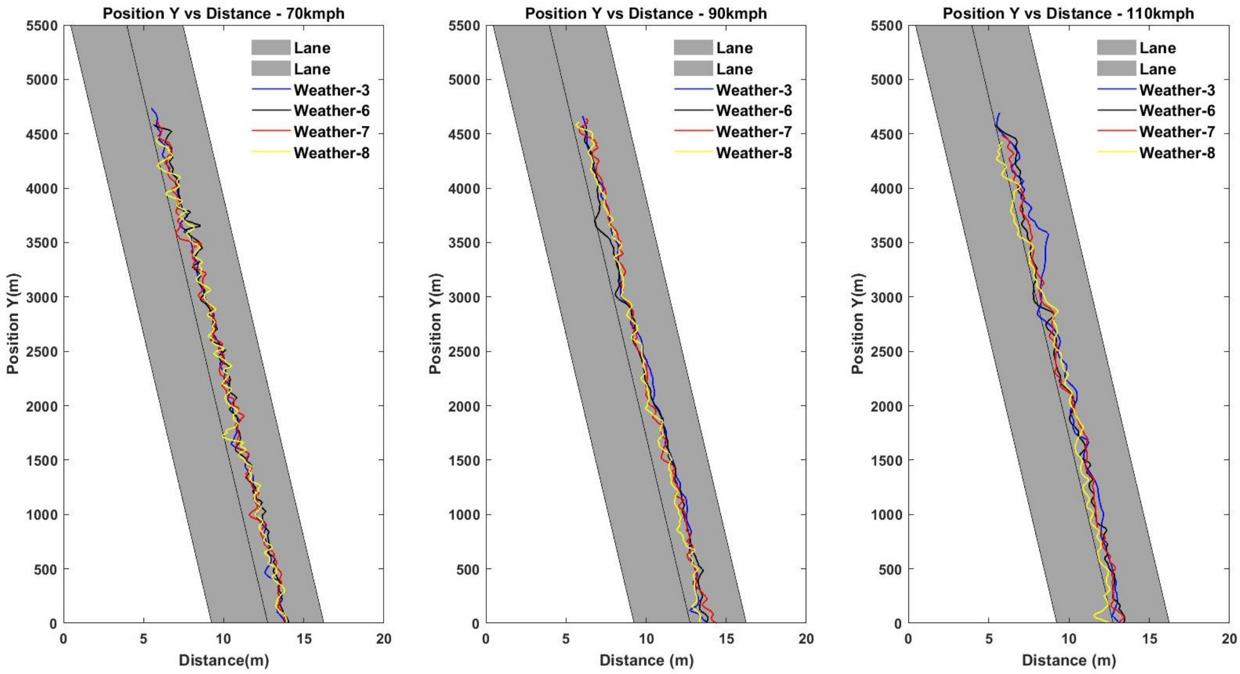


Figure 4.17: Straight line driving in car for 3 different speeds

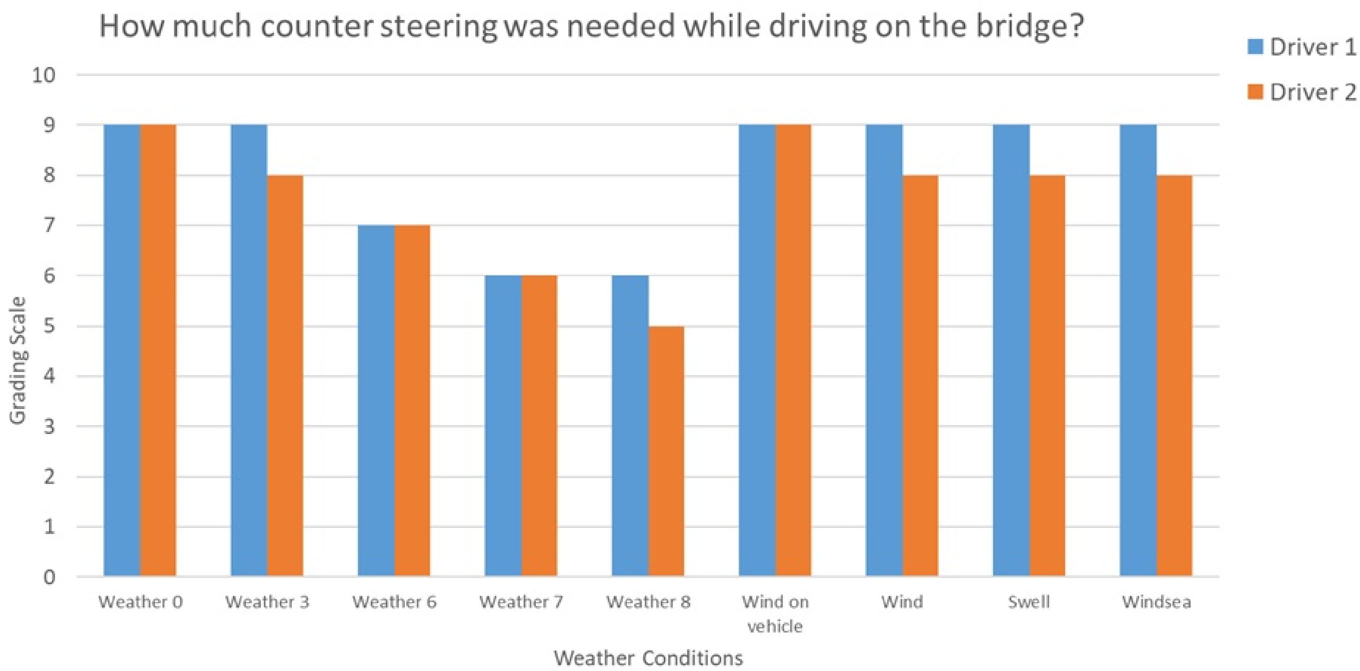


Figure 4.18: Level of counter steering needed in straight line driving in a car at the speed of 70 kmph

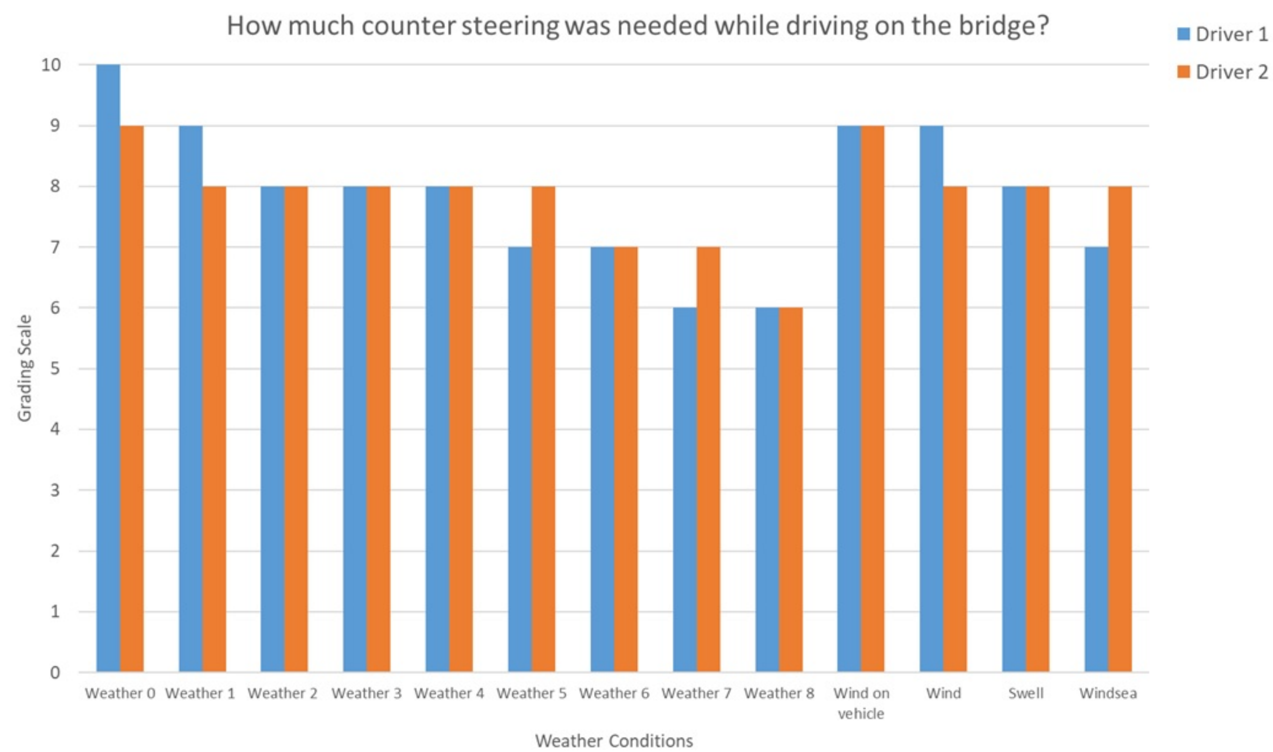


Figure 4.19: Level of counter steering needed in straight line driving in a car at the speed of 110 kmph

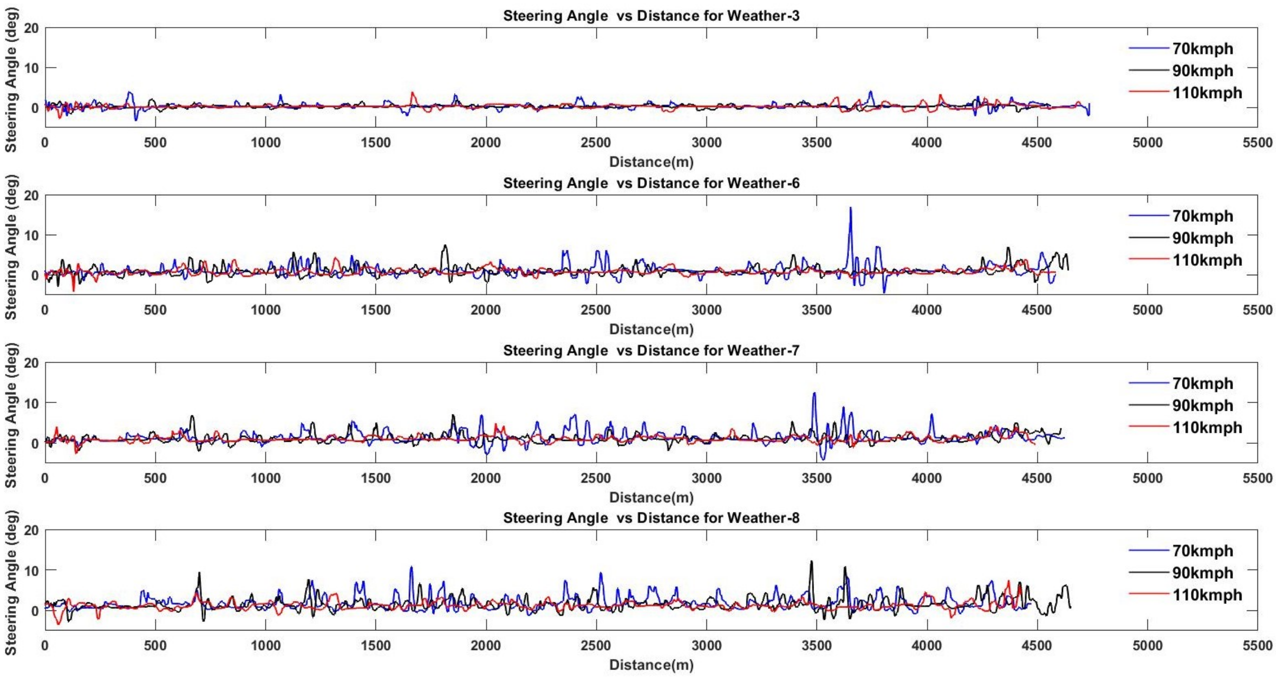


Figure 4.20: Steering corrections in straight line driving in a car for different speeds and weather conditions

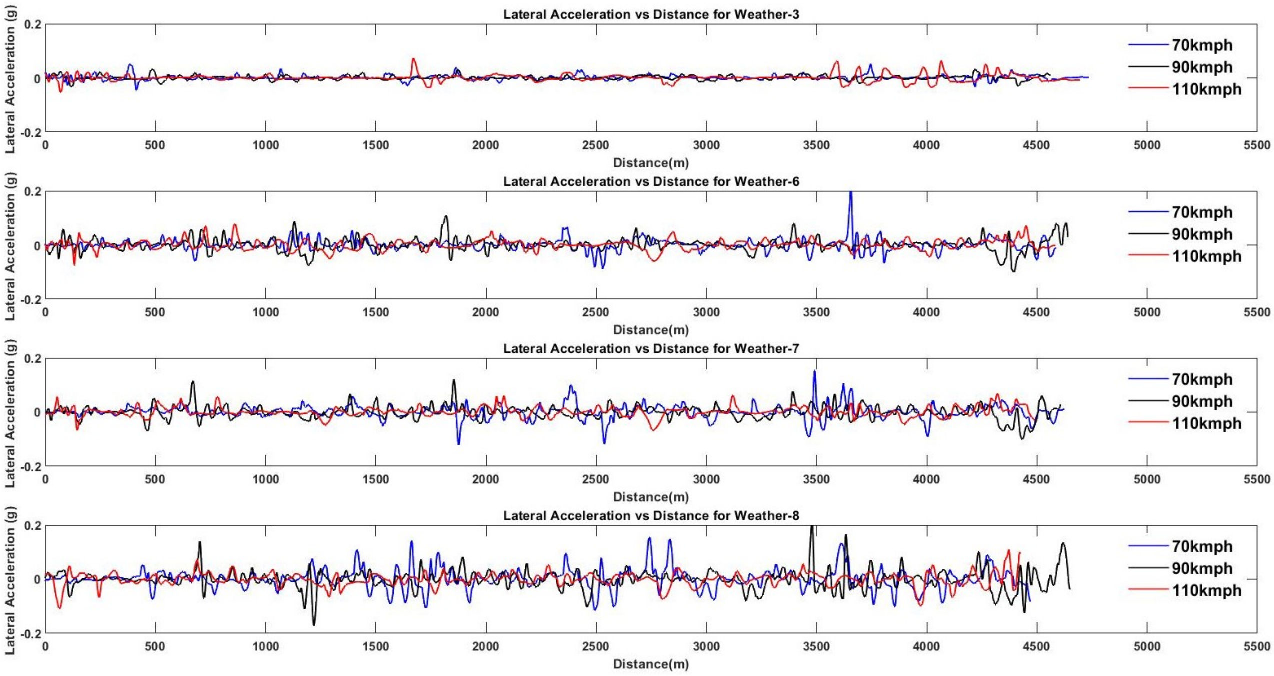


Figure 4.21: Lateral acceleration in straight line driving in a car for different speeds and weather conditions

The steering inputs and the lateral accelerations generated for the car at different speeds is slightly different than the expected results. From the steering and lateral acceleration plots above, it can be seen that higher steering inputs were given at 70 kmph rather than 110 kmph. This discrepancy could be due to different driving styles. These driving trials were done at different times which could affect the driver's behaviour in the driving simulator. However, general trend of difficulty in driving is increasing with storm severity. When compared with different speeds, the results are different than expected. This could be due to the differences between real life driving and driving in the driving simulator. More driving trials with different drivers needs to be conducted to find the specific speed limits for each weather condition.

If trackability plots are considered, even though lateral acceleration and steering inputs are less, it was difficult for the driver to stay in the lane. Most of the time the driver drove close to the center line. The driving behaviour can be different when traffic on the bridge is considered.

4.6 Lane Change and Overtaking - Bus

Similar driving trials were conducted with the bus model to understand the impact of weather conditions and moving bridge on driving behaviour. Later, comparisons are done with the car scenario to check if there are any similarities or differences.

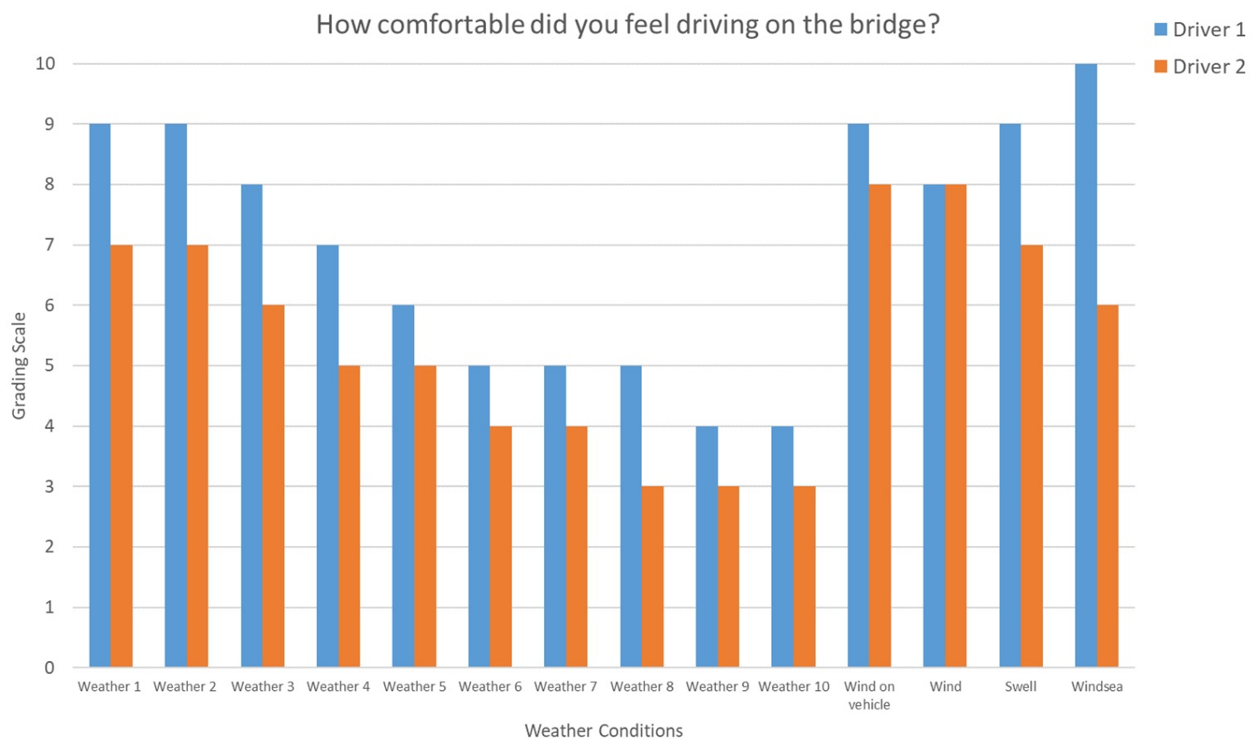


Figure 4.22: Level of driving comfort in a bus at the speed of 70 kmph during lane change and overtaking

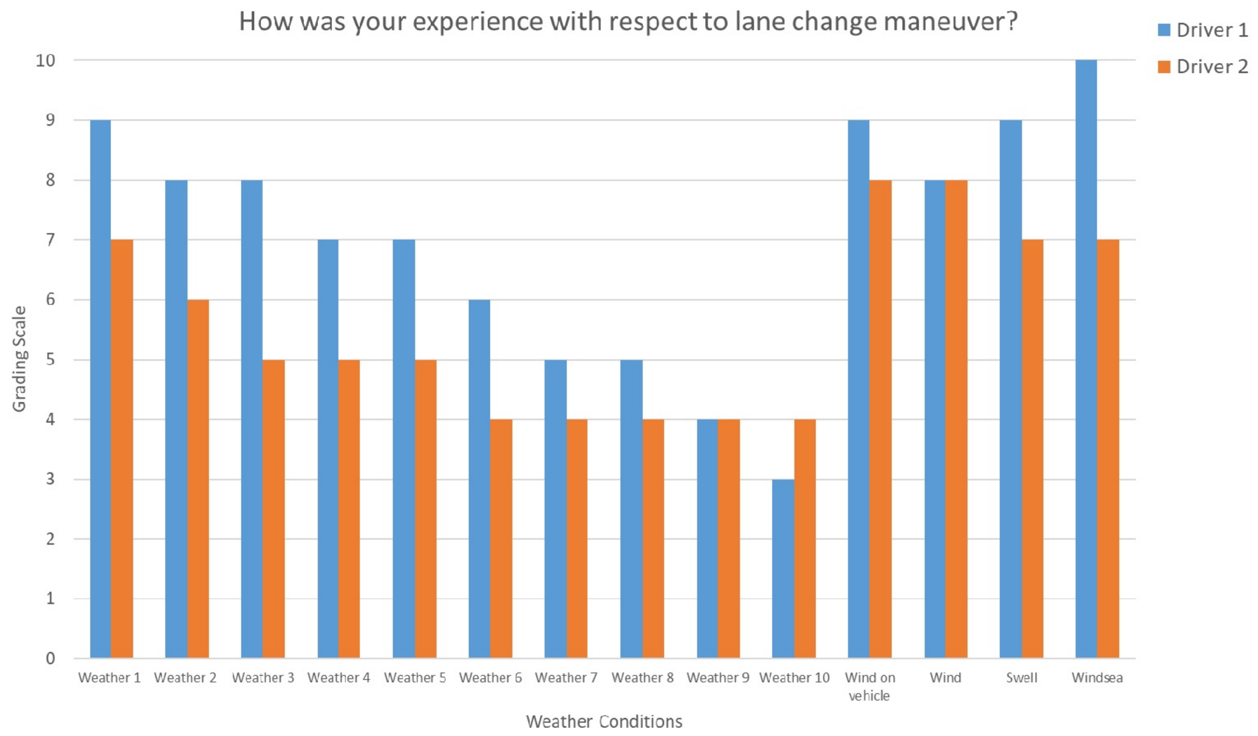


Figure 4.23: Lane change maneuver when driving a bus at the speed of 70 kmph

We can already see that the level of comfort when driving a bus reduces from weather 4-5 which is much lower when compared with a car. Since the track-width of the bus is much more when compared with a car, the driver has lesser space to move in the lane and this makes overtaking and driving with bridge motion much harder.

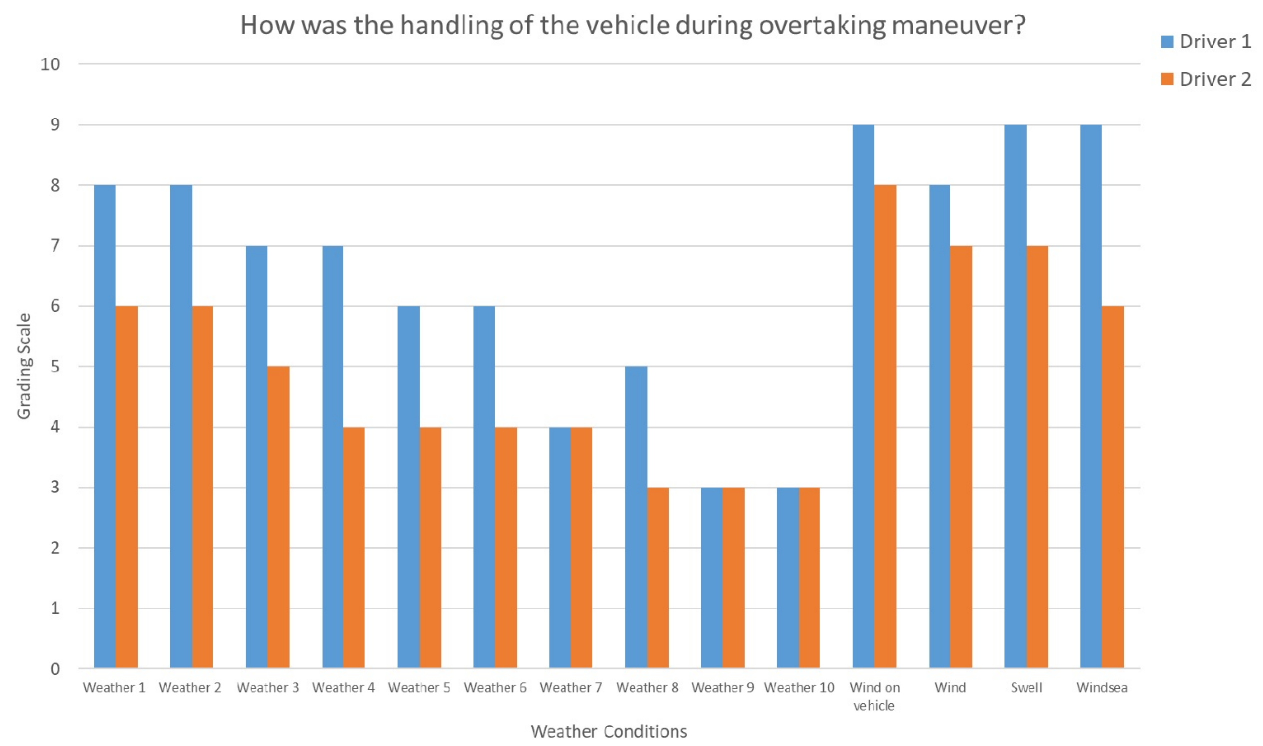
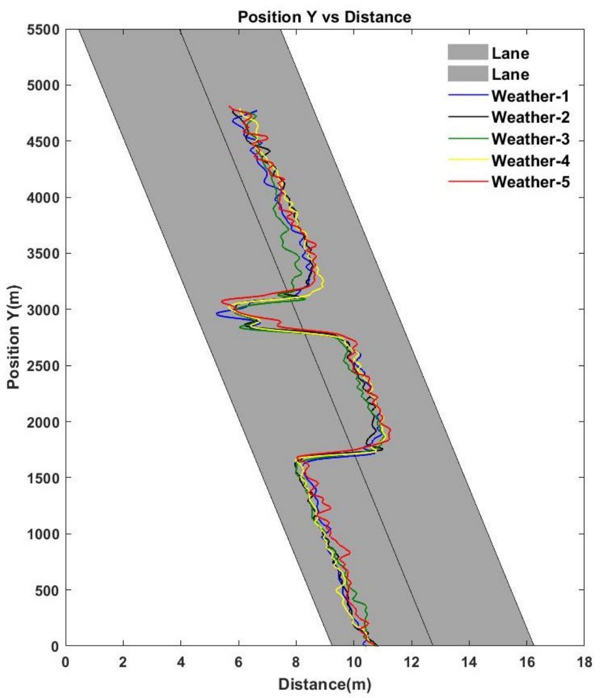


Figure 4.24: Overtaking maneuver when driving in a bus at the speed of 70 kmph



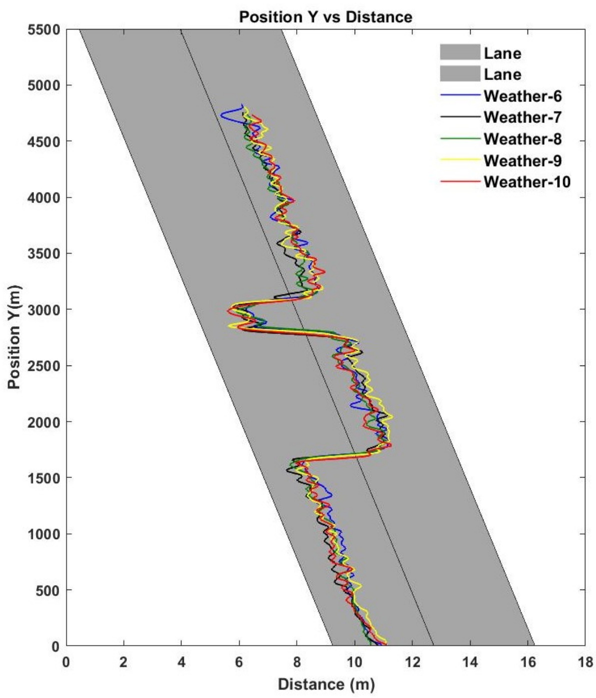


Figure 4.25: Track-ability of the bus on the bridge at the speed of 70 kmph for weather 1-10 during lane change and overtaking

In the above figure, path travelled by bus over the bridge during the driving trial is plotted for all weather conditions. It can be seen from the plots that, the bus follows similar trend as the car i.e in lower weather conditions the driver could stay in the lane, perform lane change and overtaking. However, when higher weather conditions are considered the driver had difficulties staying in the lane. Constant and more frequent deviations can be seen in the right side plot.

Another thing to be noticed is that, after the lane change and overtaking the driver takes some time to maintain a straight line during which the driver gives significant amount of steering corrections.

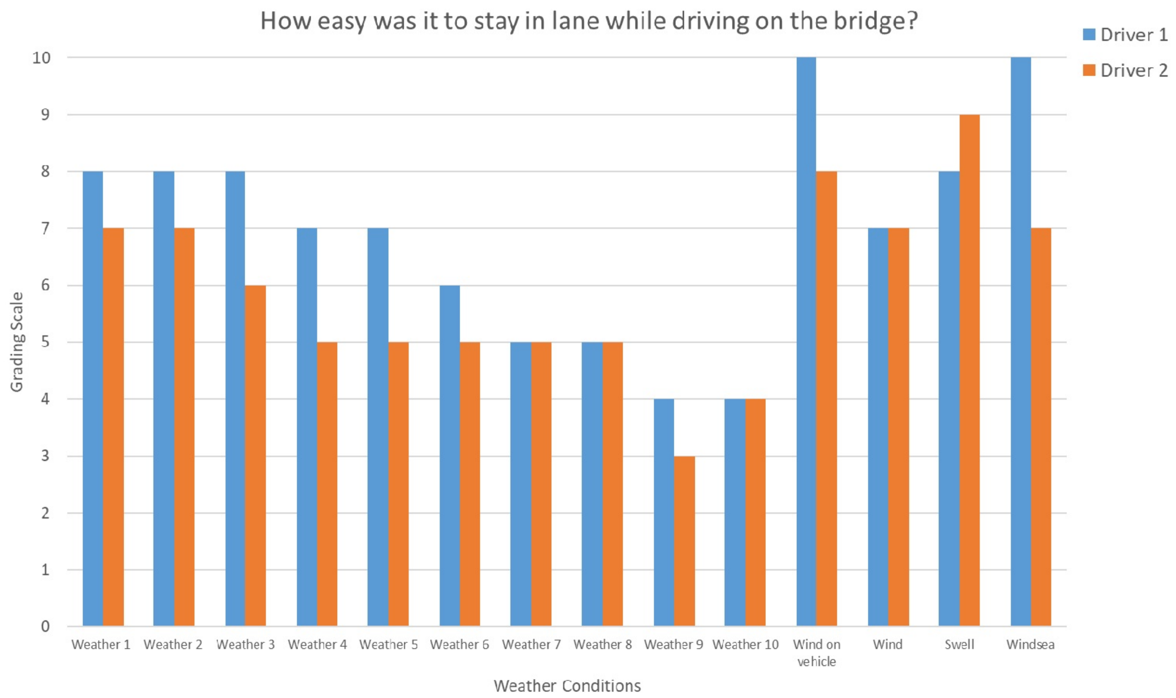


Figure 4.26: Ability to stay in lane when driving in bus at the speed of 70 kmph during lane change and overtaking

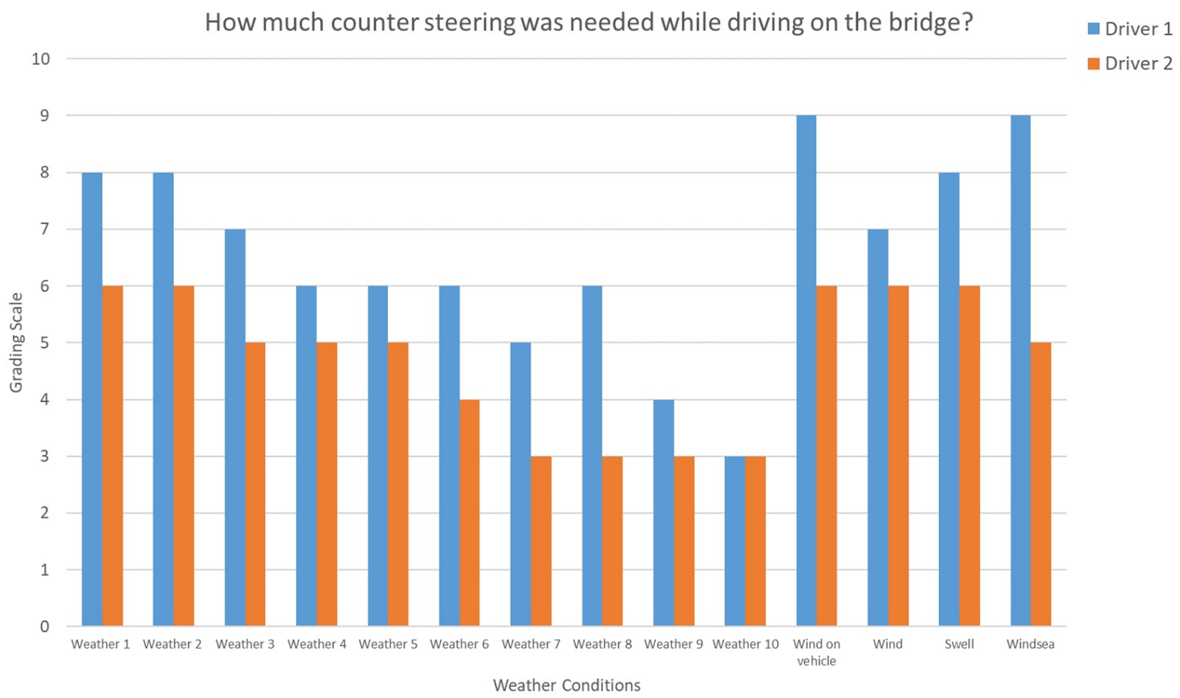


Figure 4.27: Level of counter steering needed when driving in bus at the speed of 70 kmph during lane change and overtaking

We can see that the amount of counter steering needed is also higher in the case of the bus. The amount of counter steering is high and the driver feels uncomfortable even at weather 3-4 as per the feedback given by driver 2. This is important to be noted as too much counter steering might lead the bus to come in close proximity with other vehicles in the lane and the bus might also go close to the railings.

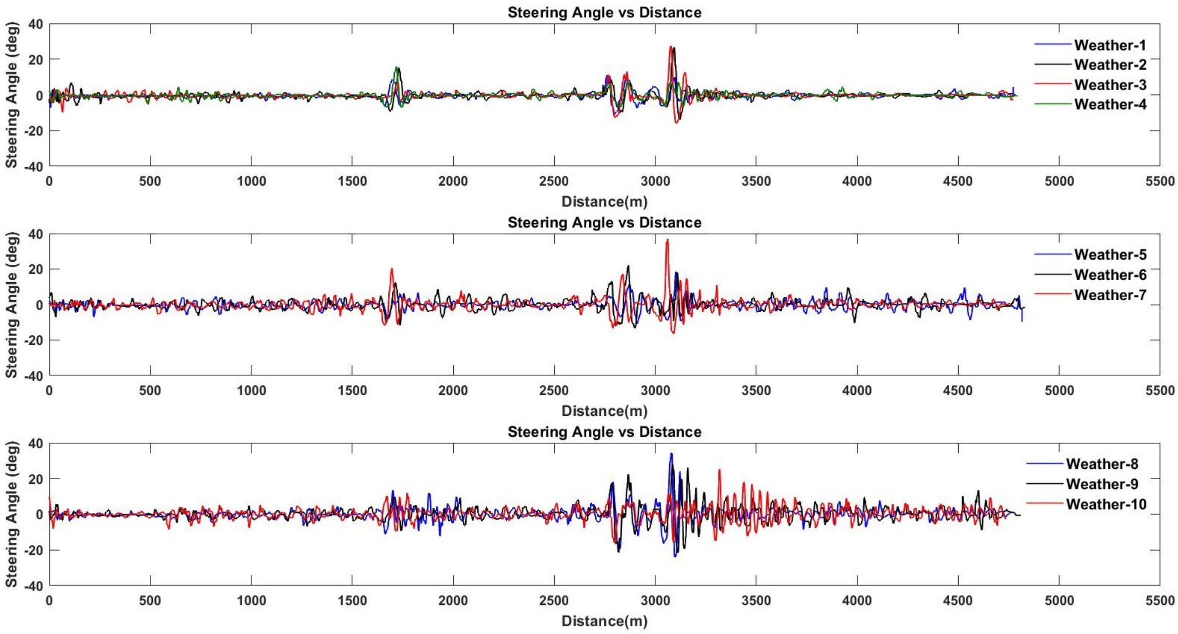


Figure 4.28: Steering inputs of the driver during lane change and overtaking at a speed of 70 kmph

The steering wheel angle plots shows that at a distance between 1500m-2000m and between 3000m-3500m on the bridge, high amplitude steering corrections were given by the driver. This is where lane change and overtaking is carried out respectively. After these maneuvers, driver gave continuous large steering corrections over longer distances. These corrections continue to increase as the weather becomes more harsh.

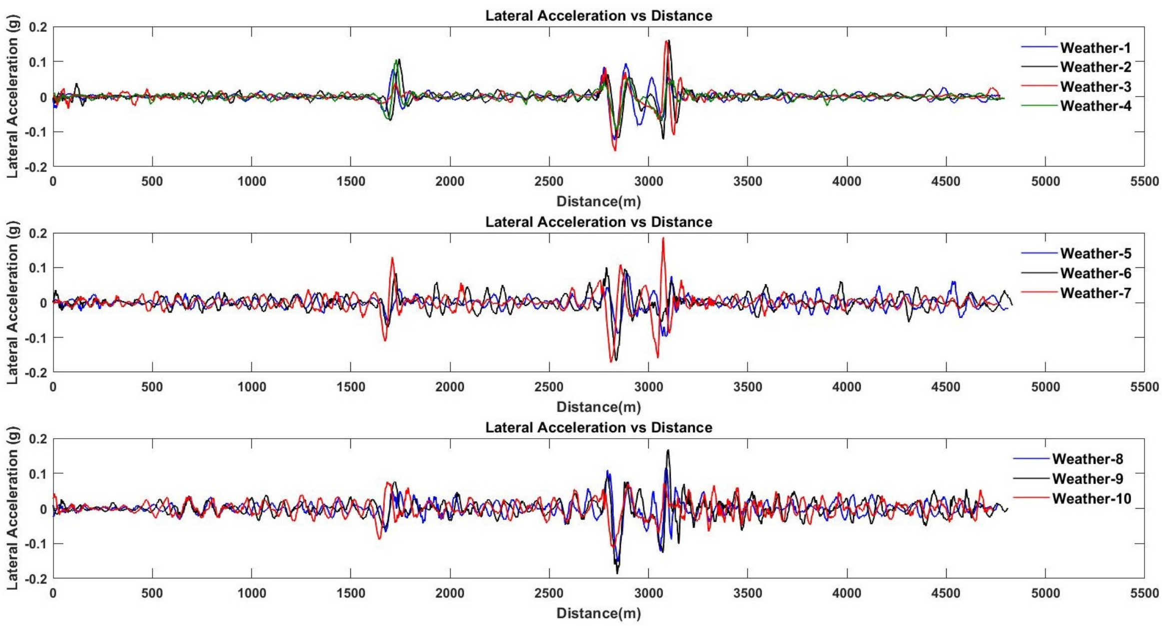


Figure 4.29: Lateral acceleration of the bus during lane change and overtaking at a speed of 70 kmph

Due to the continuous steering corrections, bus faces continuous lateral accelerations. From the graph above, it can be seen that the maximum lateral accelerations are in the range of 0.1-0.2g which could make bus driver as well as the passengers uncomfortable.

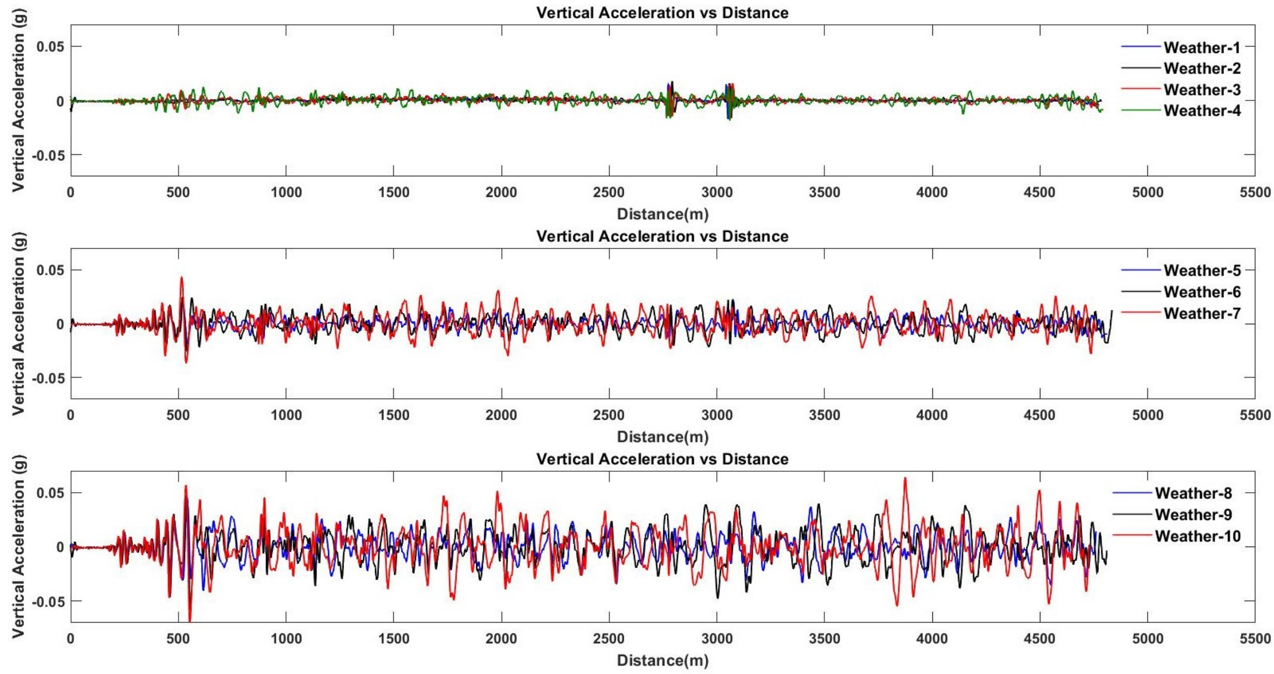


Figure 4.30: Vertical acceleration of the bus during overtaking and lane change at a speed of 70 kmph

Similar to the car scenario, vertical accelerations due to bridge motion are very less compared with lateral accelerations. Since the road is considered to be an A-class, it can have very less contribution in making the drive uncomfortable and difficult.

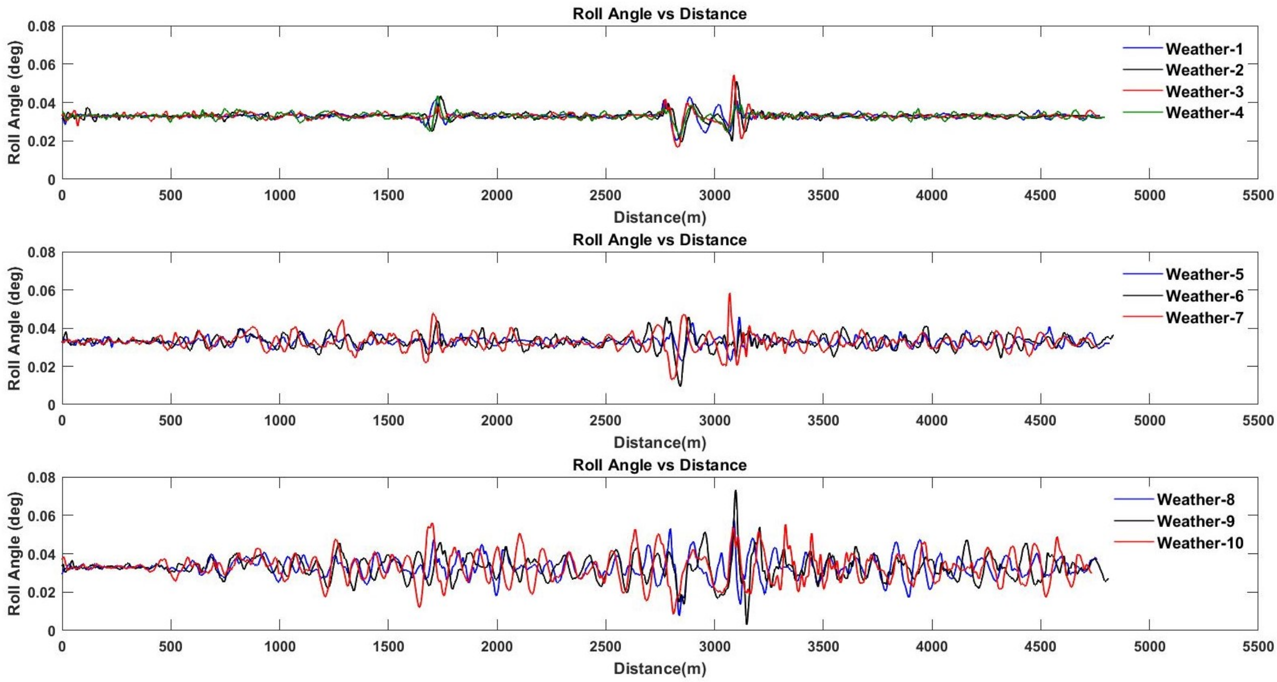


Figure 4.31: Body roll angle of the bus for 70 kmph during lane change and overtaking

Another factor contributing to the overall bridge motion is the roll motion. The body roll of the bus can be seen in the image above. As the weather gets worse, roll motion continues to increase. The roll angles are quite higher than the car scenario, but overall the values are very less in amplitude. The peaks are due to increase in roll angle during lane change and overtaking because of bridge motion and lateral load transfer combined.

4.7 Straight Line - Bus

High lateral displacements and lateral accelerations due to large steering correction were observed during lane change and overtaking. It becomes necessary to investigate how difficult it is to drive the bus over the bridge without any lane change maneuvers. This section is similar to the car scenario explained before.

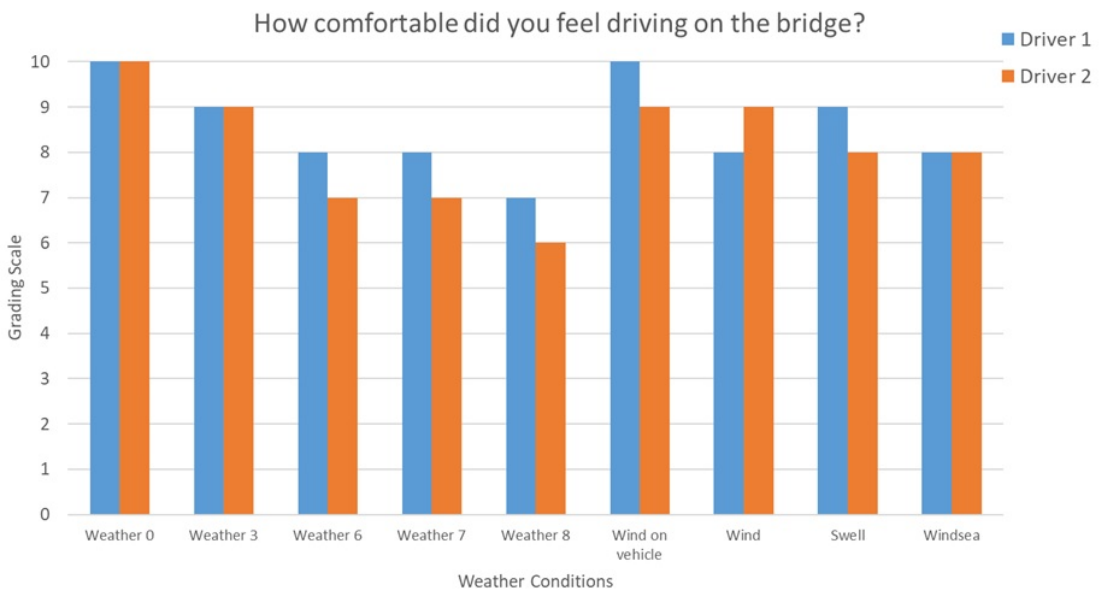


Figure 4.32: Level of comfort in straight line driving in a bus at the speed of 70 kmph

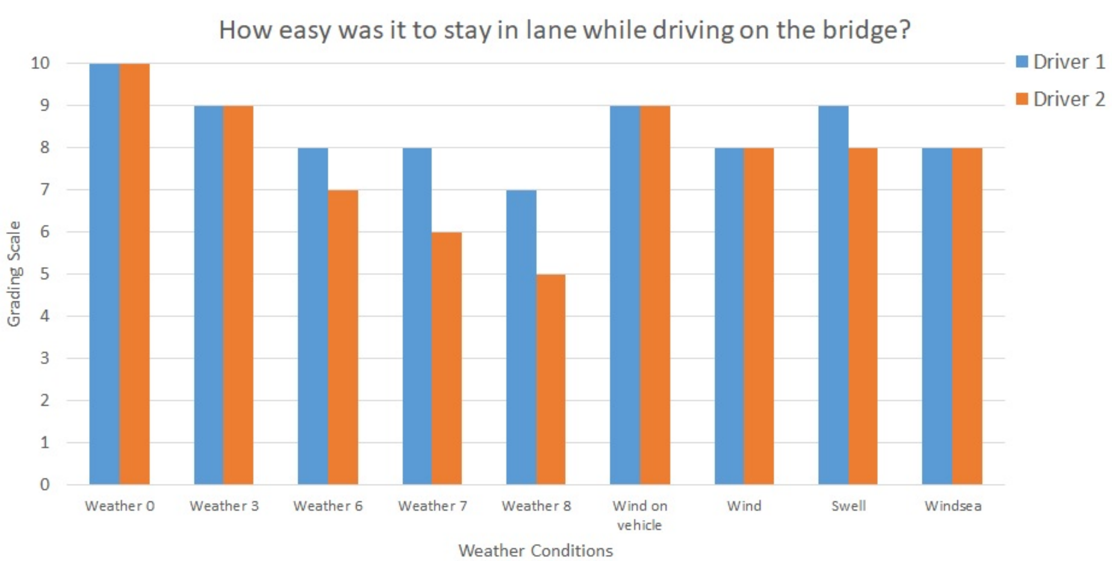


Figure 4.33: Ability to stay in lane in straight line driving in a bus at the speed of 70 kmph

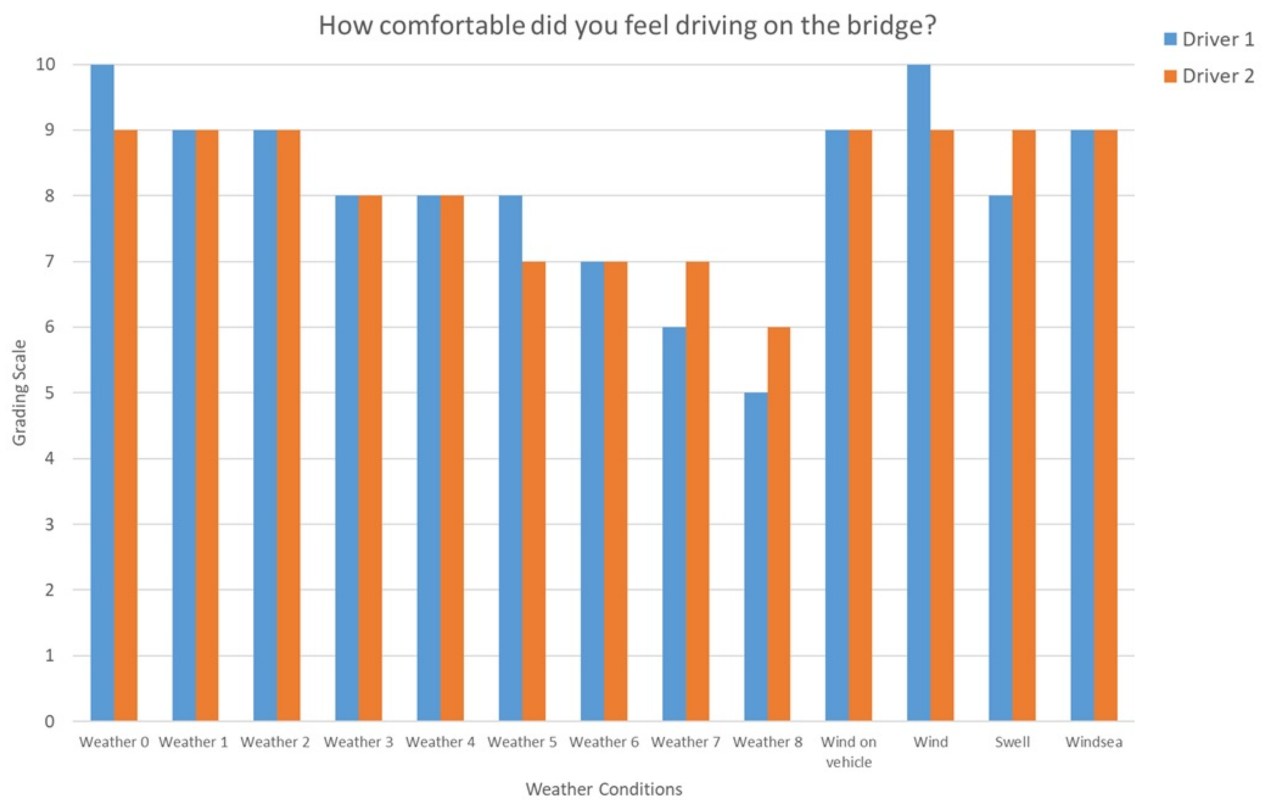


Figure 4.34: Level of comfort in straight line driving in a bus at the speed of 90 kmph

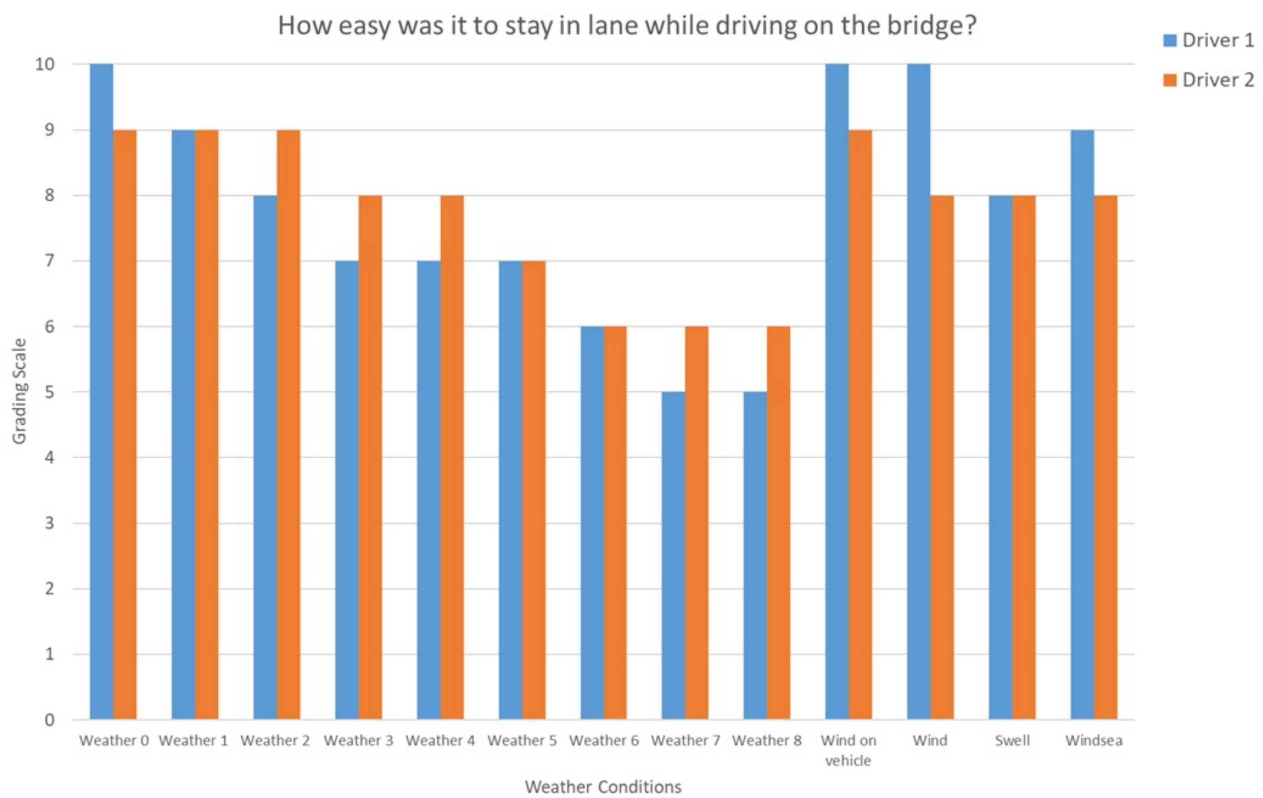


Figure 4.35: Ability to stay in lane in straight line driving in a bus at the speed of 90 kmph

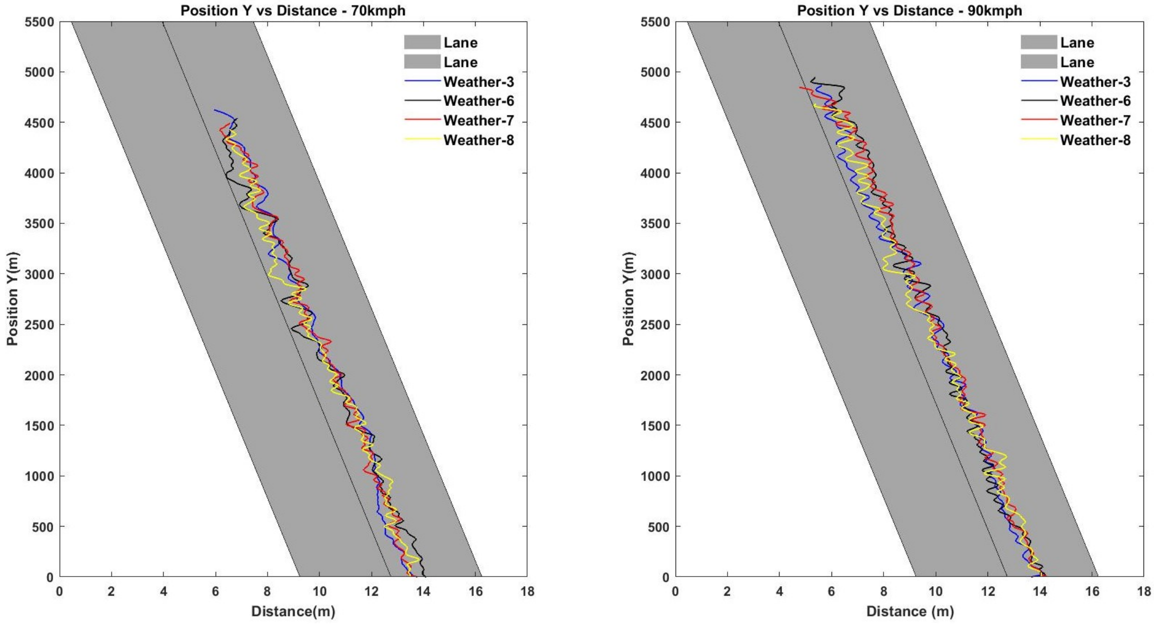


Figure 4.36: Track-ability of the bus over the bridge for both 70 and 90 kmph speeds

One important detail that can be observed from the trackability plots is that in all trials, the driver tried to stay close to the center line dividing the two lanes. The driver is aware of the railing in the right side and is conscious to drive closer to the railings. Whereas, there is another lane on the left side. Since there are no other vehicles on the bridge during the driving trials, the driver tried to stay away from the right end railing.

The above image illustrates the trackability of the bus for two different speeds 70 kmph and 90 kmph respectively. From the trackability plot of bus from the previous section, it is understood that increase in storm severity makes the handling of the vehicle more difficult. Here, the effect of speed can be explained. Though there is similarity in both the plots, it can be seen that increasing the speed has less effect. However, for higher speeds the frequency of the path or the frequency of steering corrections are higher. So increasing speed causes some difficulty to stay in the lane.

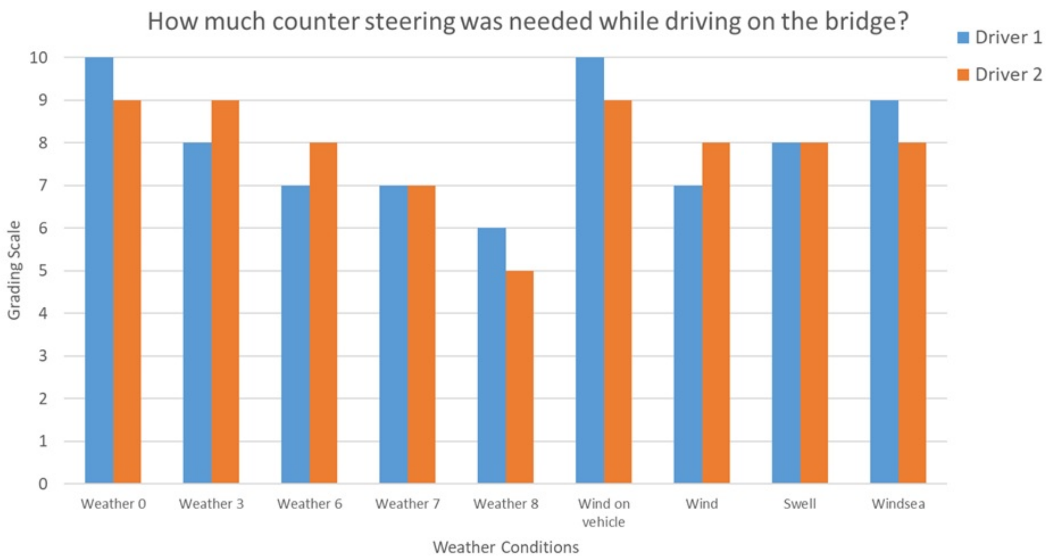


Figure 4.37: Level of counter steering needed in straight line driving in a bus at a speed of 70 kmph

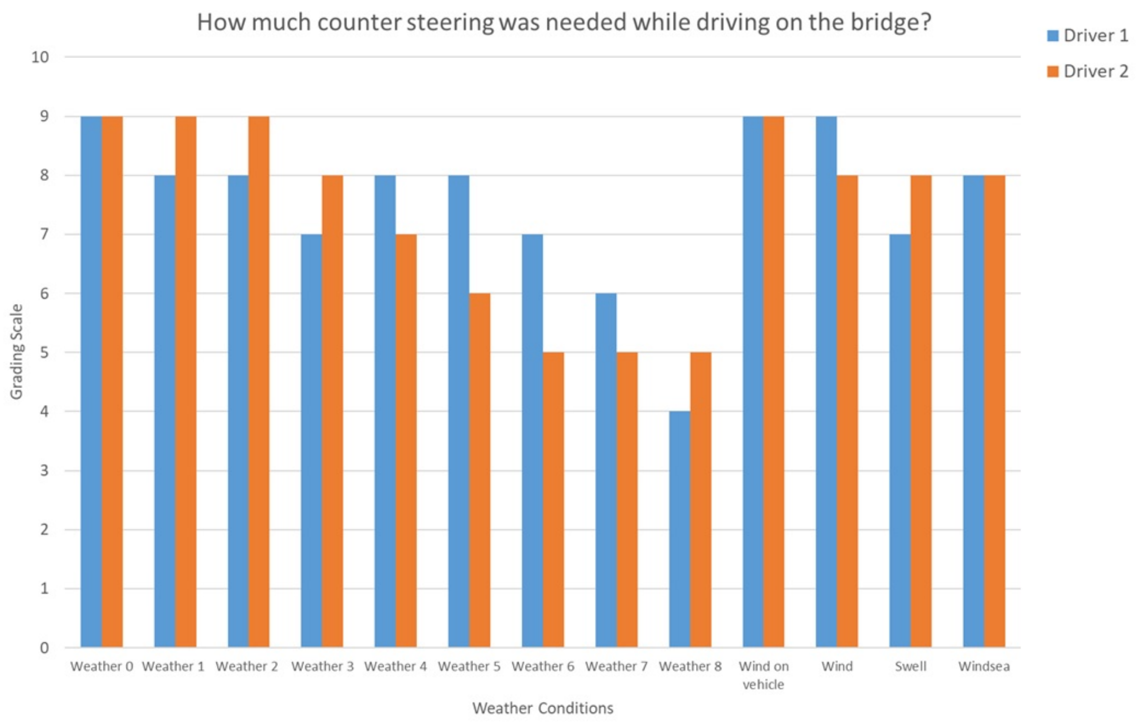


Figure 4.38: Level of counter steering needed in straight line driving in a bus at a speed of 90 kmph

We can see from the feedback that the driver feels more counter steering is needed at higher speeds and higher weather conditions. Another detail that needs to be kept when looking at the level of counter steering is that when driving in the driving simulator, a smaller steering wheel was used. However, in the real case scenario, the bus steering wheel is bigger and the steering ratio is different. This can affect the levels of counter steering needed and the driver interaction with the steering wheel.

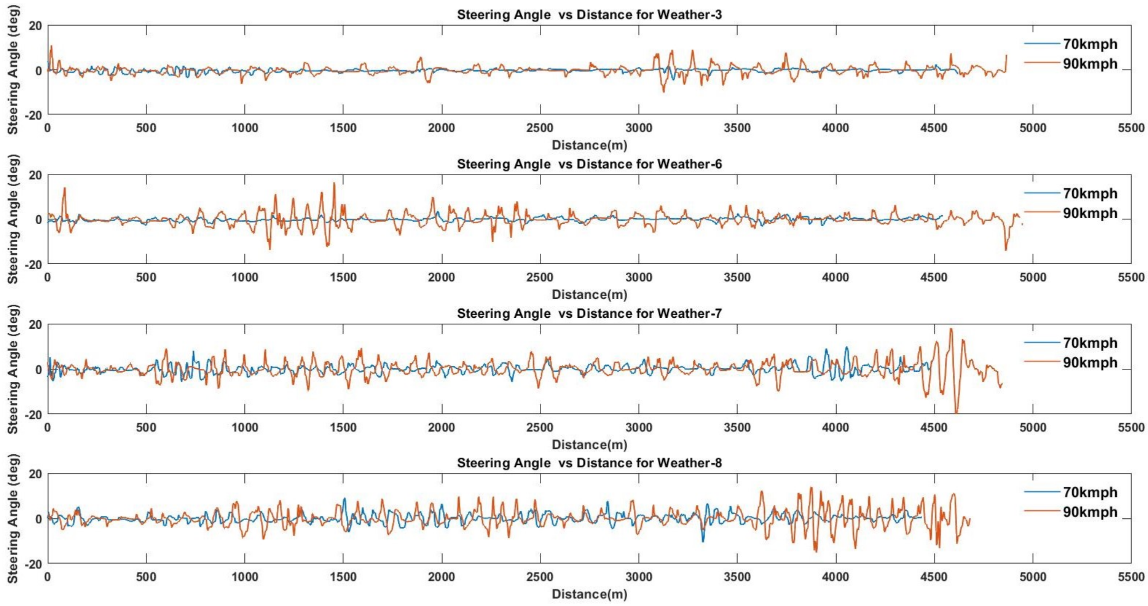


Figure 4.39: Steering angle of the bus over the bridge for both 70 and 90 kmph speeds

Previous image of trackability can be supported with the steering corrections given by the driver for the weather conditions mentioned previously. It can be seen that peaks and frequency for 90 kmph trial are more than for the 70 kmph driving trial. One more detail that can be observed is that, increasing speed also makes the steering correction demand more frequent along with increasing weather conditions.

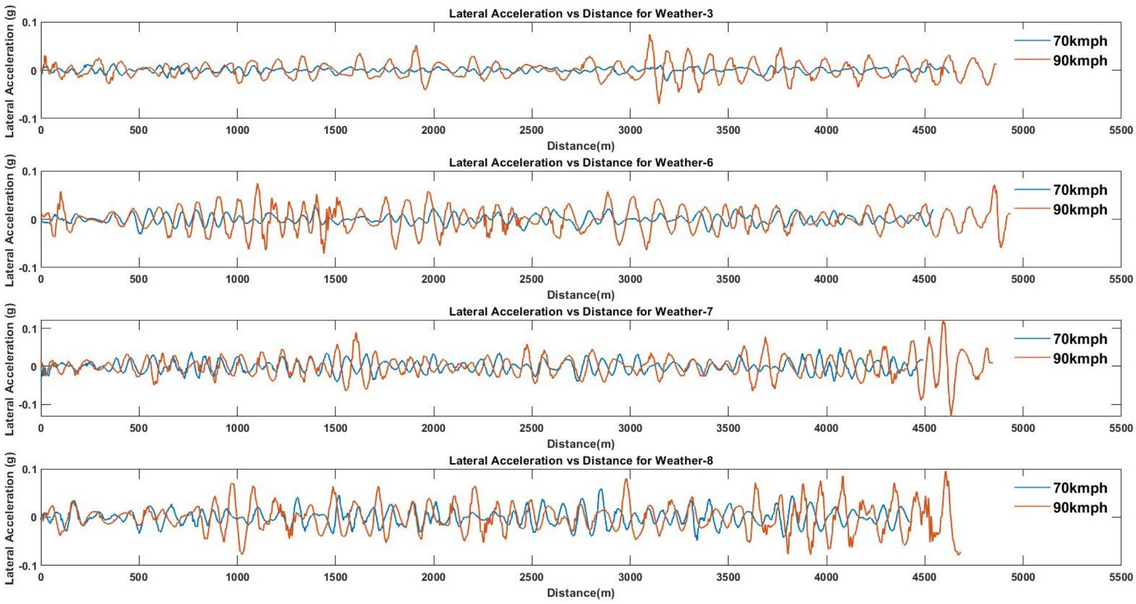


Figure 4.40: Lateral acceleration of the bus over the bridge for both 70 and 90 kmph speeds

It is obvious that with continuous steering corrections the bus would have significant lateral acceleration outputs. For weather-8 i.e. 10 years storm, high lateral accelerations were recorded even if the bus was going in a straight line without changing lanes. These accelerations get amplified with increasing speed.

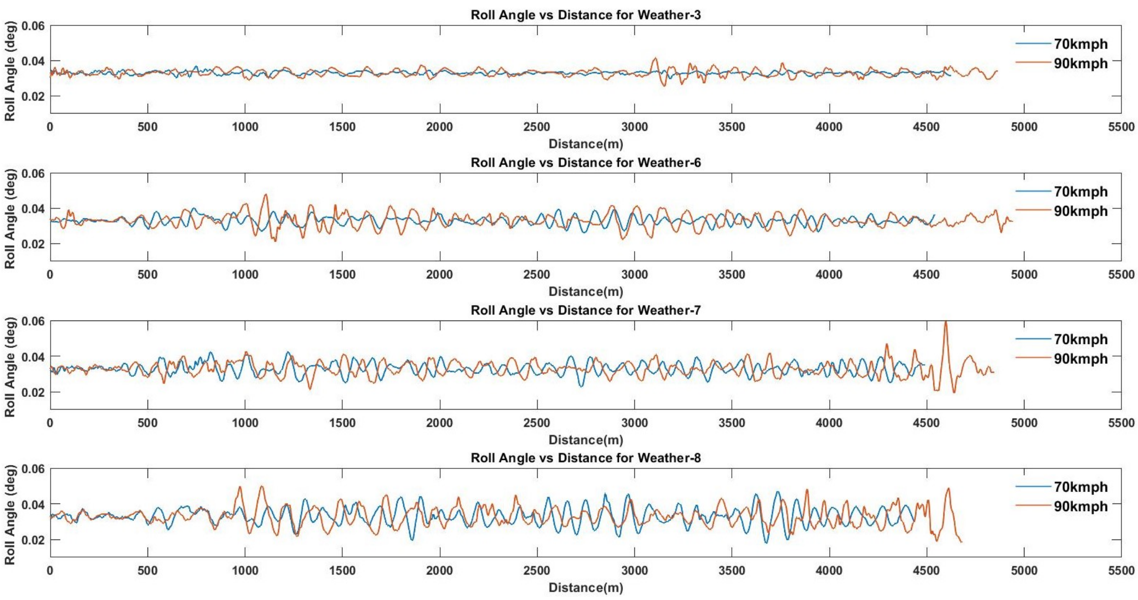


Figure 4.41: Body roll angle of the bus over the bridge for both 70 and 90 kmph speeds

As discussed earlier, the roll angle recorded was very low. From all the plots it is clear that the bus rolls more if the weather is worse as the large side area of the bus is exposed to the side wind. Here, it can be observed closely that the speed has some significant impact on the roll motion as well.

4.8 Driver Modeling

The literature survey facilitated in the selection of two approaches proposed for the driver model.

In reference to the first approach, using a reference example from Simulink, we studied the integration of vehicle model block with a driver model. The main concern was incorporating large weather input data in environmental and vehicle dynamics block and model the path generation block as per bridge conditions. Furthermore, when modelling a driver model a drawback is that identifying the gain parameter for dynamic vehicle behaviour i.e. for each weather condition gain (K) value had to be re-tuned. Therefore, due to complexity in studying and modelling the complete driver and vehicle block structure, an alternative second approach is proposed.

The second approach is less complicated when compared to the first approach because MPC controller block available in Simulink is designed such that it is capable of choosing and adjusting the gain values of various parameters such as steering, lane deviation by itself. However, the main issue with the model is feeding the reference inputs obtained from the driving Simulator. The reference input matrix is quite large for the controller to process the inputs.

Chapter 5

Discussion

In this project a total of 157 driving trials were performed, and significant results were obtained from the driving simulator data and it could be co related to the subjective assessment as well. When dealing with such a large data set it is important to understand the pattern in order to draw suitable conclusions.

The following things needs to be kept in mind when reading the results:

- The results obtained from driving trials performed in the CASTER driving simulator is presented in this chapter
- The data from the subjective feedback is based on 3 drivers. The level of experience driving in the driving simulator can have influence on the subjective feedback.
- The results show similar patterns and help us to understand the driving on the floating bridge
- In order to draw more comprehensive conclusions more drivers and driving trials will play an important role

5.1 Questionnaire

As discussed above, the questionnaire consisted of 8 questions. A few questions were framed in order to check the consistency in the feedback. For instance, questions 1 and 6 aimed at understanding the drivers level of comfort and confidence while driving. Questions 5 and 7 were also very similar and aimed at understanding the driver's ability to stay in lane. It was observed that similar questions in the questionnaire had similar grading levels. This shows that the results from the questionnaire are reliable.

5.2 Lane change Vs Overtaking at 70 kmph

The first set of driving trials were performed for lane change and overtaking maneuvers. In general, it was found that the lane change maneuver was easier compared to the overtaking maneuver. In the case of driving in a car, based on the subjective assessment it can be observed that overtaking and lane change maneuver is comfortable till weather 5 for the car and becomes uncomfortable after this point. We see in the objective assessment graphs (Figure 4.7) after the overtaking maneuver corresponding to around 3000m in the Y axis, we see a lot of fluctuations which indicates significant amount to counter steering needed to maintain the lane.

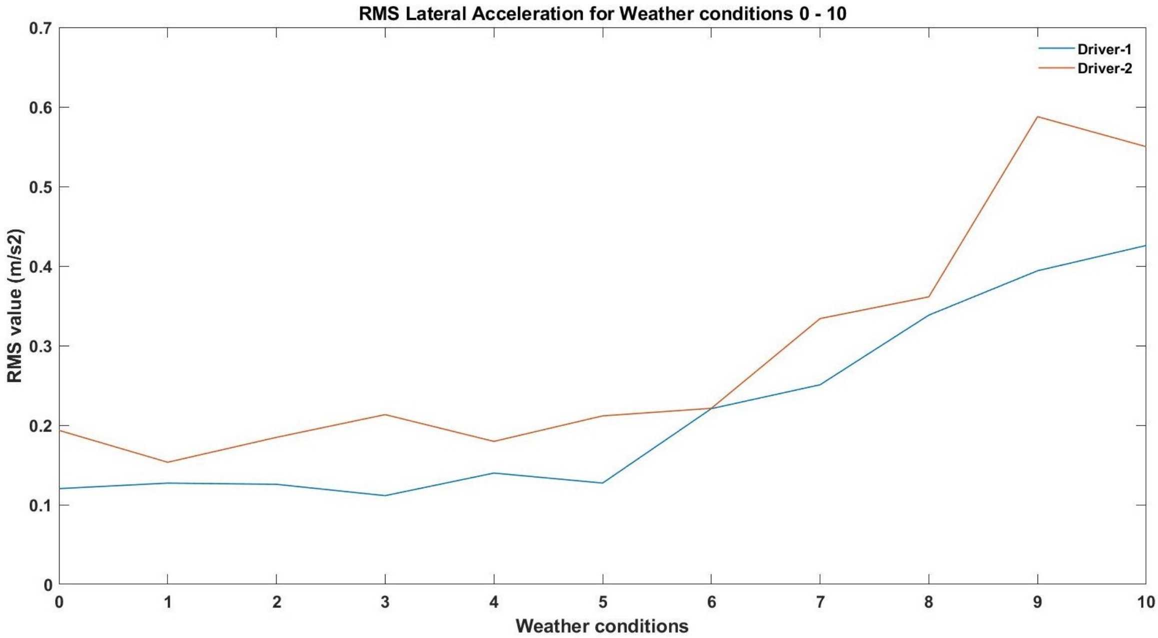


Figure 5.1: RMS value of lateral acceleration for a car when driving at 70 kmph for lane change and overtaking maneuver

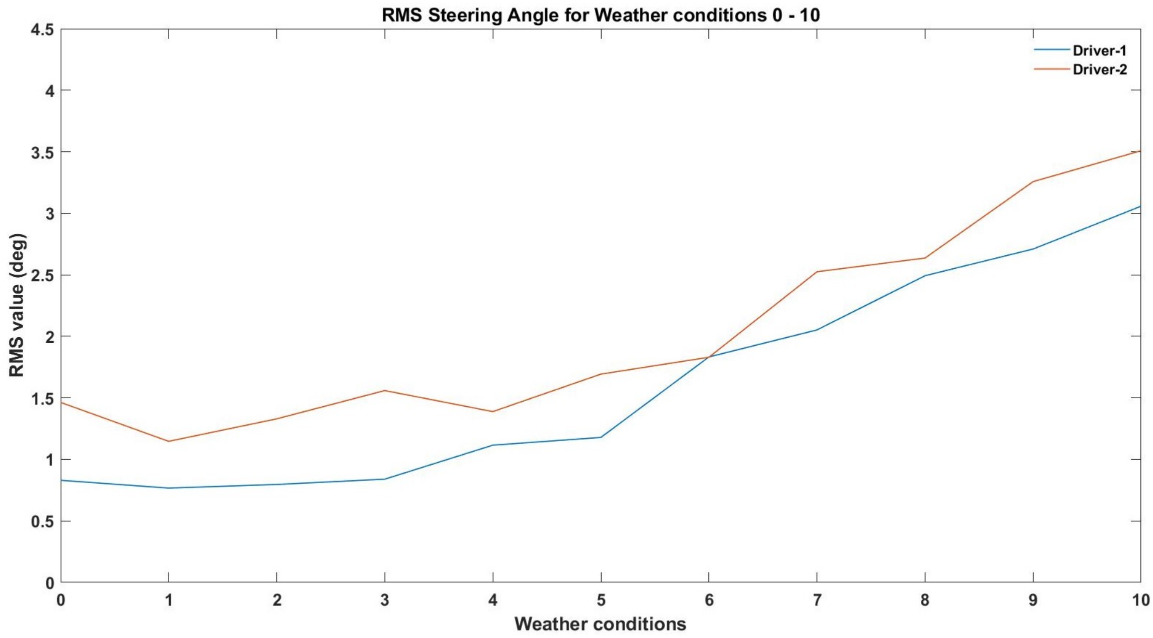


Figure 5.2: RMS value of steering angle for a car when driving at 70 kmph for lane change and overtaking maneuver

The above plots shows the RMS values of lateral accelerations and steering inputs given by both the drivers. It can be observed that after weather 5, the graph ascends suddenly due to the fact that after weather 5 larger and more frequent steering corrections were needed which is also seen in the RMS steering plot above.

In the case of bus, the thresholds are much lower. We see that in the case of bus driving, overtaking and lane change is comfortable till weather 3 and becomes uncomfortable after that. The bus having a larger side area, higher CoG and track width makes it harder to perform overtaking maneuver in the presence of various environmental loads. Also, getting closer to the railing and closer to the the traffic lane are two possible challenges during a overtaking maneuver in the bus.

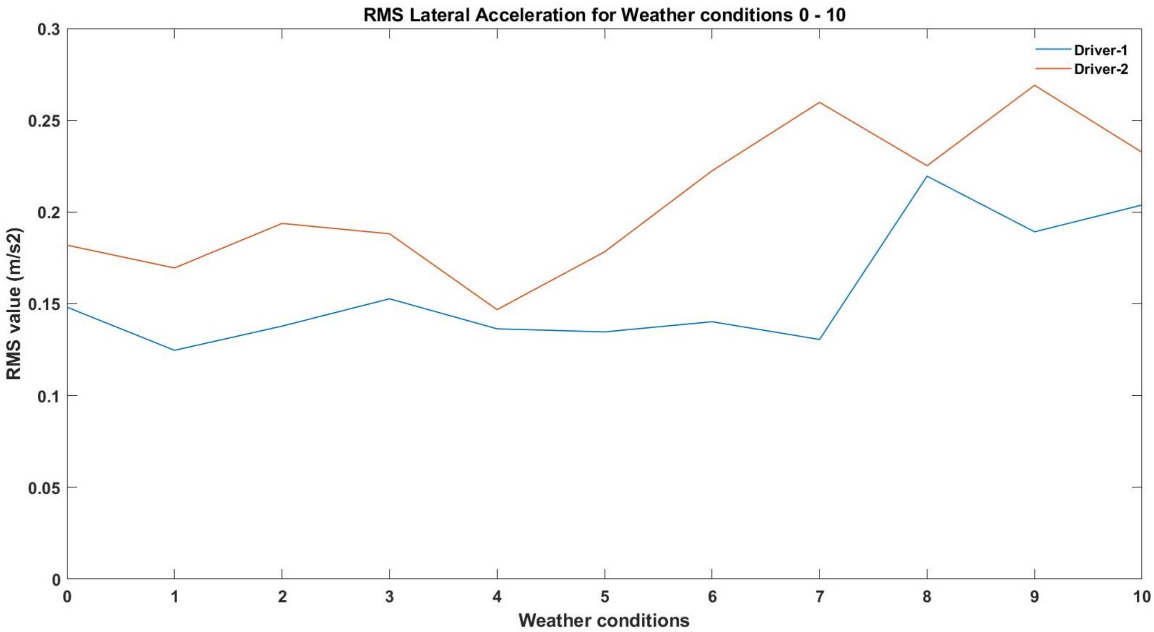


Figure 5.3: RMS value of lateral acceleration for a bus when driving at 70 kmph for lane change and overtaking maneuver

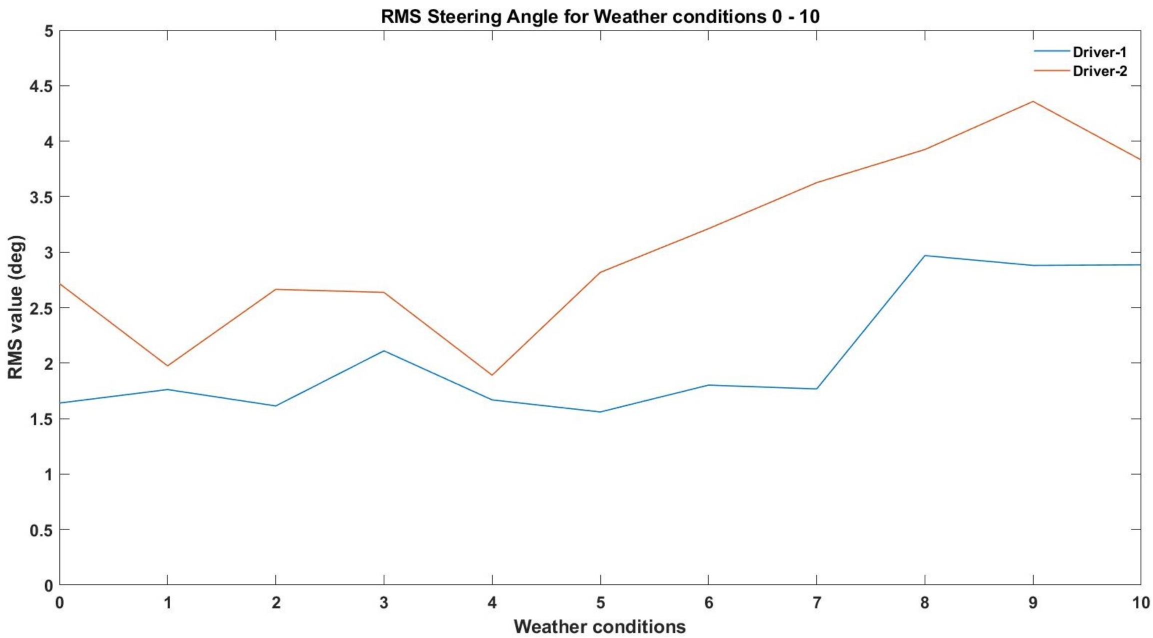


Figure 5.4: RMS value of steering angle for a bus when driving at 70 kmph for lane change and overtaking maneuver

From RMS plots, it is observed that the rapid change in the values are recorded after weather 3 and one important detail to be noted here that the steering corrections have higher values for bus but lateral acceleration is higher for car. This conflicts of data mismatch can be explained in a simple way.

The important factor is the weight of the vehicle. car weighs less and can move easily sideways with lesser steering angle. In case of a bus, higher lateral tire forces must be generated as bus weighs more. To generate these higher lateral forces, higher steering angles are given by the drivers.

5.3 Straight Line Driving

It was very evident from the above data analysis that the straight line driving had higher levels of comfort compared with other maneuvers. In the case of car, straight line driving at speeds 70, 90 and 110kmph had similar levels of comfort till a certain weather condition.It was possible to drive at a speed of 110kmph in a straight line till weather 7 with good levels of comfort. For higher weather conditions it is recommended to reduce the speed.

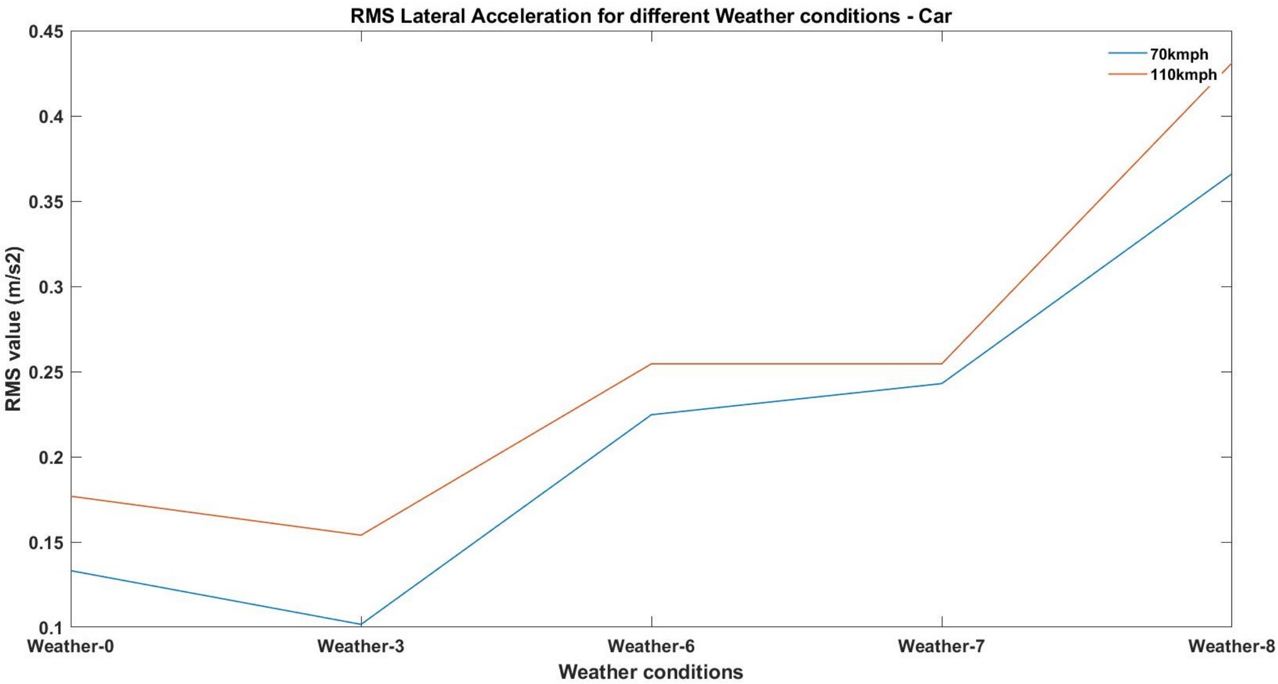


Figure 5.5: RMS value of lateral acceleration for a car in straight line driving for both 70 and 110 kmph speeds

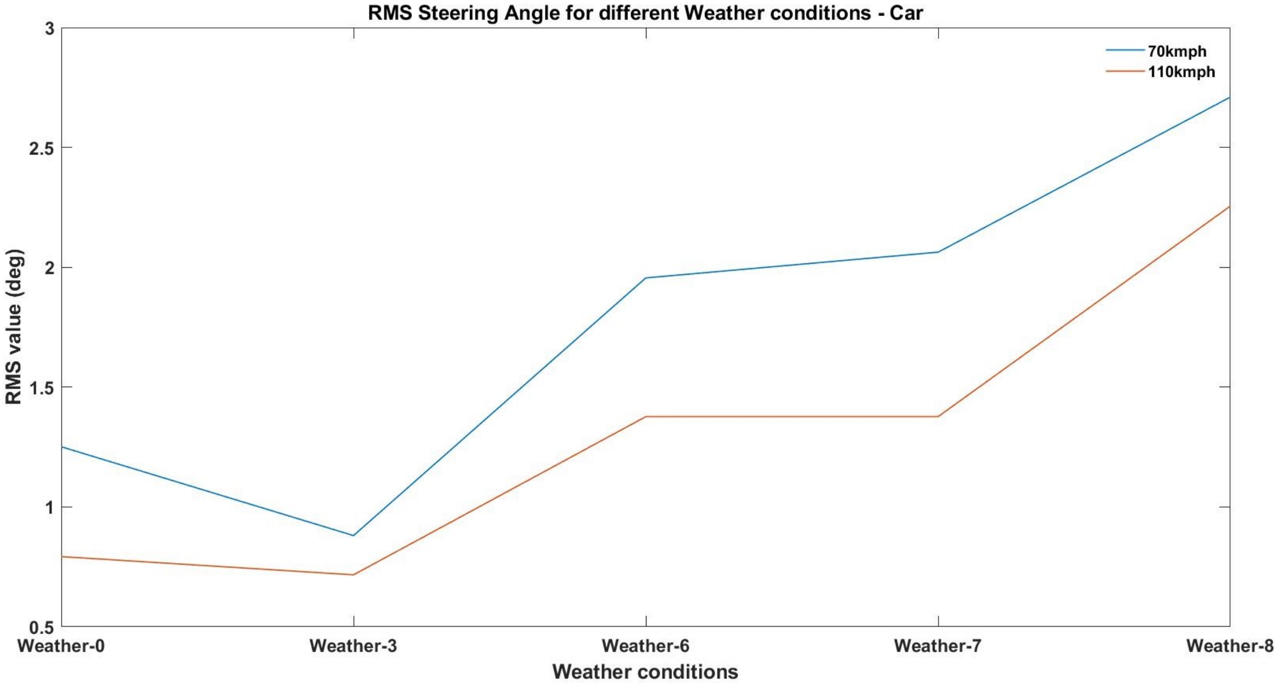


Figure 5.6: RMS value of steering angle for a car in straight line driving for both 70 and 110 kmph speeds

RMS values of lateral acceleration and steering wheel angle are plotted above for the car in straight line driving for two different speeds. Interesting detail to be observed here is that lateral acceleration is more for higher speed where as the driver given more steering corrections in the scenario with lower speed. The lateral acceleration is given by,

$$a_y = \dot{v_y} + \omega_z.v_x \tag{5.1}$$

where a_y is lateral acceleration, $\dot{v_y}$ is change is lateral velocity, ω_z is yaw rate and v_x is speed of the vehicle. This explains that the lateral acceleration not only depends on the steering angle but also on the speed of the vehicle. If the vehicle is driven with variable speed and constant steering angle then the lateral acceleration would be higher for higher speed.

In the case of bus, speed had some impact but it was possible to drive at a speed of 90kmph till weather 6 with good levels of comfort. Seeing the above trends it looks like increasing the bus speed at straight line driving will further reduce comfort level which can be seen in RMS plots below.

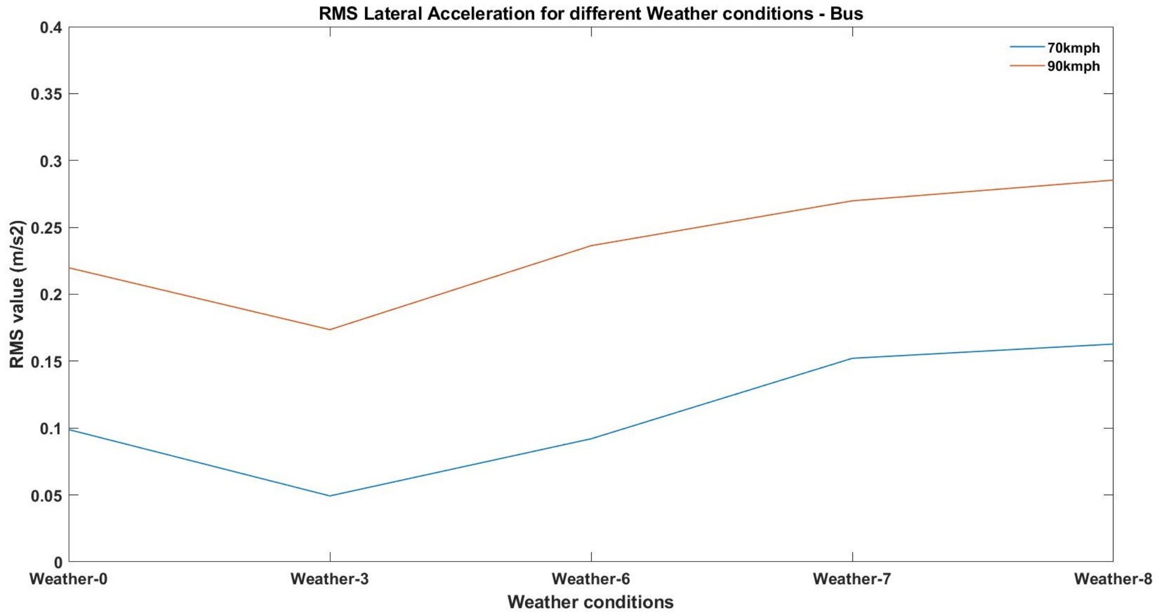


Figure 5.7: RMS value of lateral acceleration for a bus in straight line driving for both 70 and 90 kmph speed

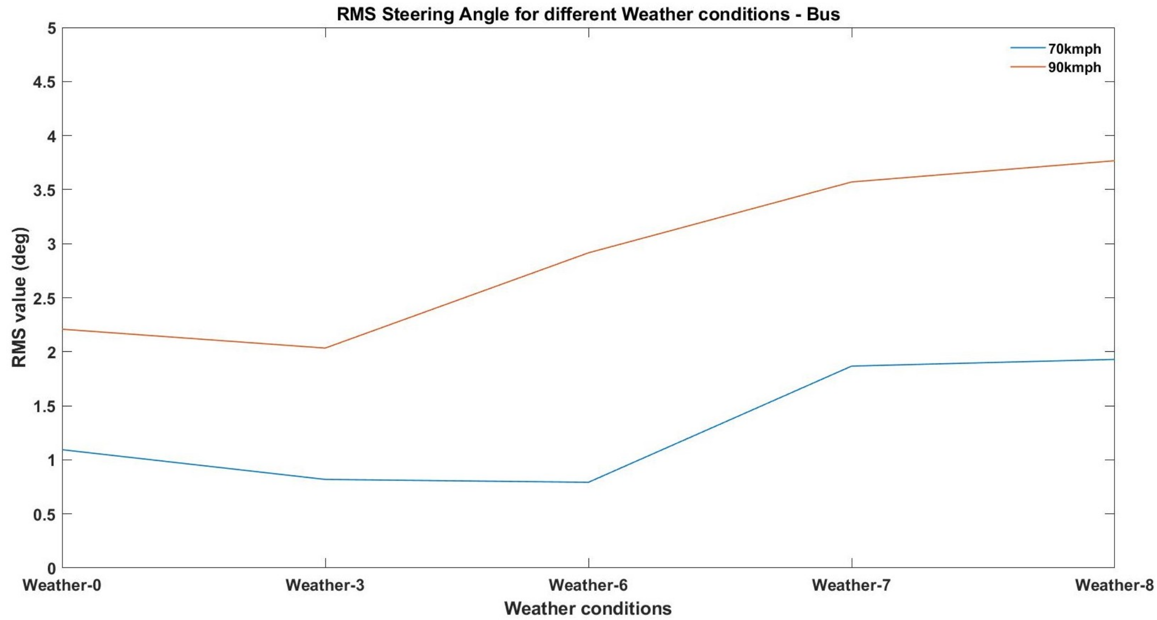


Figure 5.8: RMS value of steering angle for a bus in straight line driving for both 70 and 90 kmph speed

RMS values for bus can be seen increasing with the speed. As discussed in the result section, with higher speeds it becomes difficult for the driver to stay in lane as continuous steering corrections were observed. After weather 6 sudden rise in the values can be observed. As weather condition becomes worse and With traffic on the bridge, the driver might face difficulties in driving.

5.4 Effect of Environmental Loads

As mentioned earlier in any storm conditions there are 4 loads which are constantly acting on the vehicle and the bridge. Those are side wind forces on vehicle, bridge motion due to wind itself, Swell motion of the sea and the sea waves. In this section how these different environmental factors affect the driving behaviour is discussed for 1 year storm (weather-6) condition including lane change and overtaking scenarios.

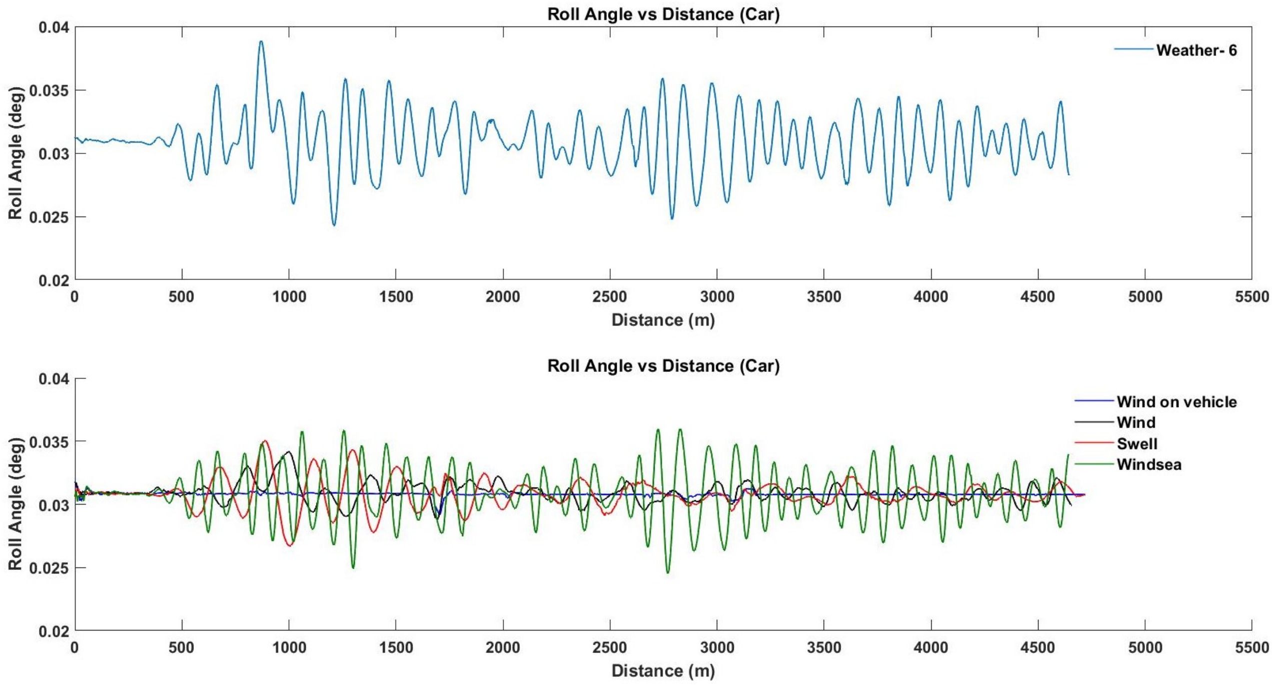


Figure 5.9: Roll angle of car for different environmental factors for weather 6 at the speed of 70 kmph

The figure above is the body roll angle of the car over the bridge caused by wind, sea swell and windsea are plotted. It can be observed that the windsea i.e the short wavelength sea waves have the major impact on the roll motion followed by the long wavelength sea swell motion. One thing can be seen in the plots that the roll angle is always positive which is the effect of constant side wind force from west side of the bridge. The effect of the side wind on the vehicle can be seen as a continuous force without much roll effect on the car i.e. Wind has least impact on the roll motion of the car.

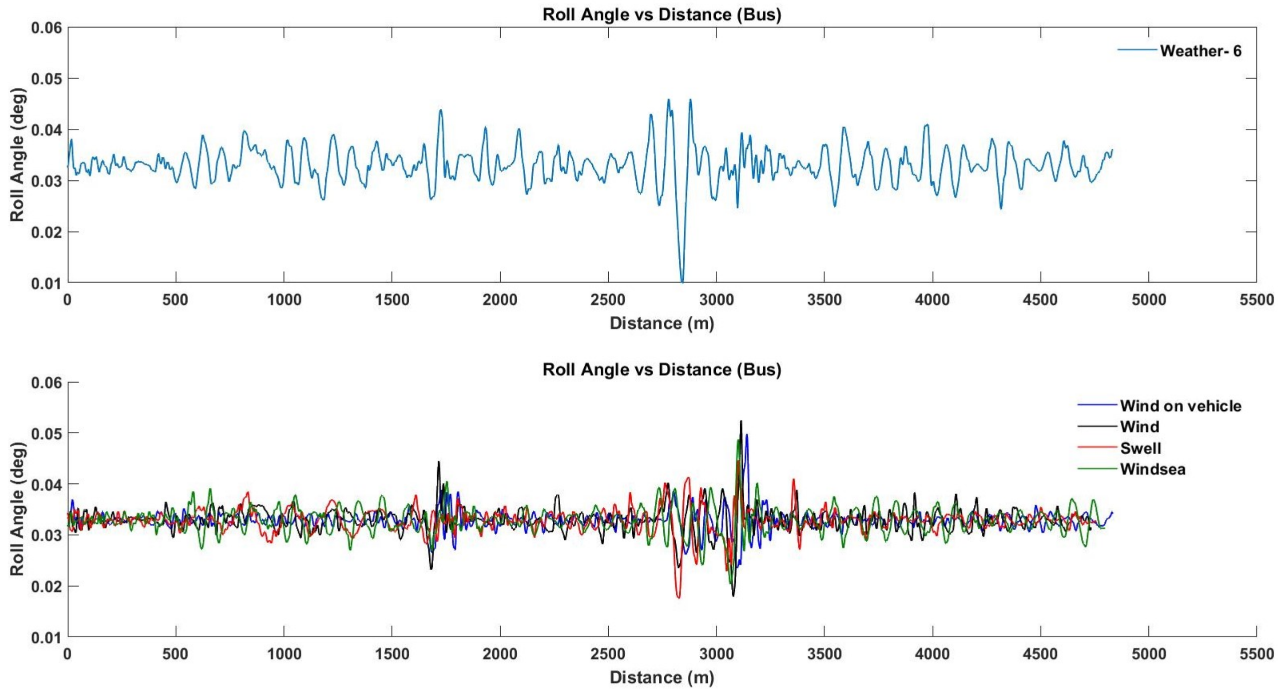


Figure 5.10: Roll angle of Bus for different environmental factors for weather 6 at the speed of 70 kmph

Considering bus with same weather condition and same environmental loads, it is clear that sea waves causes most of the roll motion of the bridge as the roll angle amplitude is higher compared to other loads. Sea swell on the other hand causes higher roll motion of the bridge but the motion is periodic with lower frequency.
Moving on to the side wind forces, it can be observed in the plots for bus, side wind causes some significant impact on the bus roll motion. As the bus has larger side surface and the center of gravity is higher compared to the car, the continuous side wind adds some roll motion to the bus.

5.5 Recommended strategies for driving over the bridge

The following recommendations are based on the results from the driving trials as specified in this report. To develop and establish any restrictions to driving on the bridge, further driving trials are required as suggested in the Future work. In the case of car driving, lane change and overtaking is possible till weather 5 and post this only lane change can be allowed till weather 7 but overtaking should not be allowed. Straight line driving is possible at speeds 110 kmph till weather 7. Post weather 7, it is recommended to reduce the speed.

In the case of traffic on the bridge, it is recommended to allow only straight line driving and lane change in the case of the bus. However, all driving maneuvers can be allowed in the case of the car but only till weather 5. Allowing the bus to drive only in a straight line is a better option than allowing overtaking and lane change. As it was observed from the driving trials, it becomes challenging after weather 3. In case of straight line driving, the bus can be driven at higher speeds (90 kmph) and with good levels of comfort and lesser counter steering till weather 6.

From the data analysis, it can also be seen that the driver generally tries to stay away from the railing while driving on the bridge. However, this is in the case of driving when there is no traffic in the bridge. Thus, in the case of traffic in the bridge, the driver might be more conscious when more vehicles are driving by and the driver might then feel that driving in the center of the lane would be a good choice. This would give enough room to make steering corrections in the case of bridge motion and enable the driver to maintain sufficient distance from the other vehicles. So being too close to the railing or too close to the other lane is not recommended.

Summary of recommendations

Car	Bus
Straight line driving recommended till weather 7 with speed of 110 kmph	Straight line driving recommended till weather 6 with 90 kmph
Overtaking and lane change recommended till weather 5 at 70 kmph	Overtaking and lane change recommended till weather 3 at 70 kmph
Wind sea and Swell has more impact than wind on vehicle for the car	Swell, wind sea and wind on the vehicle have a significant impact on the bus driving

Table 5.1: Recommendations summarised based on the subjective and objective assessment results

5.6 Driver Model

The main aim of the project is to conduct the driving trials in the CASTER driving simulator and establish a conclusive subjective and objective evaluation. In order to complete a set of 15 driving trials, it was observed that it takes close to 3 hours. In order to reduce the overall time spent on driving trials, a driver model can be useful. However, due to time constraints in the project, different approaches of modelling a driver is evaluated and proposed but could not be implemented. As a part of the future work, a conclusive result can be drawn between the driving simulator and the driver model in order to study how a driver would influence the vehicle track-ability on floating bridges.

Chapter 6

Scope for future work

The method that has been developed in the two projects at Chalmers have proved that driving trials in a driving simulator will give good information about how the drivers are affected by weather conditions on the floating bridge. Due to the time constraints in this project, it was not possible to conduct more number of driving trials. This section explains about the possible scope for future work, which can help in drawing more recommendations for driving on the floating bridge.

- Driving trials as per the planning schedule with the aim of developing and establishing any restrictions for safe driving on the bridge
- Driving trials in a driving simulator with high degree fidelity
- Further development of vehicle models.
- Modelling of the suspension system in MSC Adams car software to understand the impact of forces on the suspension system. The data for the vertical forces acting on the tire can be harnessed with the help of the telemetry data obtained from the driving simulator.
- A comparative study can be done based on vehicle track-ability by implementing with and without electronic stability control in CASTER driving simulator model to analyse its effect on lateral control while driving on the bridge.
- Improvement in visuals on the screen to simulate night time driving, fog and rainy seasons.
- Driving trials with new vehicle models for articulated vehicles can be carried out and analysed its response under different weather conditions.
- By using the established Driver model, larger number of driving trials can be conducted to understand the effect of driving at different speeds, different road friction surfaces and so on.

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url: https://se.mathworks.com/help/vdynblks/index.html?category=index s tid=CRUX gn documentation index

Appendix

DRIVING TRIAL FEEDBACK FORM

Driver Name: **Date:** **Trial No:**

1. How comfortable did you feel driving over the bridge?

Unacceptable comfort (1) Uncomfortable (5) Very comfortable (8)

0 1 2 3 4 5 6 7 8 9 10

Not possible to grade (0) Very uncomfortable (3) Comfortable (6) World class comfort (10)

2. Did you experience any motion sickness while driving in the simulator?

0 1 2 3 4 5 6 7 8 9 10

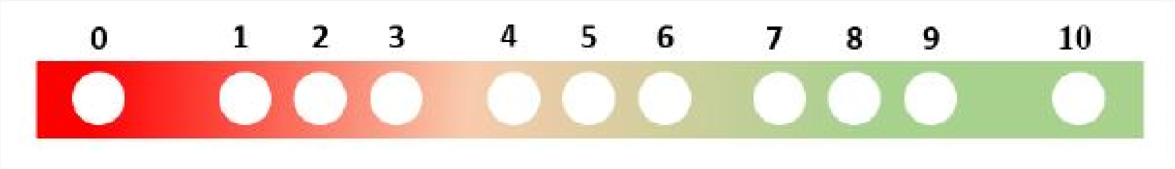
3. How was your experience with respect to lane change maneuver?

0 1 2 3 4 5 6 7 8 9 10

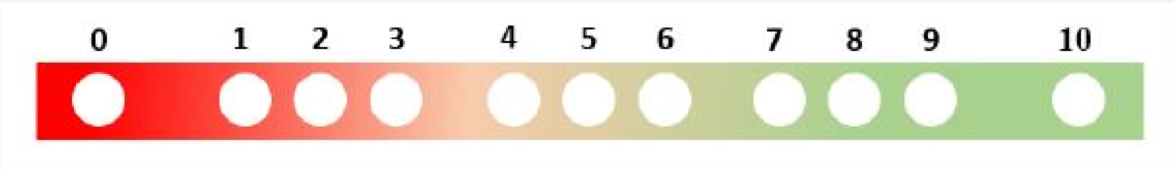
4. How was your experience with respect to the handling of the vehicle during the overtaking maneuver?

0 1 2 3 4 5 6 7 8 9 10

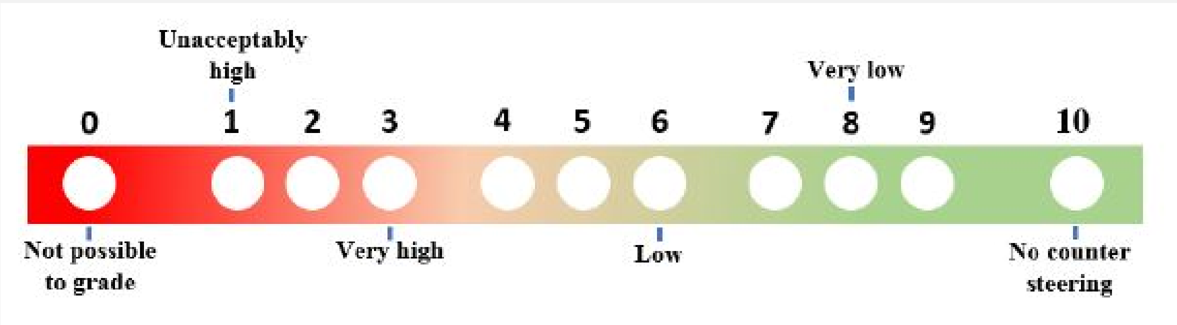
5. Were you able to stay in the lane while driving over the bridge?



6. How comfortable would you be driving under these conditions with significant amount of vehicle traffic around you?



7. How much counter steering did you feel was necessary while driving over the bridge?



8. Did you have any previous experience of driving in a vehicle simulator with motion?

◯ Yes ◯ No

Any other feedback or comments: