

Aerodynamic Interaction Effects and Surface Pressure Distribution During On-Road Driving Events

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ABSTRACT

Temporal changes of the onset flow field during on-road driving events, such as overtaking and passing, causes a complex interaction between aerodynamics of two vehicles. This can affect vehicle dynamics as well as steering input from the driver. In extreme situations this can cause a risk to driving comfort and safety. In order to optimize the shape of a vehicle, a fundamental understanding of the underlying pressure distribution during these scenarios is necessary. This paper describes the experimental method to measure the surface pressure and vehicle motion during overtaking a vehicle and passing a vehicle on a proving ground. Two primary vehicles, a C-Hatchback and a B-Crossover, were instrumented and a medium sized van and a 3.5 t truck were used as secondary vehicles without instrumentation. The highly asymmetric pressure distribution acting on the primary vehicles during the driving events is characterized using a simplified illustration method. The pressure experienced by the test vehicles were qualitatively the same, but were more severe when passed or overtaken by vehicles with a larger displacement area and corresponding vehicle front end pressure field.

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1. INTRODUCTION

Car manufacturers using the traditional tools such as Computational Fluid Dynamics (CFD), wind tunnel testing or a combination of both for vehicle aerodynamics development (i.e. [1]). Automotive wind tunnels are trying to ensure a high airflow quality associated with a low turbulence level. Some of the reasons for this idealized environment are the lack of a thorough description of "on-road" conditions and the complexity of implementing appropriate turbulence generators. However, the conditions found on-road are far more complex than could be reproduced to date in a full-scale wind tunnel facility. The on-road environment is influenced by temporal and spatial variations of the natural wind relative to the driving direction and cross-winds. In addition, obstructions next to the road, wake shedding and pressure interactions caused and influenced by other vehicles are influencing the on-road environment.

Specific events of overtaking and passing of two vehicles on-road, as shown in Figure 1, represent a complex environment for vehicle aerodynamics. Several attributes need to be looked at when considering the investigation of the "real world" aerodynamic environment. It includes, on-road turbulence and pressure transients, crosswind and resulting relative yaw angles to the vehicle, and the interaction between pressure fields of other vehicles [2],[3].

Fortunately, the area of unsteady aerodynamics and on-road environment has been well explored by numerous studies and advances in test methods and facilities, as summarized below.

Extensive work on the investigation and categorization of turbulence in different on-road terrains and traffic conditions has been published by Wordley and Saunders [2]. Measurements were carried out using a multi-hole pressure probe mounted on the front of a test vehicle. A correlation has been determined, in which dominant turbulence intensities and turbulence length scales are influenced by terrain type, road side obstacles and wake interaction between other vehicles on-road.

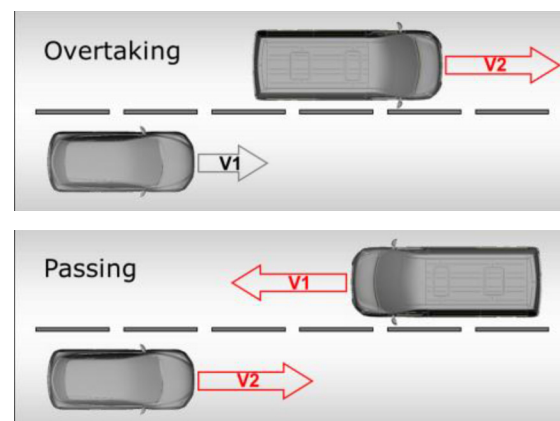


Figure 1. Schematic of the overtaking and passing event on-road.

A large diversity of research work relating to the on-road environment was reviewed and categorized by Sims-Williams [4]. He presented an overview of the on-road unsteadiness, its effects and the capabilities of different simulation tools and was able to compare different works to each other. He concluded that on-road conditions with turbulence length scales of 2-20 vehicle lengths can be seen as

the most important and critical for the impact on vehicle stability and comfort, and are high enough that they cannot be simulated in a steady environment.

There is a need for a more advanced approach to simulate on-road transients and to develop vehicles which are robust for the environment conditions, experienced for customer use. A turbulence generation system was implemented in a model scale, $\frac{3}{4}$ open jet wind tunnel at Durham University [5]. The TGS is able of reproducing on-road conditions with yaw angles of up to $6-8^\circ$ corresponding to a lateral turbulence intensity of 8-10% with a frequency range up to 10Hz and can be programmed for specific events measured on-road. Nowadays, even full-scale wind tunnel facilities offer the capabilities to test under the influence of controlled turbulent flow by means of active devices placed in the nozzle area of the wind tunnel. Two examples of such facilities are the Pininfarina wind tunnel in Italy and the full-scale wind tunnel at the FKFS in Germany. A thorough description of the Pininfarina wind tunnel is published by Cogotti [6] and Carlino et. al [7], whereas a description of the FKFS wind tunnel is published by Schröck et. al [8].

On-road and wind tunnel measurements by means of surface pressure measurements allow time-dependent recording of unsteady effects. Mayer et al, [9], conducted controlled experiments in a wind tunnel with TGS and on-road measurements. It was concluded that wind tunnel tests were more accurate, but unsteady forces and moments achieved were small. On-road test accuracy is lower, but the measured results are more representative for natural gusts. The admittance, which is the relationship between the sensitivity of unsteady forces and moments to steady forces and moments, was seen to be more useful in the wind tunnel. The on-road measurements did not show differences in the admittance for different vehicle configurations due to a lack of sensitivity.

A specific on-road environment that combines all aspects of real world unsteadiness, and that can lead to instability between the vehicle and driver system, is the overtaking event of two vehicles. A thorough investigation using a scale wind tunnel setup and generic vehicle models was conducted by Gillieron and Noger [10]. It was shown that the side force impact of the overtaking vehicle was imposed on the overtaken vehicle with a phase shift. The amplitude increased with increased relative overtaking velocity.

Howell et al, [11], used a scale model wind tunnel to setup a quasi-steady experiment to investigate the loads applied on to a small car by a truck during overtaking. It was concluded that the pressure field generated by the front end of the truck has the highest impact on the car's aerodynamic characteristics. In addition, the effects of a superimposed crosswind were measured, resulting in an increase of the forces and moments when the car was on the leeward side of the truck.

A generic overtaking simulator, implemented first in a scale model and finally in a full scale wind tunnel, was introduced by Van Grevenynghe and Noger, [12]. The work resulted in a methodology to

measure the aerodynamic sensitivity of road vehicles in an overtaking event for vehicle development in a full scale wind tunnel environment. The metric used for characterization was rate of change of side forces and yawing moments. The final generic box shape displacement body can be traversed next to the test vehicle and was proven to generate the same flow topology as the model truck.

The study presented in this paper focuses on vehicles exposed to asymmetric flow fields leading to a temporary disturbance on the vehicles motion. These disturbances occur during overtaking and passing manoeuvres and cause a complex aerodynamic interaction. Furthermore, vehicle dynamics, driving comfort and in extreme situations, driving safety might be impaired, [13].

The asymmetric pressure distribution around the vehicle and the temporal change in forces and moments might lead to a required steering correction of the driver which can lead to instability of the driver-vehicle system, [14]. Therefore, information of the pressure acting on the vehicle and the rate of change of vehicle moments are key indicators on the robustness of vehicles in on-road conditions.

In order to develop vehicles with a low sensitivity to transients and on-road disturbances, a sound understanding of the mechanisms during specific events needs to be acquired first. This paper aims to give a brief description of the experimental setup used for measurements of surface pressure and vehicle motion during overtaking and passing events. The experiment was conducted on-road on a proving ground.

Surface pressure and vehicle motion data were recorded on a C-hatchback (Nissan Tiida) and a B-Crossover (Nissan Juke) whilst overtaking or passed by a mid-sized van (Nissan NV400) and a small truck (Renault Midlum). Surface pressure and vehicle motion data on the van and truck were not measured and only served as secondary vehicles to generate the aerodynamic interaction effects. An overview of the vehicle dimensions is given in [Table 1](#).

This paper is based on previous work, [15], which focused on initial results from overtaking and passing between the C-hatchback and the van only. In this paper more detailed cases are presented, such as effects of vehicle distance, shape and speed, in order to give a more thorough description of the findings.

The objectives of this project are to supply experimental data of surface pressure and vehicle motion for the validation of a CFD model developed by Hokkaido University. In the future, correlation to a multi-physical CAE tool including aerodynamics and vehicle dynamics and the introduction of an advanced development process with a driver model will be possible. Only the results from the experiment and some first results of the correlation with CFD simulations are presented in this paper.

Table 1. Dimensions of the primary instrumented vehicles, (Car A, Car B), and secondary vehicles, (Van, Truck), without instrumentation.

		Image	Length [mm]	Width [mm]	Height [mm]
Car A	Nissan Tiida		4250	1685	1535
Car B	Nissan Juke		4125	1765	1570
Van	Nissan NV400		5560	2470	2500
Truck	Renault Midlum		6705	2470	2640

2. EXPERIMENTAL SETUP

Honeywell 40PC pressure transducers were installed in predetermined locations on the front, body side, roof and rear of car A and car B. The transducers have an accuracy of 0.2% corresponding to $\pm 0.027 c_p$. In order to reduce the signal noise and phase shift from the transducers a 50mm tube was added between the body hole and the transducer. The resonance frequency of the tube is in the order of 1.7 kHz and has no impact on the measurement results. All pressure signals were zeroed when driving at test speed but away from the influence of overtaking and passing. All results presented in this paper stand for the Δc_p pressure difference and not the absolute values. The reported Δc_p values are based on the driving speed of the primary test vehicle. A more detailed description of the experimental setup can be found in [15].

To capture the motion of the test vehicles, data from a Tokyo Keiki motion and GPS sensor were logged with a Keyence data logger at 1000 Hz. An optical distance sensor measured the relative position between the two test vehicles and was mounted on the front wheel fender area on the vehicle. It also served as reference point for the data analysis. A schematic of the location of the pressure transducers, distance sensor and camera guidance system as installed on car A is shown in Figure 2.

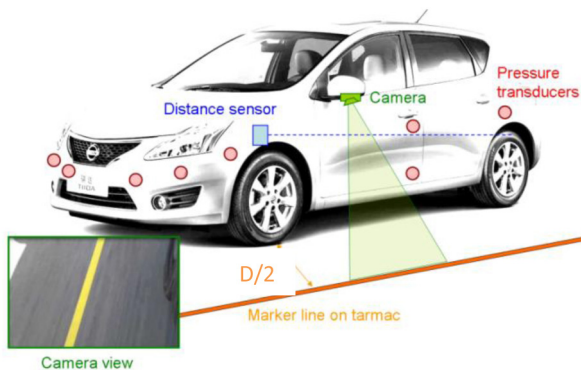


Figure 2. Illustration of the test vehicle and experimental setup.

The IDIADA Applus proving ground near Barcelona, Spain was chosen for this test as it has a long enough flat test track (1.6 km) and low crosswind conditions all year long. All tests were conducted on the straight section of the Dynamic Platform A, [16].

Both vehicles followed a guide marker line which was applied on the tarmac. A camera mounted on the door mirror provided a live image to the driver keeping the vehicles on the desired path and distance. With this procedure the driver could monitor the relative position of the vehicle to the marker line and keep the vehicle close enough along the straight line and the distance between the test vehicles could be maintained. This method proved to be reliable for the purpose of this first experiment. Each procedure for overtaking and passing was repeated four times, twice from each direction. The drivers for both the instrumented vehicle and the secondary vehicle were not changed.

At this point it is to be emphasized that transient ambient wind conditions at the location of the test vehicles were not recorded nor corrected. Also, due to simplification, no steering torque was measured. Therefore, the results for vehicle motion include the driver and vehicle reaction as a whole system.

3. RESULTS FOR OVERTAKING

The test procedure and the chosen test equipment has been determined adequate for its purpose: the test data delivered sensible results that can be used for further studies, whilst the test procedure was robust and repeatable to be used as a guideline for future testing. In line with predictions made prior to the tests, the surface pressure measured during the maneuvers was determined to be highly asymmetric. A noticeable vehicle response could be observed subjectively for all tests.

Post processing of the data comprised of a simple low pass filter to diminish spurious noise signals above 10 Hz. The results for different scenarios will be described in the following.

3.1. Van Overtaking a Car

It was believed that the most severe scenario is when the van is overtaking the car due to the van's larger displacement and therefore more pronounced change in flow field against the car. In the proving ground experiment, car A was traveling at a speed of 100 km/h and was being overtaken by the van at 130 km/h. The measurements recorded surface pressure and vehicle motion for the car A only. The distance between the vehicles was approximately 0.6 m. The door mirror on the van and car A are located in different positions in Z and therefore a possible collision of the mirrors was precluded. Figure 3 shows a description of the vehicle orientations where x denotes the distance from the rear end of the car to the front end of the van.

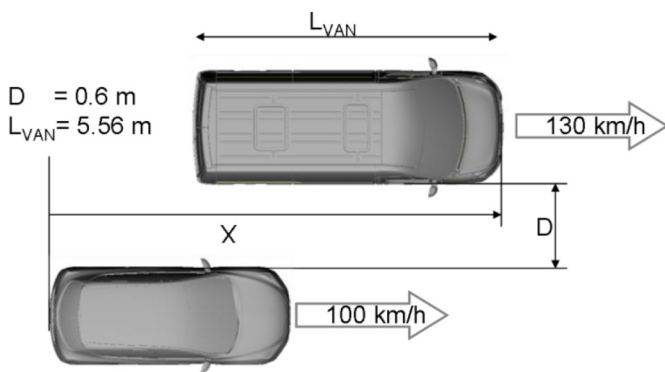


Figure 3. Schematic of the overtaking specification.

The change in the pressure distribution as recorded by the surface pressure transducers during the overtaking manoeuvre for the front left fender, left door and left rear fender is given in Figure 4. The graph can be read as the van overtaking the car A from left to right and with the distance given for the overtaking event between $X/L_{VAN} = -1$ and $X/L_{VAN} = 2.5$. The pressure is given in pressure difference (as mentioned earlier the pressure signal was zeroed) and not the absolute surface pressure to highlight only the effects caused by the overtaking event alone. Figure 4 shows distinctive pressure signals for each measurement position. The pressure increases to a maximum slightly before the van front end has reached the position, followed by a sudden drop in pressure and a pressure recovery thereafter. The highest peak to peak pressure change is recorded for the door position.

The pressure distribution on the front and rear of the car is given in Figure 5 and 6 respectively. On the front left corner, the positive pressure increase is the highest for the front. The pressure on the front centre and front right corner are only slightly influenced due to the overtaking event. The evolution of the pressure on the rear of the car is similar for all measurement positions with an increase of negative pressure from $X/L_{VAN} = -0.25$ to $X/L_{VAN} = 1.5$. It can be noticed that the highest pressure changes occurring when the van is approximately half way next to the car. In the following a more detailed description of the overtaking event is given.

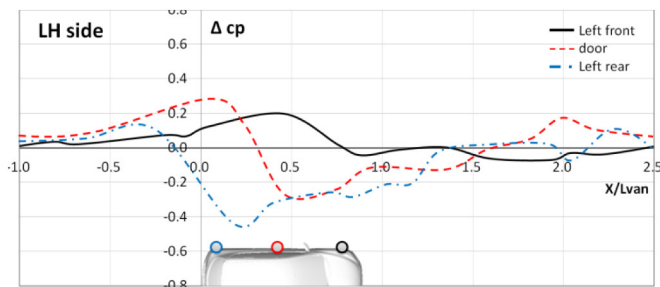


Figure 4. Change in pressure on the left side of the car A as the van is overtaking.

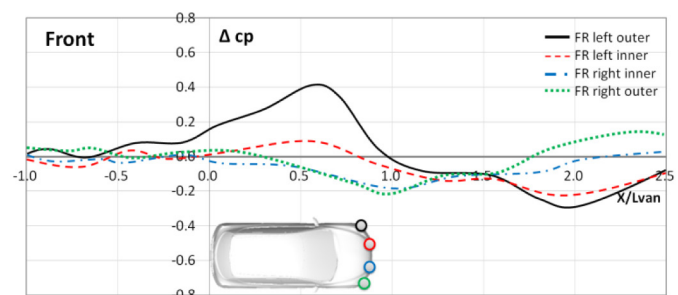


Figure 5. Change in pressure at the front of the car A as the van is overtaking.

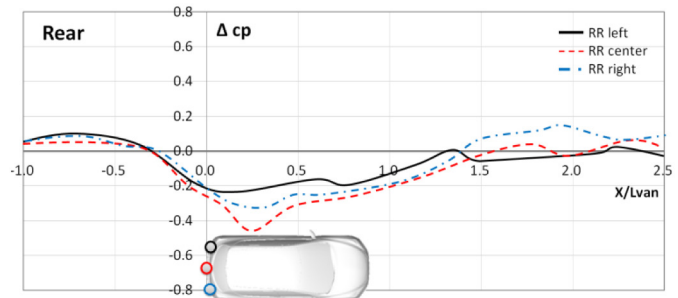


Figure 6. Change in pressure on the rear of the vehicle as the van is overtaking.

It is of interest to discuss the change of pressure of all locations around the car during the overtaking event, however quite confusing to be illustrated in one single pressure plot. Therefore, a simplified schematic during specific overtaking snapshots is illustrated in Figure 7. The schematic shows frames as the van is overtaking the car with the sequence starting on top left and moving downwards. Surface pressure is indicated in red colour for positive pressure and blue for negative pressure respectively. The pressure change is given for 13 transducers located approximately around the waist line of the vehicle. The flow field and pressure distribution on the car as experienced for this case of overtaking is explained in the following.

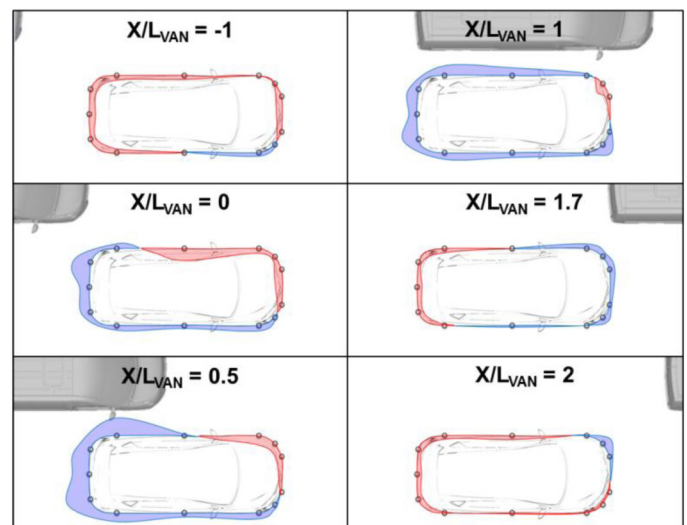


Figure 7. Simplified illustration and snapshots of the pressure distribution as measured along the waist line of the car A during the overtaking maneuver.

$$X/L_{VAN} = -1$$