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LTR-AL-2014-0013

July 14, 2014

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Abstract

Through its ecoTECHNOLOGY for Vehicles (eTV) program, Transport Canada has commissioned a study to investigate safety implications of using boat-tails for the drag reduction of heavy-duty vehicles (HDVs) on Canadian roads. A wind tunnel study was carried out in 2012 to investigate the dynamic wind loads experienced by passenger vehicles travelling in the wake of a boat-tail-equipped HDV. Two passenger-vehicle models, representing a compact car and a sport utility vehicle, were placed in the wake of a 1/10-scale tractor + dry-van-trailer model and the dynamic wind loads experienced by the vehicles were measured with and without different combinations of boat tails and side skirts. The results of this study have shown that the addition of a boat-tail to the base of an HDV trailer can increase the dynamic wind loads related to directional stability of a following vehicle.

This report presents the results of vehicle-dynamic simulations using the wind loads measured in the wind tunnel as an input to evaluate the impact on the directional stability of the vehicle. The simulations were performed using the SIMPACK Automotive model software which is a suitable tool used for vehicle-dynamic analysis. The cases that have shown the largest amplification of the dynamic wind loads in the wind tunnel, especially for the side force and yawing moment, were selected to evaluate the impact on vehicle stability. For this study, the influence of road-friction and driver-response were additionally varied to identify any scenarios in which the presence of a boat-tail-equipped heavy vehicle may influence the stability of the vehicle in the wake.

This study revealed that the amplified wind loads, as measured on a vehicle following a tractor-trailer equipped with a boat-tail, did not adversely influence the lateral stability of the vehicles studied. This conclusion is mainly based on the results obtained for the lateral deviation and the wheel reaction force and their limit values as defined in this report.

Table of Contents

List of Figures

List of Tables

Nomenclature

Symbols:

A	area [m^2]
C_D	drag-force coefficient $\left(= \frac{F_D}{1/2\rho U_{ref}^2 A}\right)$ [ ]
C_L	lift-force coefficient $\left(= \frac{F_L}{1/2\rho U_{ref}^2 A}\right)$ [ ]
C_P	pitching-moment coefficient $\left(= \frac{M_P}{1/2\rho U_{ref}^2 AL}\right)$ [ ]
C_R	rolling-moment coefficient $\left(= \frac{M_R}{1/2\rho U_{ref}^2 AL}\right)$ [ ]
C_S	side-force coefficient $\left(= \frac{F_S}{1/2\rho U_{ref}^2 A}\right)$ [ ]
C_Y	yawing-moment coefficient $\left(= \frac{M_Y}{1/2\rho U_{ref}^2 AL}\right)$ [ ]
F	force [N]
L	length [m]
M	moment [Nm]
U	wind speed [m/s]
ρ	air density [kg/m^3]

Acronyms:

eTV	ecoTECHNOLOGY for Vehicles
FFT	fast fourier transform
GHG	greenhouse gas
HDV	heavy duty vehicle
IFFT	inverse fast fourier transform
MBS	multi-body simulation
NRC	National Research Council
PSD	power spectral density
rms	root-mean-square
SUV	sport utility vehicle
TC	Transport Canada
VEH	(VEH)icle-only configuration

1. Introduction

Boat-tails have been demonstrated to provide a fuel savings for combination vehicles employing dry-van trailers, and in recent years their use on North-American roads has increased. Transport Canada, through its ecoTECHNOLOGY for Vehicles program, has been working with the National Research Council Canada to investigate the use of boat-tails on Canadian roads and in particular their potential aerodynamic influence on other road-users. A first study was carried out (McAuliffe, 2013) to examine the dynamic wind loads experienced by vehicles in the wakes of boat-tail-equipped heavy vehicles, and identify any influence of these loads on the following vehicles.

The wind-tunnel investigation in year 1 of the project (McAuliffe, 2013) was undertaken to measure changes to the unsteady structure of the wake of a boat-tail-equipped heavy vehicle, and to identify any differences in dynamic loads experienced by vehicles travelling in these wakes. Two passenger-vehicle models, representing a compact car and a sport utility vehicle, were placed in the wake of a 1/10-scale tractor + dry-van-trailer model and the dynamic wind loads experienced by the vehicles were measured with and without different combinations of boat tails and side skirts. The study examined the effects of 1) changes in boat-tail + side-skirt combinations, 2) the passenger vehicle type, 3) the following distance of the passenger vehicle, 4) the lateral offset of the following vehicle, 5) the cross-wind magnitude and angle, and 6) the level of turbulence in the wind. The results showed that the boat-tail had a strong influence on the magnitude of vortex-shedding strength experienced near the ground in the wake of the truck. In the frequency range over which this influence occurred (0.6 to 3.7 Hz for a full-scale vehicle travelling at 100 km/h) , increased dynamic wind loads related to directional stability of a following vehicle were observed.

It was therefore considered important to examine the impact of the amplified dynamic wind loads on the stability of the following vehicle using a vehicle-dynamic simulation, especially for frequencies higher than 0.5 Hz and related to vortex-shedding. A driver can withstand low-frequency gusts but, for frequencies higher than 0.5 Hz, the driver-vehicle response is unknown. A similar approach using vehicle-dynamic calculation has been used by other researchers in the past (Baker, 1986, Baker, 1988, Kobayashi and Kitoh, 1983) and was found efficient to evaluate the vehicle-response to external loads and the potential for vehicle instability.

This study was carried out in this second year of the project with vehicle-dynamic simulations that were obtained using the SIMPACK software package for 14 cases that were selected based on their amplified wind loads measured in the wind tunnel and/or for comparative purpose. For this study, the influence of road-friction and driver-response were additionally varied to identify any scenarios in which the presence of a boat-tail-equipped heavy vehicle may influence the stability of the following vehicle and its driver in a Canadian environment.

This report presents the work carried out for the vehicle-dynamic simulations setup with first the preparation of wind data used as an input for the simulations, the software setup, the definition of stability conditions, the results and analysis and, the conclusions.

2. Simulation Setup and Procedures

2.1 Test Cases

In the first year of the project (McAuliffe, 2013), wind tunnel tests were performed in order to quantify the dynamic wind loads experienced by a vehicle following a tractor-trailer under different conditions. A detailed description of the parameters are provided in McAuliffe, 2013. In summary, three vehicle types were used for the study: a tractor-trailer, a sport-utility vehicle (SUV) and a medium-size car, all of them being scaled by a factor of 1:10. The small vehicles were tested alone (VEH case) but most of the tests were done in the wake of a the tractor-trailer which had a standard trailer configuration or was equipped with a boat-tail and/or side skirts. Figure 2.1 shows on the left the vehicle alone (VEH case) and on the right, the vehicle positioned behind the tractor-trailer. Figure 2.2 shows on the left the trailer equipped with the (S)hort boat-tail and (L)ower (P)anel (SLP case) and on the right, the truck equipped with the (S)hort boat-tail, (L)ower panel and (S)ide skirts (SLS case).

Figure 2.1: Left: view from upstream of vehicle alone (case VEH), Right: view from downstream of vehicle and HDV model.

Measurements were performed for a range of wind angle from 0° to 8°, for different lateral position from ± 1 trailer length from the centreline, for different following distances from 0.5 to 3 vehicle lengths and, under smooth and turbulent flow conditions. In total, more than 1400 cases were tested to cover the different combinations of parameters enumerated above. An analysis of these results was presented in McAuliffe, 2013 and it was found that some cases have shown an important amplification of the dynamic loads especially for the side force coefficient and yawing moment coefficient. As discussed in Section 4.4 of McAuliffe, 2013, these two coefficients are of prime importance for the directional stability of the vehicle.

Figure 2.2: Photographs of 2 HDV configurations tested: Left: SLP: short boat-tail with lower panel, Right: SLS: Short boat-tail with lower panel and side skirts.

Tables 2.1 and 2.2 present the list of cases that were selected to perform the vehicle-dynamic simulations. The simulations combine the vehicle response, based on its geometry and mechanical components with driver capabilities, with the external loads applied to the vehicle to see if the driver-vehicle system has a stability issue which can lead to a loss of control. The cases listed in the tables were selected among all the tests performed in the wind tunnel because the results had indicated higher dynamic wind loads. All the runs selected were performed in turbulent flow. Turbulent flow conditions promoted larger variation in the low-frequency dynamic loads compared to similar test configurations done in smooth flow conditions but without significant effect of the turbulence on vortex-shedding strength. The VEH cases for both the SUV and the car were selected with the intention of comparing the response obtained from the vehicle-dynamic simulations for the vehicle alone with the vehicle following the tractor-trailer. The "boat-tail" case refers to the trailer equipped with a 4 panel boat-tail extending 2 feet (0.6 m) behind the trailing edge of the trailer.

Table 2.1: Runs selected to perform vehicle-dynamic simulations for SUV vehicle.

Run	Vehicle	HDV Config.	Wind angle	Lateral position (Y/W)	Following distance (X/L)
VEH259	SUV	none (VEH)	8 °	-	-
BAS424	SUV	Baseline	4 °	-0.25	3.0
BAS426	SUV	Baseline	8 °	-0.25	3.0
SLP392	SUV	Boat-tail	0 °	0	2.0
SLP416	SUV	Boat-tail	4 °	0.5	2.0
SLS420	SUV	Boat-tail+side skirts	4 °	-0.25	3.0
SLS442	SUV	Boat-tail+side skirts	8 °	0.5	1.0

Table 2.2: Runs selected to perform vehicle-dynamic simulations for a car vehicle.

Run	**Vehicle**	**HDV Config.**	**Wind angle**	**Lateral position** (Y/W)	**Following distance** (X/L)
VEH264	CAR	none (VEH)	8 °	-	-
BAS280	CAR	Baseline	8 °	-0.5	3.0
BAS326	CAR	Baseline	0 °	0.25	3.0
SLP369	CAR	Boat-tail	0 °	0	2.0
SLP371	CAR	Boat-tail	0 °	0	3.0
SLS273	CAR	Boat-tail+side skirts	0 °	0	2.0
SLS318	CAR	Boat-tail+side skirts	8 °	0.5	1.0

2.2 Data Processing

The dynamic loads obtained from the wind tunnel tests for different HDV/SUV and HDV/CAR configurations required some processing before they could be used as an input for the vehicle dynamic simulations. The following steps describe the data processing:

1) After a preliminary analysis of the dynamic load data, it was found that many runs were affected by a mechanical resonance which was translated into a peak in frequency for the six aerodynamic components measured on the vehicle with a fast-response six-component force/torque sensor (McAuliffe, 2013). The resonance occurred in the range of 50-70 Hz and was associated with vibrations of the wind tunnel ground board system or the motion of the lateral traverse rig system used to move the vehicle behind the HDV. The effect was described in Section 3.3 of McAuliffe, 2013. To filter this resonance from the data, the frequency peak was fitted with a mechanical admittance function which represents the single degree-of-freedom mechanical resonance. The original time series was split in blocks of appropriate length and the fast-Fourier Transform (FFT) of each block of the time series was divided by the admittance function before being converted back in the time domain using the inverse fast Fourier transform (IFFT). All blocks of time series were re-combined together to obtain the filtered time series. Figure 2.3 shows an example of the fit function with the original and, the filtered spectrum for the six wind loads.

2) The corrected time series were low-pass filtered at 80 Hz using a Butterworth digital filter. The energy contained in the range of frequencies higher than 80 Hz is not relevant for this study. Phenomenon related to vortex shedding or other flow structures that developed around the vehicle model occured at a lower frequency.

3) A peak of energy was also observed for many cases between 0-10 Hz which was attributed to the presence of the free-stream turbulence. The aerodynamic loads as measured on the vehicle were sensitive to the free-stream turbulence and this was reflected in the lower range of frequency. The turbulence system used during this wind tunnel test campaign provided an intensity of the vertical component of the turbulence that was large compared to what would be expected on the road for a vehicle. The aerodynamic response of the vehicle to this

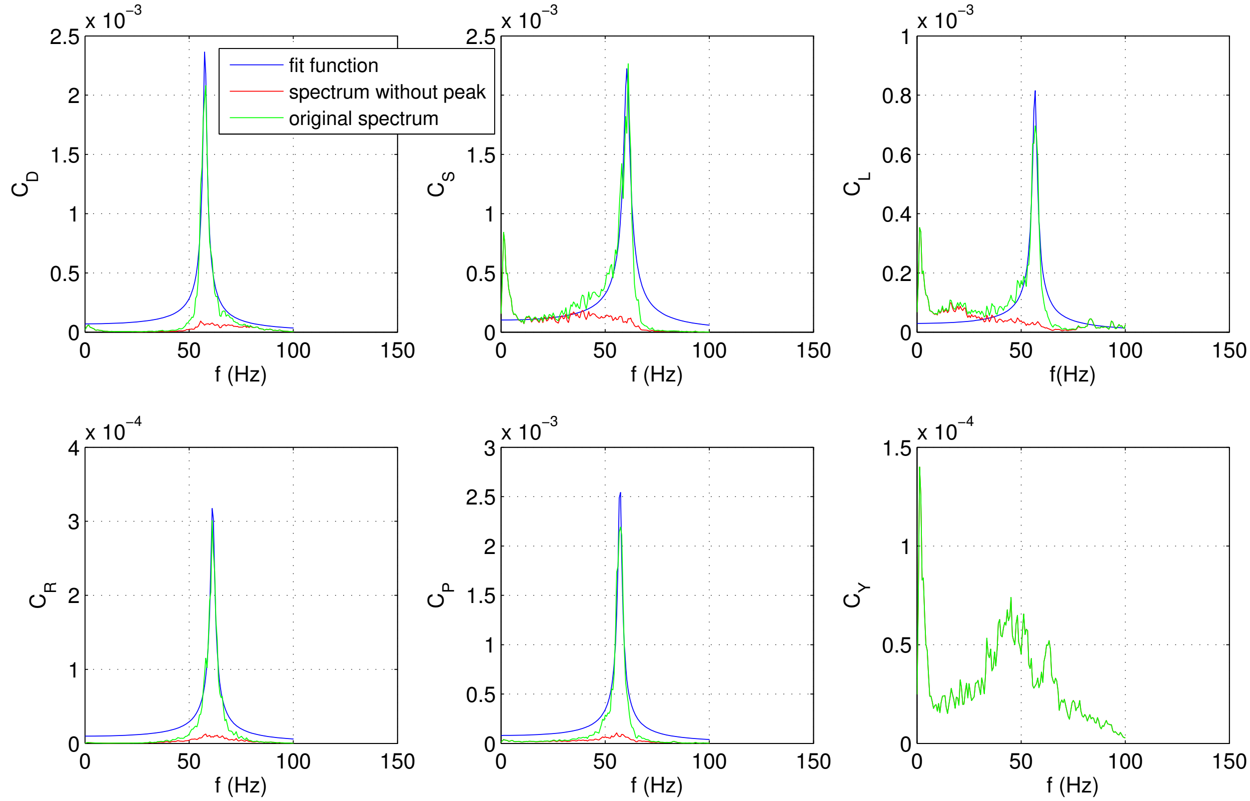

Figure 2.3: Spectrum of the six aerodynamic components for the case of the SUV following the baseline HDV (BAS424) with a fit function for the mechanical resonance peak.

turbulence was therefore amplified to some extent at low frequency, especially for the lift force and pitching moment. A correction was applied to the aerodynamic loads and moments using a high-pass digital filter at 3 Hz which allowed to reduce the energy in the range 0-10 Hz to a level in between the turbulent and smooth flow conditions.

Figure 2.4 shows an example of the original spectra of the aerodynamic coefficients and the resulting spectra after the data processing was applied to remove the non-relevant content.

4) The mean value of the drag coefficient obtained during this wind tunnel investigation for the different cases was affected by the presence of the lateral traverse actuator behind the model. The presence of the actuator affected the wake of the model and contributed to lower value of the mean drag coefficient than what would be expected for a similar model. As well, the geometry of the models was simplified for fabrication purpose with sharper edges at the front and back of the vehicles. This contributed to increase the value of the lift coefficient and pitching moment compared to values expected based on the experience of testing vehicles in the wind tunnel for similar vehicle shapes. An appropriate offset was therefore applied to C_D, C_L and C_P. The offsets were calculated based on the difference between the averaged value of previous wind tunnel tests for similar vehicles and the mean value obtained during the test for the VEH case which is the vehicle alone without the HDV in front. For the SUV, the average

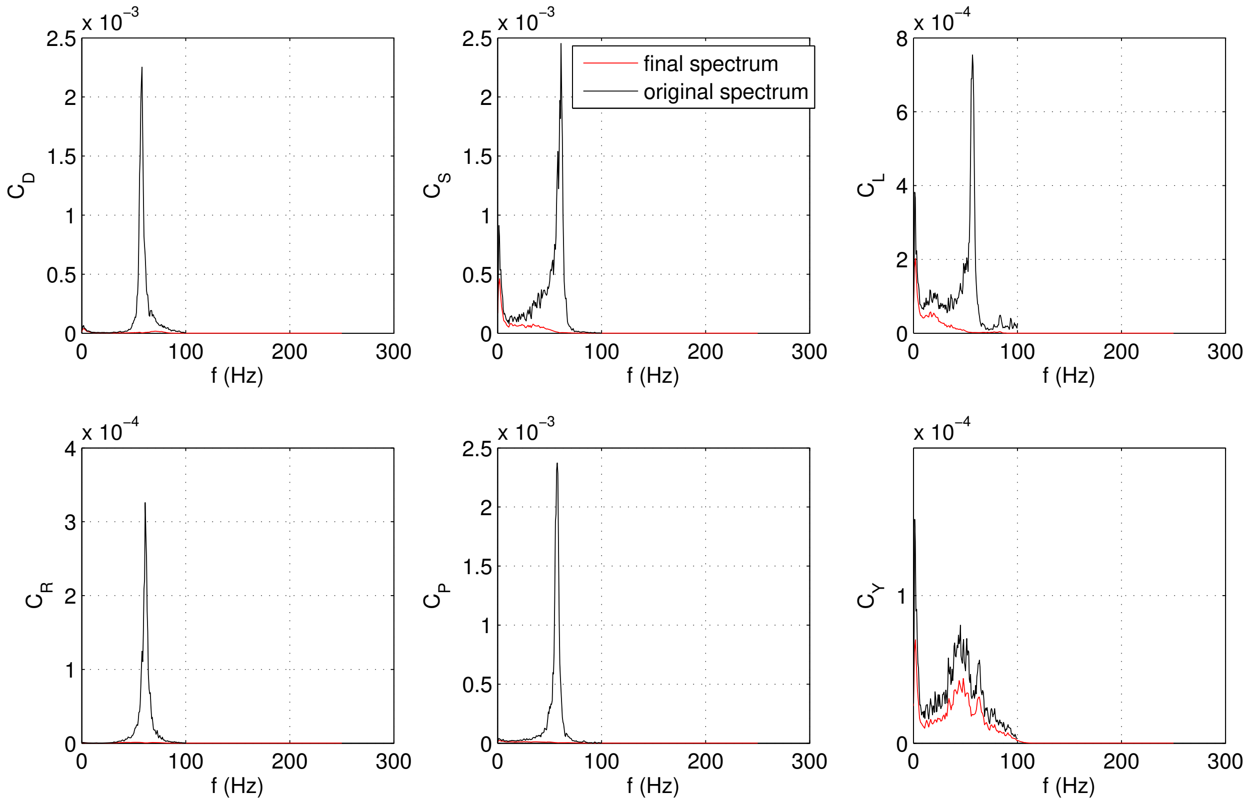

Figure 2.4: Spectrum of the six aerodynamic components for the case of the SUV following the baseline HDV (BAS424) compared with the final spectrum peak filtered and low frequency content reduced.

values used at 0 ° wind angle were C_D of 0.41, C_L of 0.2 and C_P of -0.2. For a car, the average values used at 0 ° wind angle were C_D of 0.31, C_L of 0.2 and C_P of -0.15.

5) The force and moment coefficients were used to calculate the representative forces on a full-scale vehicle travelling at 100 km/h. It represents highway driving conditions. The forces and moments were appropriately scaled to full size using the full scale frontal area of the vehicle and the full scale length of the vehicle. The sampling time during the wind tunnel tests, for a model at 1:10 scale and a wind speed of about 42 m/s, was 30 seconds which in full scale is converted to a period of about 465 seconds for a wind speed of 100 km/h.

A second set of data was also prepared to obtain forces and moments at 80 km/h. These results were used for the vehicle-dynamic simulations for cases with low coefficient of friction of the road-tire (0.2-0.3) as it is expected that this reduced speed would be more appropriate for such conditions.

6) The time series of the wind forces and moments were also modified to allow the simulation to stabilize before the wind loads were applied. An artificial no-wind condition that was created for the first 40 seconds of the input time series. Between 40 and 50 seconds, the wind

forces were gradually increased from zero to the mean value of the signal followed by an amplification to reach the maximum variation of the signal. After 50 seconds, the actual wind loads were used as an input for the simulations. This procedure provided a better vehicle-dynamic response to the input signal using a progressive increase of the wind loads. To obtain meaningful data, the statistical values of the vehicle-dynamic simulations response were calculated based on the results from 100 seconds up to the end of the time series.

2.3 SIMPACK software

SIMPACK, originally developed by German Aerospace Centre, is a general purpose Multi-Body Simulation (MBS) software used for the dynamic analysis of any mechanical or mechatronic system. It enables engineers to generate and solve virtual 3D models in order to predict and visualize motion, coupling forces and stresses.

The SIMPACK Automotive model is used for the dynamic analysis, prediction and optimisation of all automotive mechanical and mechatronic components and vehicles. SIMPACK's ability to simulate high-frequency vibration and harsh shock contact, in both the frequency and time domain, were important considerations when choosing simulation software for this project.

The SIMPACK Automotive model in time domain was used for this study. The low frequency dynamic handling analysis was performed under various wind conditions. In the multi-body model, vehicle body, suspension components and tires etc. are all modelled by their centre of gravity positions, masses and moments of inertia in order to describe the relative motions following the physical laws. These components and body are connected by characteristics of stiffness and damping components of each type of vehicle. The tire/ground behaviour is modelled by a well-known and well-validated magic formula model. All physical links in the steering system are included to yield a correct steering ratio. The time histories of wind forces measured during the wind tunnel tests were applied to the centre of the body.

The influence of wind on steering stability can be studied through real-world tests, but the inability to control the ambient winds makes it a difficult and lengthy process. With a well-developed SIMPACK model, simulation runs can be performed with identical environmental conditions (with the exception of the wind forces). Also, important responses such as tire-ground forces, which are difficult to measure in road test, can be used in the evaluation and comparisons.

To understand the influence of a boat-tail on the steering stability of a following vehicle, a dynamic simulation approach using Simpack has been selected as an appropriate evaluation tool.

Two vehicles were used in the simulations: a SUV and a compact car. Figure 2.5 shows the vehicles representations as modelled in the software.

A Toyota Highlander was used to represent a typical SUV and a Honda Civic Sedan was used to represent a typical compact car. Table 2.3 provides the geometric parameters of the SUV

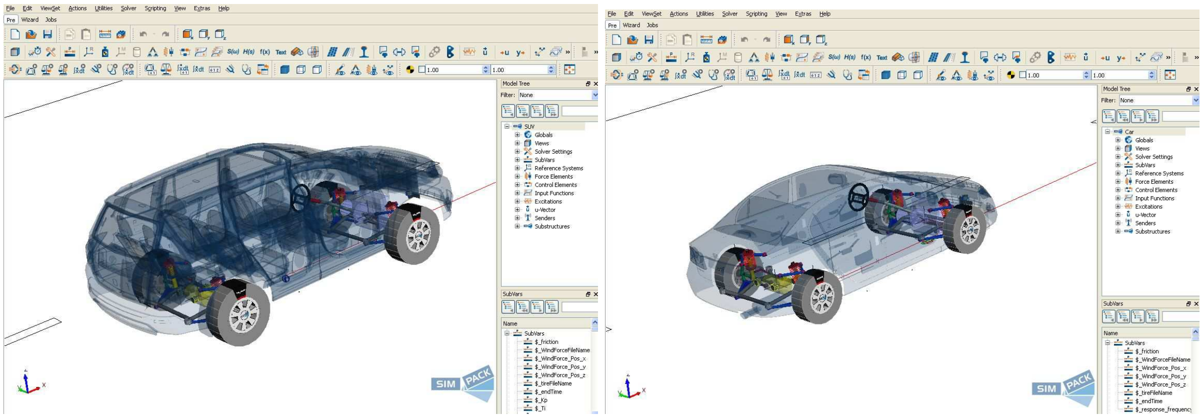

Figure 2.5: SIMPACK vehicle models: SUV and car.

and car used in this study.

Table 2.3: Specifications of the SUV and car models used for the SIMPACK simulations.

	SUV	**CAR**
Wheel drive system	4WD	FWD
Wheelbase	2.79m	2.67m
Track (Front / Rear)	1.625 m	1.499 m / 1.522 m
Width	1.91 m	1.752 m
Height	1.76 m	1.435 m
Length	4.785 m	4.556 m
Steering ratio	17	14.89
Tires	P245/65/R17	P195/65/R15
Curb weight	1895 kg	1285 kg

2.4 Stability conditions

To assess the potential for vehicle stability problems, a definition of the parameters that describe the vehicle stability and typical limit values of these parameters are required. It was found in the literature that important criteria for directional stability of a vehicle are associated with the vertical reaction at the four wheels, the lateral deviation and the angular deflection (Baker, 1986, Baker, 1988). It will be assumed in this report that the limit values for those three criteria will be as follow:

1) vertical reaction at the four wheels should be higher than zero and pointing downwards to avoid a situation where the vehicle is partially lifted from the road and the driver being unable to keep the vehicle in the desired direction. The vertical reaction is a combination of the weight of the vehicle and its response to the external load (lift force, pitching moment, rolling moment);

2) the lateral deviation of the vehicle (relative to the main vehicle path) should not exceed 0.5 m within a 0.5 second wind gust (Baker, 1986);

3) the angular deflection of the vehicle should not exceed 0.2 radian within a 0.5 second wind gust (Baker, 1986).

The limit values defined by Baker, 1986 were established for a bus. It is considered conservative to use similar values for a car or a SUV, which are smaller vehicles, and should be less affected in a cross-wind flow environment.

Since it is expected that these values will be affected by the driver capabilities as well as the coefficient of friction of the road/tire and as such, both parameters were varied in the simulations.

3. Results and Analysis

3.1 Results

The results of the vehicle-dynamic response provided by the SIMPACK software were given as time series of parameters that describe the dynamic response of the vehicle to wind loads:

1) the lateral deviation: represents the side motion of the vehicle due to the external loads.
2) the lateral acceleration: represents the side-to-side acceleration of the chassis of the vehicle (without lateral vehicle acceleration) due to the external loads applied on the vehicle.
3) the force ratio: represents the ratio of the maximum lateral wheel force to the lateral wheel force limit. The lateral wheel force limit is calculated based on the vertical force on the wheel and the coefficient of friction of the road/tire. A force ratio value close to 1 means that the vehicle can side-slip because the lateral wheel force is of similar magnitude than the lateral wheel force limit that is the opposite force. A force ratio value closer to 0 means that the lateral wheel force limit is large enough to counteract the lateral force applied on the wheel.
4) the steering wheel angle: represents the angle at which the driver has positioned the steering wheel.
5) the slip angle on the 4 wheels: represents the angle between the wheel main axis and the main direction of the vehicle. It will be used as an indicator for the angular deflection of the vehicle.

The simulations were performed with the variation of two input parameters: the coefficient of friction of the road/tire and the steering angle velocity. The coefficient of friction of the road was varied from 0.2 to 1.0 for the SUV and from 0.3 to 1.0 for the car. This range represents the conditions experienced by a vehicle on the road with 0.2-0.3 being slippery-icy conditions, 0.5 being wet conditions and 1.0 being dry road conditions (Wong, 2001). The steering angle velocity represents one parameter that describes the driver capability to react under unexpected loads acting on the vehicle due to change in the external conditions (wind or road). The range of steering angle velocity used to perform the vehicle-dynamic simulations was from $45^\circ/s$ to $400^\circ/s$. The initial steering angle velocity range used was from $45^\circ/s$ to $90^\circ/s$ based on SIMPACK recommendations which should cover the range of typical response rates from drivers. However, after an analysis of the preliminary results and, an additional literature search (Uno and Hiramatsu, 2001, Day and Metz, 2000), it was found that steering rates between 90 and 400 deg/s are typically used for evaluation of the response of a vehicle/driver system to unexpected events. It would have been advantageous to use additional input parameters to describe the driver capabilities, such as the reaction delay time for example. However, the SIMPACK software package did not offer this possibility.

3.2 Effect of coefficient of friction of the road

Figures 3.1 and 3.2 show the results of the effect of the coefficient of friction of the road/tire (hereafter named coefficient of friction) obtained from the vehicle-dynamic simulations for the SUV and for the car respectively, for four dynamic response parameters of the vehicle: maximum lateral deviation, the force ratio, the root-mean-square (rms) of the lateral acceleration and the maximum steering wheel angle. In general, the results indicate that the response of the vehicle was always negatively affected with a decrease of the coefficient of friction. Also, the results were generally worse for the SUV than for the car. Specifically, it was observed that:

1) the maximum lateral deviation was for a coefficient of friction of 0.2 with a deviation of about 0.6 m when a vehicle was travelling behind the HDV. However, the lateral deviation seems to be always larger for the case of the vehicle alone. One case ran at a coefficient of friction of 0.3 indicated that the maximum lateral deviation of the SUV could reach about 1 m. It is important to note that the vehicle-only case for the SUV was for strong gusty cross-wind conditions (8°) and therefore the mean side force and yawing moment had large values compared to the other cases for which simulations were performed. A look at the time series of the lateral deviation of the vehicle indicated that one period of lateral motion was completed in a minimum amount of time of 5 seconds which translated into a frequency of motion of 0.2 Hz. The time series indicated also that the lateral deviation from 0 to 0.5 m occurred in a time period larger than 0.5 s which is above the criteria defined for the stability conditions in the previous chapter. Also, for a vehicle speed of 100 km/h, the longitudinal distance covered in 5 seconds is about 140 m which translates into a deviation of 0.4 ° for a maximum lateral deviation of 1 m from the centreline of the vehicle. This frequency of motion can be handled by drivers on the road (Day and Metz, 2000).

2) the force ratio had a trend similar to the maximum lateral deviation. The force ratio indicates if the vehicle will be susceptible to sideslip when its value is close to 1. The force ratio was found to be higher for a coefficient of friction of 0.2 and reduced when the coefficient of friction was increased up to 1.0, regardless of the simulation cases of vehicle travelling behind the HDV. The maximum force ratio was about 0.65. However, the results for the vehicle alone show that the force ratio can go as high as 0.82 for a coefficient of friction of 0.3. The results show that all for the cases simulated, with the vehicle behind the HDV or on its own, the vehicle will be able to sustain the external dynamic loads imposed to the vehicle for this study.

3) the rms chassis acceleration results were all below 0.35 m/s^2 which represents 0.035 of the gravitational force g. This parameter is more often used for comfort level of vehicle passengers. A rms acceleration value of $0.035g$ does not represent a concern for comfort nor a potential for stability issue (Day and Metz, 2000).

4) the maximum steering wheel angle was found to be approximately 20° which can be handled by the driver.

5) the slip angle (not shown here) had a maximum value of 2.3°. Typically, values below 4° are not a concern for the directional stability of the vehicle (Wong, 2001, Baker, 1986).

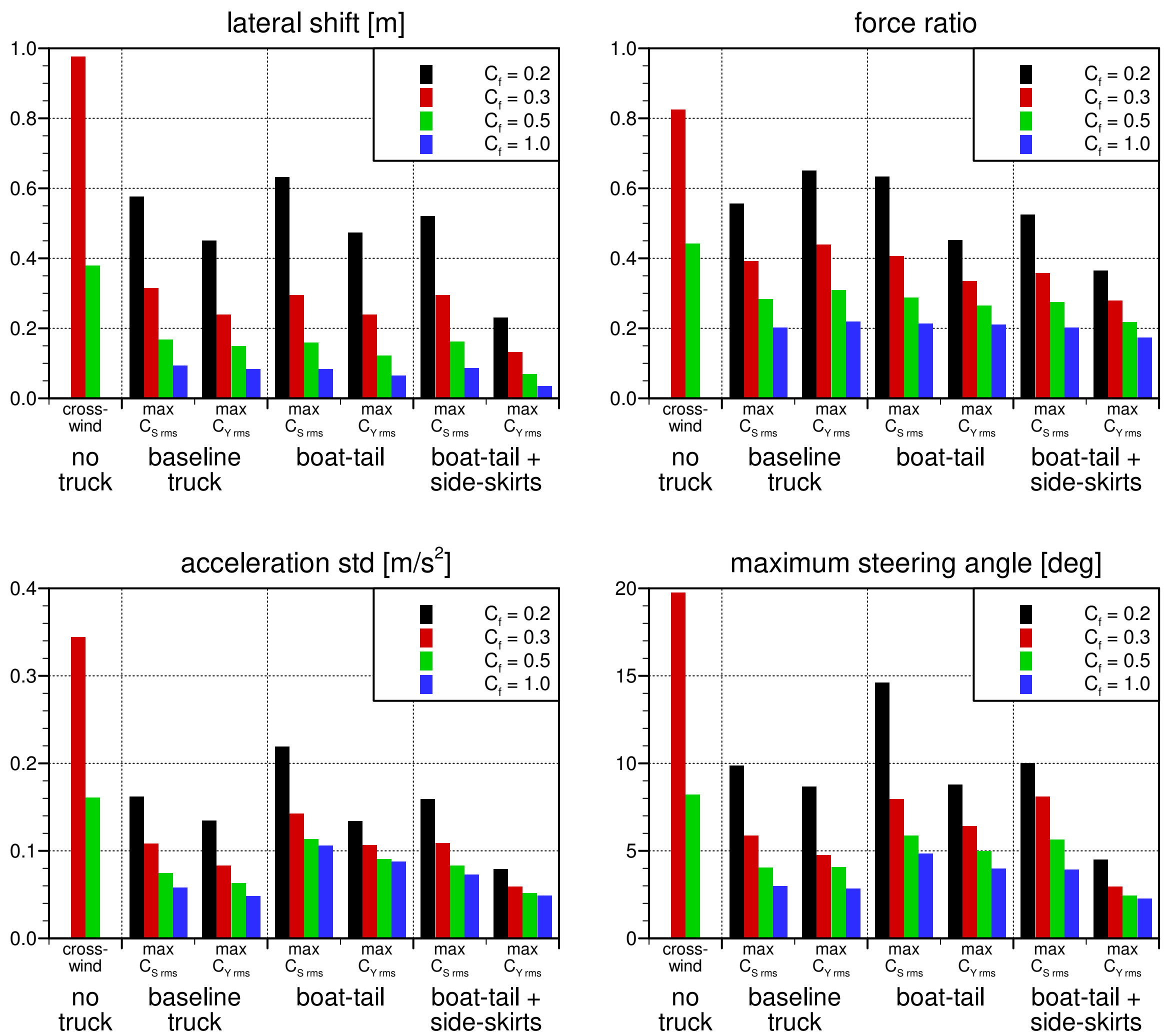

Figure 3.1: Effect of coefficient of friction of the road on the maximum lateral shift, force ratio, acceleration and maximum steering angle for 7 cases of HDV/SUV configurations at a steering angle velocity of 90 deg/s.

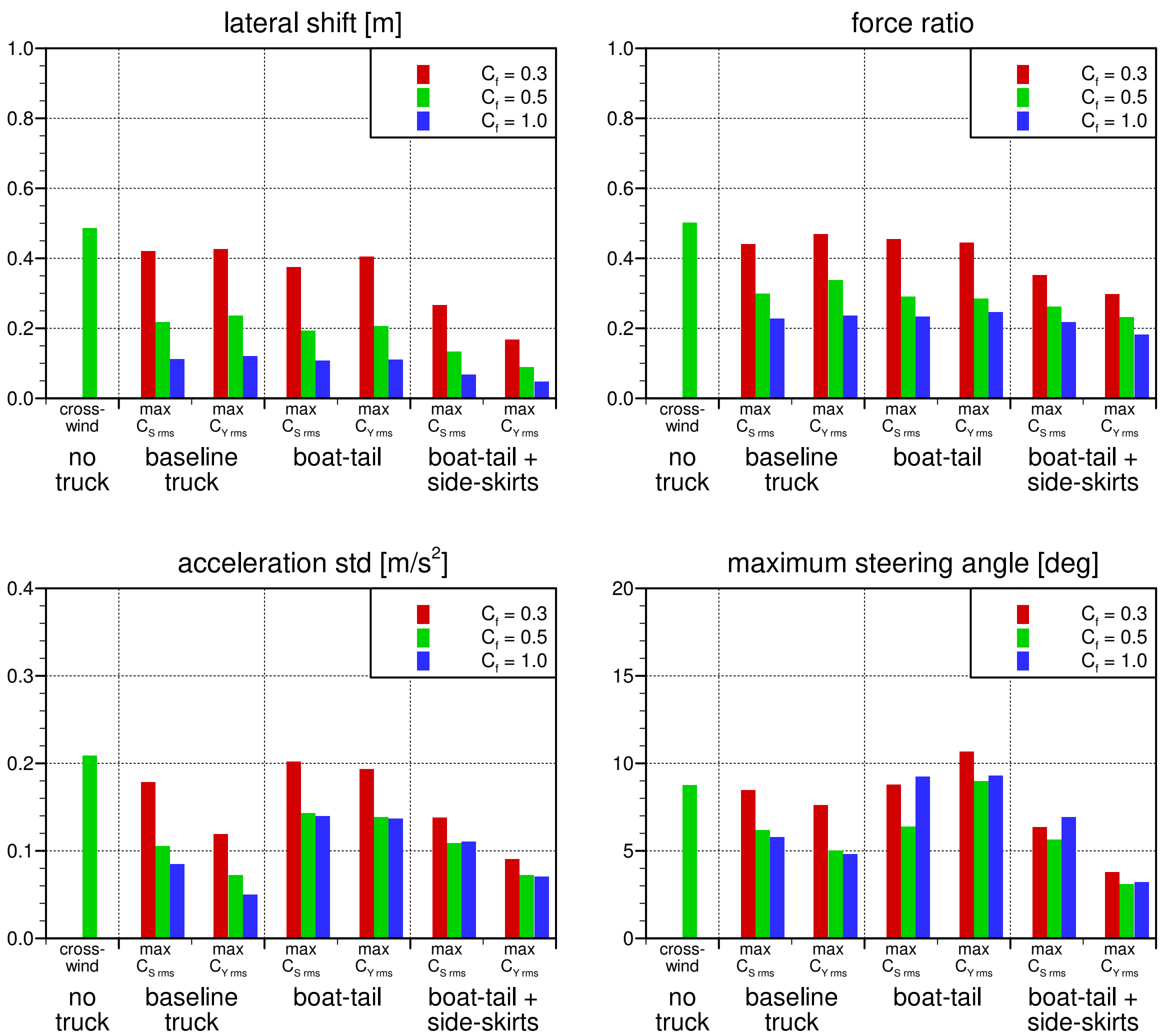

Figure 3.2: Effect of coefficient of friction of the road on the maximum lateral shift, force ratio, acceleration and maximum steering angle for 7 cases of HDV/CAR configurations at a steering angle velocity of 90 deg/s.

3.3 Effect of driver response

The second parameter that was varied in the simulation is related to the driver response. The steering angle velocity is related to the driver's ability to manoeuver the vehicle using the steering wheel to keep the main direction of the vehicle. Good drivers will be capable of higher steering angle velocity which provides a greater corrective action to keep the direction of the vehicle as intended. Drivers with better ability will also have a shorter reaction time which helps control of the vehicle under large dynamic loads applied on the vehicle. However, reaction time was not adjustable in the simulations run with the SIMPACK software.

Figures 3.3 and 3.4 show the results for the effect of maximum steering rate obtained from the

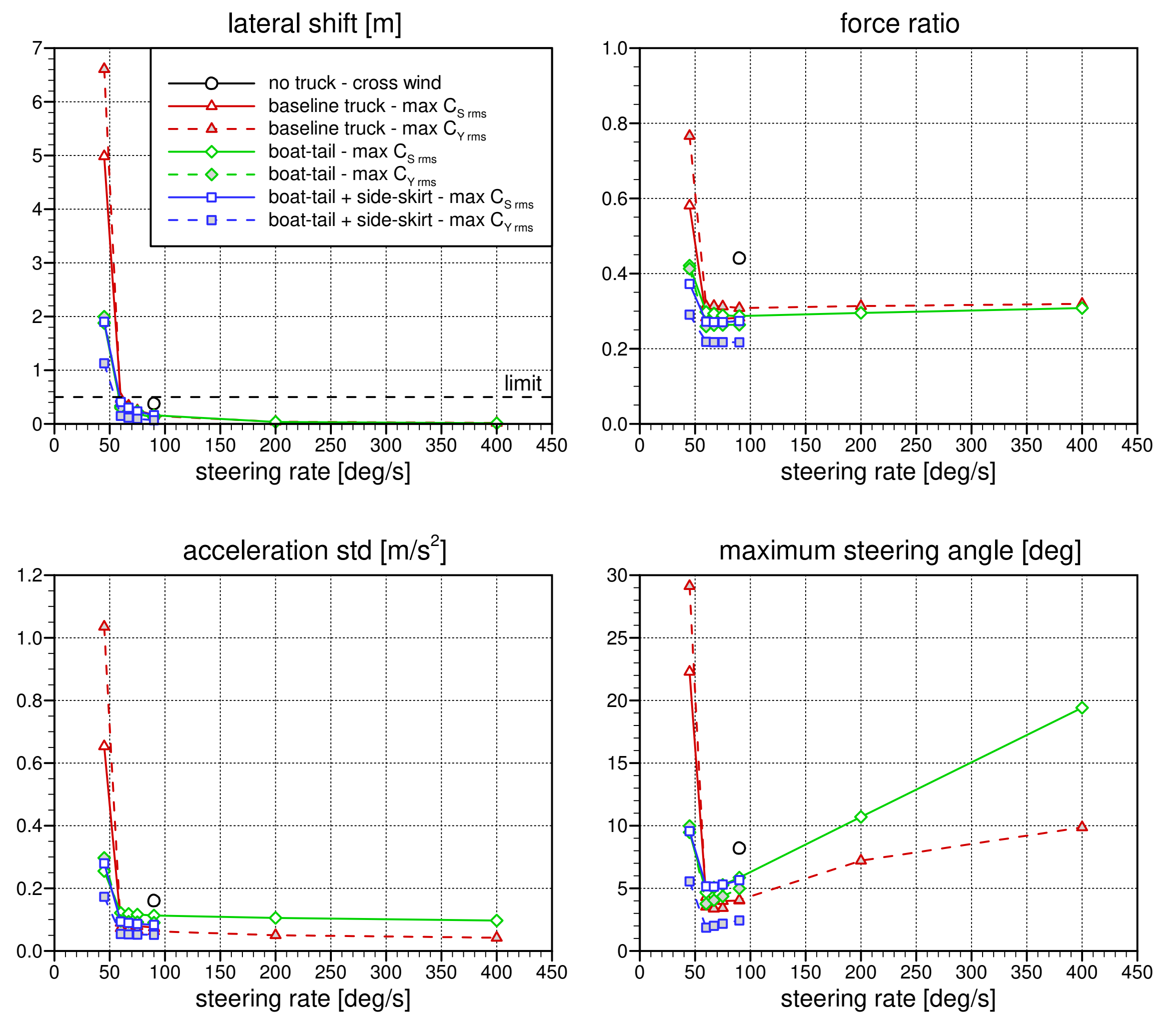

Figure 3.3: Effect of steering angle velocity on the maximum lateral shift, force ratio, acceleration and maximum steering angle for 7 cases of HDV/SUV configurations at a coefficient of friction of the road of 0.5.

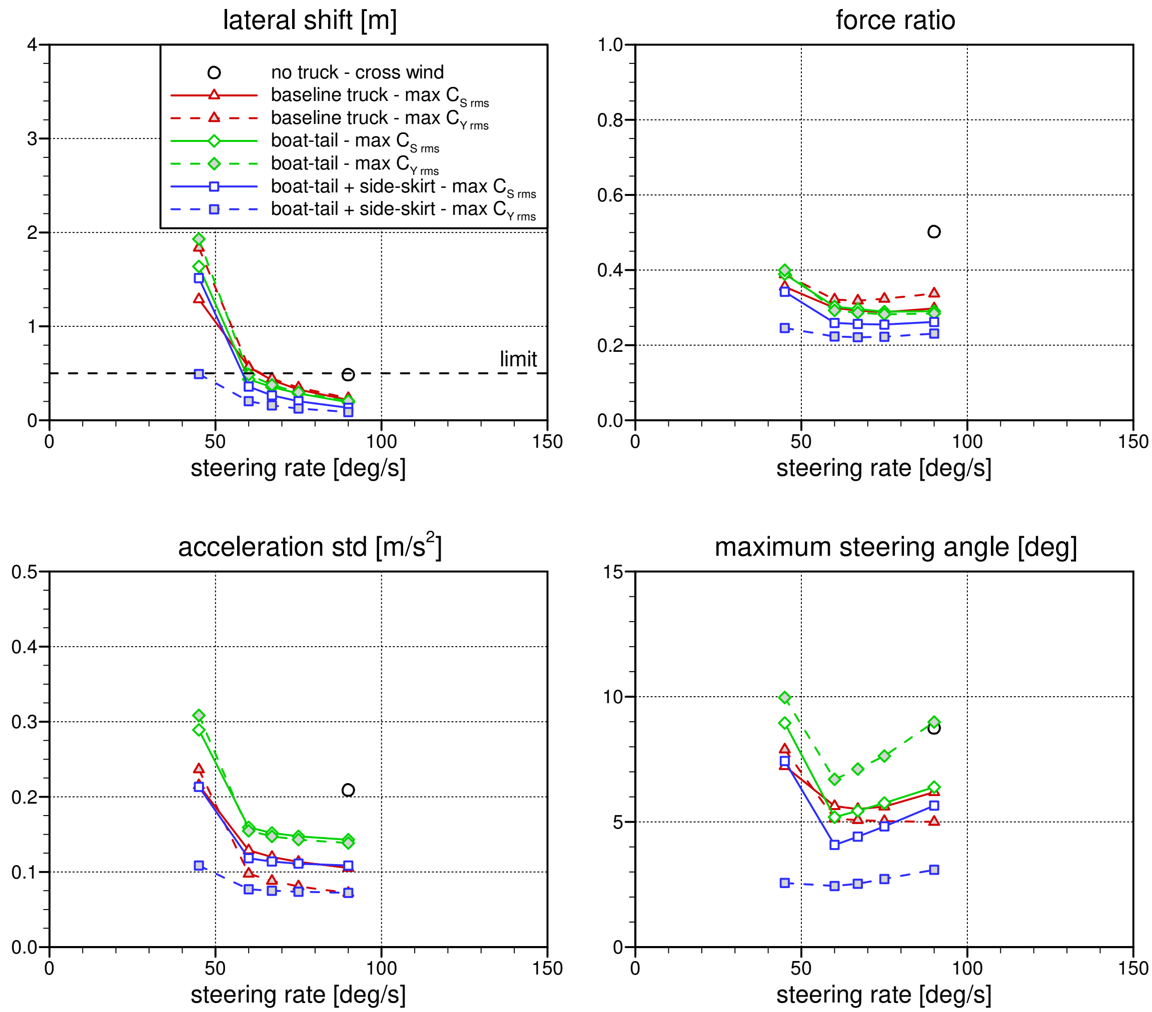

Figure 3.4: Effect of steering angle velocity on the maximum lateral shift, force ratio, acceleration and maximum steering angle for 7 cases of HDV/CAR configurations at a coefficient of friction of the road of 0.5.

vehicle-dynamic simulations for the SUV and for the car respectively. The results indicated a significant difference between the cases ran at 45 deg/s compared to higher values. However, based on the literature (Uno and Hiramatsu, 2001, Day and Metz, 2000), it was found that the lowest representative value of steering angle velocity should be around 90 deg/s. All the results for a steering angle velocity higher than 90 deg/s and a coefficient of friction of 0.5 presented on the Figure 3.3 and Figure 3.4 do not indicate the potential for directional stability issue for the vehicle. The value of the maximum lateral deviation and force ratio are well below the critical values.

3.4 Relationship between vortex-shedding and vehicle-dynamic response

A major contributor to the amplified wind loads measured for some cases of the SUV or the car following the HDV was the increased energy coming from the different vortex-shedding pattern created by the HDV equipped with boat-tails compared to a baseline HDV. The flow that separated from the trailer is affected by the presence of the boat-tail at the back face of the trailer with predominantly more lateral fluctuations directed towards the following vehicle. Of interest in this study was to verify if the vehicle/driver response will be affected by the amplified wind loads due to vortex-shedding (frequency range higher than 0.5 Hz). Figure 3.5 shows an example of the spectra of the aerodynamic side force and the spectra of the lateral force on the four wheels for different steering rates. A peak of energy around 1.5 to 3.5 Hz associated with the vortex-shedding phenomenon can be observed from the aerodynamic side wind force. This amplified energy has contributed to a small level to the lateral force on the front wheels. It can be observed in Figure 3.5 that for steering rates higher than 90 deg/s, a

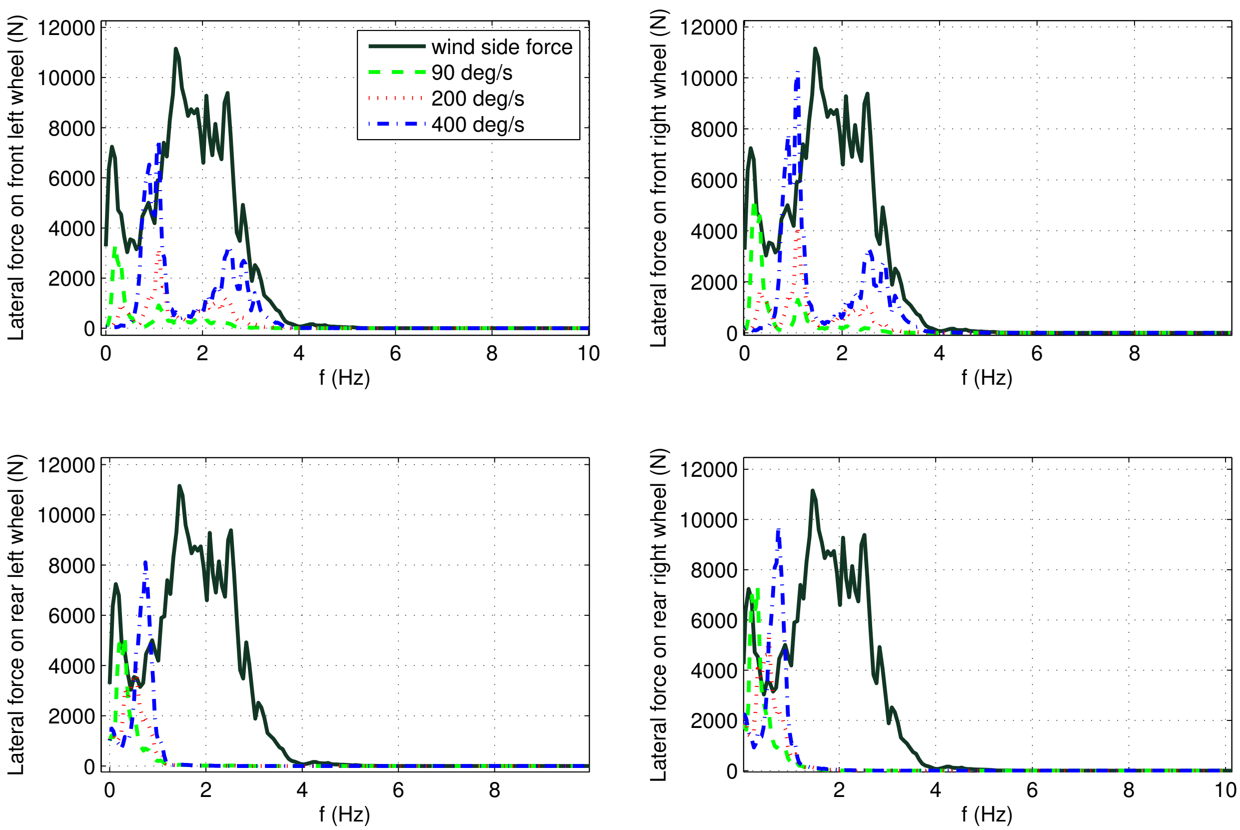

Figure 3.5: Comparison of the spectra of the wind side force with the spectrum of the lateral force on the 4 wheels of the SUV (case SLP392, max C_{Srms}) for a coefficient of friction of the road of 0.5.

spectral peak within the same range of frequency related to vortex-shedding is present. However, no potential for stability issue was depicted for the worst case results from wind tunnel tests.

3.5 Comparison of results between test cases

Vehicle-dynamic simulations were performed for 7 cases for the SUV and 7 cases for the car which all represent different combinations of tractor-trailer configurations and position of the vehicle following the HDV. The results indicated that:

1) the maximum lateral deviation and the force ratio were generally higher with increased values for the cases of the baseline tractor-trailer and the boat-tail case. This was expected as they were also the cases with the largest fluctuations of wind loads measured in the wind tunnel. The boat-tail + side-skirt case had lower values of lateral deviation and force ratio compared to the other two cases mentioned above. The side skirts reduced the impact of the vortex shedding on the following vehicle and as a result the directional stability of the vehicle is less affected than for the baseline truck and the truck equipped with boat-tail only.

2) the case with the vehicle alone (no truck upstream of the vehicle) had the worst performance, showing the highest values of lateral deviation and force ratio compared to all the simulation cases with the vehicle following the HDV. The vehicle-only case represents the vehicle exposed to a turbulent cross-wind flow at 8°. The mean side force and yawing moment for the vehicle-only case were high relative to the ones for the vehicle following the HDV and they have significantly contributed to increase the vehicle response to the wind loads. In fact, the mean side force and mean yawing moment were the highest for the vehicle-only case, slightly lower for the baseline and boat-tail + side-skirt cases, and around 0 for the boat-tail case. The fluctuating force and moment as well as their mean value both contributed to the vehicle-dynamic response.

3) the vehicle-dynamic response for the vehicle-only cases (which is for strong gusty cross-winds) provided the worst results of all cases performed during this study. As these vehicles are not known to have stability issue based on their behaviour on the road, it reduces the uncertainty related to the potential for stability issue for a vehicle following the HDV equipped with boat-tail.

4. Conclusions

The influence of boat-tails on the dynamic wind loads experienced by a typical medium car and an SUV travelling in the wake of an HDV has been examined through a wind tunnel investigation performed in the 2 m $\times$ 3 m Wind Tunnel of the National Research Council Canada. The results show that an increase in dynamic wind loads can be experienced by passenger vehicles with the addition of a boat-tail to the base of a trailer. The boat-tail directs the wake of the HDV towards the ground and amplifies the strength of wind fluctuations associated with a vortex-shedding phenomenon in the near-ground region where a passenger vehicle may be situated. This change in wind-fluctuation characteristics affects the dynamic loads experienced by such vehicles.

Vehicle-dynamic simulations were performed on the selected cases that have shown strong amplification of the dynamic wind loads in order to evaluate the impact on the directional stability of the vehicles. The driver response was modeled using a range of steering rates that represents low to high driver ability. No other driver response input variable was used. The vehicle-dynamic response, as provided by the SIMPACK software package, did not reveal a directional stability issue for the SUV nor for the car, based on the limit value of the stability criteria specified in this report. In general, the vehicle alone (vehicle-only case in strong gusty cross-wind) provided the highest values of lateral deviation and force ratio while the boat-tail + side-skirt case provided the smallest values for the same driver response and coefficient of friction used in the simulations. The simulation results presented herein show that amplified dynamic loads due to the addition of boat-tails on a dry-van trailer are not anticipated to affect the stability of the following vehicle, for the vehicles studied here, more than what a driver is already experiencing in its vehicle when travelling in a strong gusty cross-wind without an upstream vehicle.

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