On coupling methods used to simulate the dynamic characteristics of heavy ground vehicles subjected to crosswind

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Abstract

Ground vehicles often encounter turbulent flows with wide range of scales, *e.g.* crosswind gusts, when moving on-road conditions. Crosswinds can be considered as an important factor in heavy vehicle's roll-over accident due to their relatively high center of gravity and lateral surface area. However, there are few studies which investigate effects of crosswinds on heavy vehicles. Furthermore, existing studies have generally focused on lateral or yaw dynamics of heavy vehicles and neglected their roll dynamics. Therefore, effects of crosswinds on heavy ground vehicles should be understood in all aspects in order to design less wind-sensitive vehicles especially at early stages of their design processes. Inherently, crosswind studies require a multidisciplinary approach which involves coupling between aerodynamics and vehicle dynamics. In the present study, investigation of effects of the coupling

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methods, *e.g.* one-way and two-way couplings, between aerodynamics and vehicle dynamics simulations are aimed by considering both lateral and roll dynamics of heavy vehicles which are subjected to crosswind gust. Vehicle dynamics and aerodynamics results are presented. Results of the one-way coupled simulations, in general, overestimate the absolute maximum values of the vehicle dynamics results. However, differences in lateral displacement results Δy_{max} are less than 0.2 m for the studied case.

Keywords: Coupled simulations, Crosswind, GTS, Heavy ground vehicles, IDDES

1. Introduction

In previous methods of classical aerodynamics, design procedures of ground vehicles have generally been limited to optimization of their external geometries at either zero yaw angle or certain steady yaw angles. Therefore, in general, effects of the unsteady aerodynamic forces on the vehicles are ignored. Hence, over the last century, as a result of the investigations on the vehicle aerodynamics, drag force has been decreased by 70%, but the yaw moment at crosswinds of 20 degrees has been increased by 150% (Kee et al., 2014). In fact, depending on dynamic properties of the vehicle and behaviour of the driver, transient aerodynamic excitations, such as caused by crosswind gusts, may be enhanced or damped (Wojciak, 2012). Therefore, a reliable prediction of the crosswind stability of the vehicles early in their development processes is essential in order to avoid costly modifications after the production or even recalls (Theissen, 2012).

Nowadays, understanding of the crosswind stability is also essential for

the next generation electric vehicles or hybrid drive vehicles since their new architecture give rise to new combinations of basic parameters compared to standard vehicle layouts, *e.g.* mass distribution and vehicle dimensions, which may have a negative impact on the crosswind stability (Favre, 2011). Besides, there are recent studies on developing new generation vehicles with motor-driven power steering systems in which crosswind events are detected to assist steering torque in an automated manner (Kim et al., 2014).

Table 1: Previous studies that conduct two-way coupling between aerodynamics and vehicle dynamics equations

Authors	Title	Vehicle Type
Nakashima et al. (2013)	Coupled analysis of unsteady aerodynamics and vehicle motion of a road vehicle in windy conditions	Heavy vehicle
Ishioka et al. (2015)	Coupled 6Dof Motion and Aerodynamics Simulation of Road Vehicles in Crosswind Gusts	Passenger car
Winkler et al. (2016)	Coupling aerodynamics to vehicle dynamics in transient crosswinds including a driver model	Heavy vehicle
Carbonne et al. (2016)	Use of Full Coupling of Aerodynamics and Vehicle Dynamics for Numerical Simulation of the Crosswind Stability Ground Vehicles	Passenger car, Heavy vehicle
Forbes et al. (2016)	A Fully Coupled, 6 Degree-of-Freedom, Aerodynamic and Vehicle Handling Crosswind Simulation using the DrivAer Model	Passenger car
Nakasato et al. (2017)	Coupled 6DoF Motion and Aerodynamic Crosswind Simulation Incorporating Driver Model	Passenger car
Huang et al. (2017)	Transient Aerodynamics simulations of a road vehicle in the crosswind condition coupled with the vehicle's motion	Passenger car
Huang et al. (2017)	Coupled Analysis of Unsteady Aerodynamics and Vehicle Motion of a Passenger Car in crosswind Condition	Passenger car
Li et al. (2018)	Coupled analysis of vehicle stability in crosswind on low adhesion road	Passenger car
Huang et al. (2019)	Investigation of vehicle stability under crosswind conditions based on coupling methods	Passenger car

Inherently, investigations of the dynamics of ground vehicles which are

24 subjected to crosswind gusts include a multidisciplinary approach in which
 25 there is a coupling between aerodynamics and vehicle dynamics simulations.
 26 In the previous literature, the number of investigations employing fully cou-
 27 pled, *i.e.* two-way coupled, simulation of aerodynamics and vehicle dynamics
 28 are very limited as presented in Table 1. In general, their main focuses are
 29 on lateral or yaw dynamics of passenger cars while investigating effects of
 30 different coupling methods or differences between results of quasi-steady and
 31 unsteady approaches. It is known that heavy vehicles are subjected to fatal
 32 roll-over accident due to their high centre of gravity and lateral surface area.
 33 Therefore crosswinds can be considered as an important factor in fatal roll-
 34 over accidents of heavy vehicles (Cheli et al., 2011a,b). Besides, Tunay et
 35 al. (2019) have shown that there are significant differences between results of
 36 the two-way coupled simulations considering no-roll and roll motions which
 37 are conducted on a heavy ground vehicle. However, despite the importance
 38 of consideration of roll dynamics, none of the previous studies has investi-
 39 gated effects of the crosswind on heavy ground vehicles by considering the
 40 roll dynamics of the vehicles with different coupling methods together. In
 41 the previous literature, Nakashima et al. (2013) have initially conducted a
 42 two-way coupled analysis of the simplified truck geometry by ignoring the
 43 roll dynamics. In their conclusion, certain differences have been identified
 44 in the vehicle path and the yaw angle between the quasi-steady and the
 45 fully coupled analyses. After that, Ishioka et al. (2015) have revealed dif-
 46 ferences between the results of one-way and two-way coupling approaches.
 47 Winkler et al. (2016) have conducted a more detailed study and they have
 48 stated that one-way coupling approach overestimate the aerodynamic loads

49 and accordingly lateral motion of the vehicle, *i.e.* one-way coupling with no
 50 driver predicts 7.3% larger deviation from the original path. They have con-
 51 cluded that two-way coupling is needed when large yaw angles are expected.
 52 Furthermore, Carbonne et al. (2016) have explained the discrepancies be-
 53 tween one-way and two-way coupling approaches with progressive change
 54 in yaw angle. Forbes et al. (2016) have presented that although there are
 55 considerable difference in lateral displacement of 9% and yaw angle of 11%
 56 between unsteady and quasi-steady approaches, variations in these param-
 57 eters are minimal in between the results of one-way and two-way coupled
 58 unsteady approaches. Therefore, they decided that one-way coupling is suffi-
 59 cient. Although the conclusion of Forbes et al. (2016) seems to conflict with
 60 the conclusion of Winkler et al. (2016), it should be noted that classes of
 61 the vehicle model which are employed in their studies are different. Whereas
 62 Winkler et al. (2016) have investigated flow around a heavy vehicle model,
 63 *i.e.* GTS model, Forbes et al. (2016) have investigated flow around a passen-
 64 ger car model, *i.e.* DrivAer model. Carbonne et al. (2016) have compared
 65 corresponding results between GTS heavy vehicle model and Windsor pas-
 66 senger car model. They have observed that one-way coupling over predicts
 67 the total deviation by only 1% for the Windsor vehicle model. They have
 68 stated that the location of centre of gravity of the Windsor model employed
 69 in their study is close to the centre of pressure which leads to low values
 70 of yaw moment. Therefore, it can be concluded that two-way coupling is
 71 needed in cases where high yaw angles are experienced.

72 In order to design less wind sensitive vehicles early in the development
 73 process, industrial applications need a sufficient fidelity and low computa-

tionally demanding numerical methods. Therefore, the main motivation in the present study is devoted to investigate effects of different coupling methods on the solutions, *e.g.* one-way and two-way coupling between aerodynamics and vehicle dynamics equations. Accordingly, because understanding of dynamic characteristics of heavy ground vehicles which are subjected to crosswind gusts is essential due to their tendency to roll-over accidents, a simplified heavy vehicle model, GTS, is employed. Details of the coupling methods and other numerical models employed in the study are given in the Methods section. Obtained vehicle dynamics and aerodynamics results are presented and discussed in detail in the Results and Discussion section.

2. Methods

2.1. Coupling Methods

For the purpose of comparison between the coupling methods, in the present study, both one-way and two-way couplings between aerodynamics and vehicle dynamics simulations are performed. Therefore, three different coupling methods are employed, namely two-way coupling, one-way coupling with moving vehicle and one way coupling with fixed vehicle.

In every time step of the two-way coupling method, first, aerodynamics equations and then, vehicle dynamics equations are solved. Crosswind is introduced in the solution of the aerodynamics equations with the aid of boundary conditions. Coupling between the simulations are performed by exchanging force and moments results of aerodynamics simulation to vehicle dynamics simulation and velocity results of the vehicle dynamics simulation to aerodynamics simulation. The computation proceeds to next time step

98 after performing five inner iterations in each time step of the simulation. To-
 99 tal number of the time steps used in the simulation is 3667. Steps followed
 100 in each iteration of the two-way coupling method are illustrated in Fig. 1.
 101 Additionally, representation of the computational flow domain in the two-way
 102 coupling method is given in Fig. 2.

Figure 1: Schematic representation of the two-way coupling method.

Figure 2: Representation of the computational flow domain in two-way coupling method.

103 On the other hand, in the one-way coupling with fixed vehicle simula-
 104 tion, closed loop feedback on updated location of the vehicle from the vehicle
 105 dynamics equations to aerodynamics equations are no longer used. Accord-
 106 ingly, because there is no update between vehicle dynamics and aerodynamics
 107 simulations during the computation, overset mesh is not employed in aero-
 108 dynamics simulation of the one-way coupled with fixed vehicle simulation.

Steps followed in each iteration of the one-way coupled with fixed vehicle simulation and corresponding aerodynamic computational flow domain are presented in Figs. 3 and 4 respectively.

Figure 3: Schematic representation of the one-way coupling method.

Figure 4: Representation of the computational flow domain in conventional one-way coupling method.

Besides employing two different ways of conventional coupling methods which are explained above, to asses effects of using overset mesh in improving results obtained in one-way coupling method, an additional modified version of the one-way coupling method in which moving vehicle in the flow domain with the aid of overset mesh is employed. Therefore, in the third method, one-way coupling with the same computational flow domain which is employed in the two-way coupling method is used.

119 2.2. Vehicle Model

120 In the present study, the Ground Transportation System (GTS) which is
 121 designed by Sandia National Laboratory (Gutierrez et al., 1996) is employed
 122 as a vehicle model. The GTS is a 1/8 scaled simplified heavy vehicle model.
 123 The original GTS is shortened to resemble a bus geometry as presented in
 124 Fig. 5. Additionally, wheels under the GTS have been excluded in CFD
 125 simulations. On the other hand, in the vehicle dynamics simulations, the full
 126 scale GTS vehicle model is employed.

Figure 5: GTS Vehicle model

127 2.3. Crosswind Profile

128 Crosswinds are unsteady on-road flow conditions which have wide range
 129 of scales and they stem from unsteady flow due to turbulence in natural
 130 wind, vehicle velocity changes itself and unsteady wakes of other vehicles
 131 and traversing through a steady spatial wind distribution produced by road
 132 side-obstacles (Sims-Williams, 2011). Their spectral energy drops at a few
 133 Hz and relevant wind gusts have 10 m to 80 m wavelengths that cause a
 134 sinusoidal variation in yaw angle (Wojciak, 2012; Theissen, 2012).

135 In the previous literature, various approaches have been used to simulate
 136 effects of crosswinds on ground vehicles. These approaches are grouped in

Figure 6: Crosswind profile

137 the study of Sims-Williams (2011) as steady crosswinds (Guilmineau et al.,
 138 2013), dynamic rotation of the vehicle model (Mansor and Passmore, 2008),
 139 isolated extreme crosswinds (Volpe et al., 2014), stationary turbulence–small
 140 scales (Watkins, 1990) and stationary turbulence–central scales (Schrock et
 141 al., 2009). All of the methods listed above have some advantages and disad-
 142 vantages. Watkins et al. (1992) show that dynamic model rotation cannot
 143 allow the correct reproduction of the conditions experienced by a vehicle
 144 traversing a generic cross wind gust. Nevertheless, this technique can be in-
 145 structive in assessing the range of scales of importance. On the other hand,
 146 Sims-Williams (2011) states that isolated, extreme transient crosswinds, cou-
 147 pled with the vehicle aerodynamic response, handling and driver reaction,
 148 pose a safety risk and it is generally suitable only late in the development
 149 cycle.

150 In the present study, the isolated extreme crosswind model (Sims-Williams,

2011) which has a trapezoidal profile with cosine inlet and exit profile is used to simulate the on-road crosswind gust. Its length is 5 times the length of the GTS. Maximum magnitude of the crosswind velocity is selected as 9 m/s so as to generate maximum 20 degree yaw angle of the incoming velocity which is 25 m/s. The other details of the crosswind model are given in Fig. 6. This crosswind profile is also employed in many other studies in which they have used two-way coupled simulations, e.g. in the study of (Winkler et al., 2016), (Carbonne et al., 2016), (Forbes et al., 2016), (Nakasato et al., 2017) and (Li et al., 2018).

The crosswind profile used in the present study is exactly similar to the one used in the study of (Winkler et al., 2016). In the two-way coupled simulation and one-way coupled simulation with moving vehicle simulation, the velocity profile of the crosswind is defined in Eq. 1. Here, w_{max} is the maximum lateral velocity magnitude of the crosswind, Δx_{slope} is the length of the transient inlet and exit part of the crosswind which is 1.5 times the length of the GTS, x_0 is the distance between the starting location of the crosswind and the origin of the coordinate system and Δx_{cw} is the length of the crosswind which is five times the length of the GTS.

$$w(x) = \begin{cases} 0 & \text{if } x < x_0 - \frac{\Delta x_{slope}}{2} \\ w_{max} \frac{1}{2} \left(1 - \cos \left[\frac{x - (x_0 - \frac{\Delta x_{slope}}{2})}{\Delta x_{slope}} \pi \right] \right) & \text{if } x_0 - \frac{\Delta x_{slope}}{2} \leq x \leq x_0 + \frac{\Delta x_{slope}}{2} \\ w_{max} & \text{if } x_0 + \frac{\Delta x_{slope}}{2} < x < x_0 + \Delta x_{cw} - \frac{\Delta x_{slope}}{2} \\ w_{max} \frac{1}{2} \left(1 - \cos \left[\frac{x - (x_0 + \Delta x_{cw} - \frac{\Delta x_{slope}}{2})}{\Delta x_{slope}} \pi \right] \right) & \text{if } x_0 + \Delta x_{cw} - \frac{\Delta x_{slope}}{2} \leq x \leq x_0 + \Delta x_{cw} + \frac{\Delta x_{slope}}{2} \\ 0 & \text{if } x > x_0 + \Delta x_{cw} + \frac{\Delta x_{slope}}{2} \end{cases} \quad (1)$$

169 Similarly, in the one-way coupled simulation with fixed vehicle, the ve-
 170 locity profile of the crosswind is defined in Eq. 2. Here, w_{max} and x_0 are the
 171 same as the definitions given in the two-way coupled simulation, ST is the
 172 period of the cosine function to define transient inlet and exit part of the
 173 crosswind which is $(1.5L_{GTS})/u_\infty$ length of the GTS, Δt_{cw} is the time of the
 174 crosswind which correspond to $(5L_{GTS})/u_\infty$ and t_0 is the initial time.

$$w(x, t) = \begin{cases} 0 & \text{if } t < \left(\frac{x-x_0}{u_\infty} + t_0 - \frac{ST}{2} \right) \\ w_{max} \frac{1}{2} \left(1 - \cos \left[\frac{(x-x_0)-u_\infty \left[t - \left(t_0 - \frac{ST}{2} \right) \right]}{u_\infty ST} \pi \right] \right) & \text{if } \left(\frac{x-x_0}{u_\infty} + t_0 - \frac{ST}{2} \right) \leq t \\ & \leq \left(\frac{x-x_0}{u_\infty} + t_0 + \frac{ST}{2} \right) \\ w_{max} & \text{if } \left(\frac{x-x_0}{u_\infty} + t_0 + \frac{ST}{2} \right) < t \\ & < \left(\frac{x-x_0}{u_\infty} + t_0 + \Delta t_{cw} - \frac{ST}{2} \right) \\ w_{max} \frac{1}{2} \left(1 - \cos \left[\frac{(x-x_0)-u_\infty \left[t - \left(t_0 + \Delta t_{cw} + \frac{ST}{2} \right) \right]}{u_\infty ST} \pi \right] \right) & \text{if } \left(\frac{x-x_0}{u_\infty} + t_0 + \Delta t_{cw} - \frac{ST}{2} \right) \leq t \\ & \leq \left(\frac{x-x_0}{u_\infty} + t_0 + \Delta t_{cw} + \frac{ST}{2} \right) \\ 0 & \text{if } t > \left(\frac{x-x_0}{u_\infty} + t_0 + \Delta t_{cw} + \frac{ST}{2} \right) \end{cases} \quad (2)$$

175 2.4. Aerodynamics

176 Incompressible continuity and Navier-Stokes equations are used to solve
 177 the flow field around the GTS vehicle model. The flow is simulated by
 178 using SST k- ω Detached Eddy Simulation model (DES) with the Improved
 179 Delayed Detached Eddy Simulation (IDDES) formulation. IDDES combines
 180 Delayed Detached Eddy Simulation model (DDES) with an improved RANS-
 181 LES hybrid model aimed at wall modelling in LES depending on the grid
 182 resolution (Shur et al., 2008).

183 Generation of the meshes and solution of the governing equations are
 184 done by using the commercial CFD software StarCCM+ version 13.02. In the
 185 computations, finite volume method and segregated solver are used. Hybrid-
 186 Bounded Central Differencing (BCD) scheme is used for the convective dis-
 187 cretization of the governing equations in which BCD is used in the separated
 188 areas and a high-order upwind scheme in the flow-attached and free stream
 189 areas. A second order implicit unsteady scheme is used as a time discretiza-
 190 tion. The resultant scalar system of equations are solved by using Algebraic

191 Multigrid (AMG) linear solver.

Figure 7: Boundary conditions and dimensions of the computational flow domains.

192 Boundary conditions and dimensions of the computational domains ap-
 193 plied in both two-way and one-way coupled simulations are presented in Fig.
 194 7. Crosswind is introduced to the flow domains with the aid of velocity inlet
 195 boundary condition on the right lateral surface of the flow domains. Details
 196 of the crosswind profile are given in the previous section. In the two-way
 197 coupled simulation, surfaces named as inlet, outlet and left lateral surfaces
 198 are set to pressure outlet boundary condition, which assumes atmospheric
 199 pressure on the boundary surface. On the other hand, inlet surface of the
 200 one-way coupled with fixed vehicle simulation is set to velocity inlet bound-
 201 ary condition, in which a uniform velocity with 91.6 m/s is assumed. Ground
 202 of the flow domain and surfaces of the GTS are treated as no-slip boundary
 203 condition in all simulations. Additionally, whereas ground is set to move with
 204 free stream flow velocity in one-way coupled simulation with fixed vehicle,
 205 the GTS is set to move with 91.6 m/s in the two-way coupled simulation and

206 one-way coupled simulation with moving vehicle. The velocity of 91.6 m/s
 207 corresponds to $Re_w = 2 \times 10^6$ in accordance to the computational study of
 208 Unaune et al. (2005) and wind tunnel measurements of Croll et al. (1996)
 209 and Storms et al. (2001). Upper surfaces of the flow domain in all simulations
 210 are set to symmetry boundary condition.

(a) Side view

(b) Top view

Figure 8: Representation of mesh structure around the GTS vehicle model and overset mesh.

211 In the two-way coupled simulation and the one-way coupled simulation
 212 with moving vehicle, movement of the vehicle in the computational flow do-
 213 main is enabled with the aid of overset mesh technique. Therefore the con-
 214 structed mesh consist of two regions, *i.e.* an overlap region and a background
 215 region as presented in Fig. 8. There is an intermediate region between the
 216 two regions at which the solution field is interpolated between them. The
 217 overlap region including the vehicle performs its motion in the background

218 region. The background mesh has a size of $22.6 \times 4.9 \times 1.4$ vehicle lengths,
 219 while the overlap region has a size of $5.3 \times 2.6 \times 1$ vehicle lengths. The
 220 meshes consist of unstructured hexahedral cells whose number is approxi-
 221 mately 22×10^6 of which 9×10^6 are employed in the overlap region. On the
 222 other hand, flow domain the one-way coupled with fixed vehicle simulation
 223 has a size of $15.7 \times 4.9 \times 1.4$ vehicle lengths. Overset mesh is not employed
 224 in the one-way coupled with fixed vehicle simulation because GTS is fixed.
 225 Therefore, the number of the computational cells employed in this simulation
 226 becomes approximately 14×10^6 . The time step used in all simulations is
 227 6×10^{-5} seconds.

Figure 9: Mesh structures around the GTS.

228 In all simulations, two refinement regions are applied around the GTS. For
 229 the resolution of the boundary layer around the GTS, 20 prism layers with
 230 a total thickness in the wall normal direction of 0.0141 m with a stretching
 231 of 1.25 and a length of 0.0044 m are applied as presented in Fig. 9. The
 232 value of dimensionless wall distance y^+ is less than 15 for the conditions used.

233 Properties and size of the cells in the mesh regions are chosen based on the
 234 work of Winkler et al. (2016) which is also conducted to investigate effects
 235 of crosswind on the GTS.

Table 2: Drag coefficients.

	Method	Re_w	C_D
Croll et al. (1996)	Experimental	1.6×10^6	0.247
Storms et al. (2001)	Experimental	1.6×10^6	0.249
Unaune et al. (2005)	Numerical	2×10^6	0.253
The present study	Numerical	2×10^6	0.251

236 Comparison between the drag coefficient C_D of the GTS obtained in the
 237 present study for the case of no crosswind with other drag coefficient results
 238 obtained in the previous literature for the same geometry is presented in
 239 Table 2. Because drag coefficient result obtained in the present study is close
 240 enough to both experimental and numerical results obtained in the previous
 241 literature, the mesh is assumed as appropriate and no further refinement is
 242 conducted.

243 Because a 1/8th scaled version of the GTS is employed in aerodynamics
 244 simulation, force and moment results, *i.e.* lateral force, yaw moment and
 245 roll moment, obtained in aerodynamics simulation should be scaled before
 246 using in the vehicle dynamics simulation. Scaling is conducted by assuming
 247 there is a dynamic similarity between the 1/8 scaled GTS model employed in
 248 aerodynamics simulation and full scale GTS prototype employed in vehicle
 249 dynamics simulation. Therefore, force and moments are scaled according to
 250 definition of the force and the moment coefficients as follows.

$$F_{ya,prototype} = F_{ya,model} \frac{u_{\infty,prototype}^2}{u_{\infty,model}^2} \frac{A_{prototype}}{A_{model}} \quad (3)$$

$$M_{za,prototype} = M_{za,model} \frac{u_{\infty,prototype}^2}{u_{\infty,model}^2} \frac{A_{prototype}}{A_{model}} \frac{L_{prototype}}{L_{model}} \quad (4)$$

$$M_{xa,prototype} = M_{xa,model} \frac{u_{\infty,prototype}^2}{u_{\infty,model}^2} \frac{A_{prototype}}{A_{model}} \frac{L_{prototype}}{L_{model}} \quad (5)$$

251 Here, F_{ya} , M_{za} and M_{xa} denote lateral force, yaw moment and roll mo-
 252 ment, respectively. The free stream velocity or the velocity of the GTS is
 253 denoted by u_{∞} . The cross-sectional area and length of the GTS are denoted
 254 by A and L respectively. The subscript *prototype* represents full scale GTS
 255 parameters and subscript *model* represents scaled parameters of the GTS.

256 2.5. Vehicle Dynamics

257 A single-track model with roll component is used to solve the vehicle
 258 dynamics equations. The state space representation of the vehicle dynamics
 259 equations are as follows (Lee et al., 2013).

$$x = \begin{bmatrix} v & \dot{\psi} & \dot{\phi} & \phi \end{bmatrix}^T \quad (6)$$

$$\dot{x} = Ax + B \quad (7)$$

$$A = \begin{bmatrix} -\frac{\lambda I_{xeq}}{mu I_{xx}} & \frac{\tau I_{xeq}}{mu I_{xx}} - u & -\frac{h C_\phi}{I_{xx}} & \frac{h(mgh - K_\phi)}{I_{xx}} \\ \frac{\tau}{u I_{zz}} & -\frac{\sigma}{u I_{zz}} & 0 & 0 \\ -\frac{\lambda h}{u I_{xx}} & \frac{\tau h}{u I_{xx}} & -\frac{C_\phi}{I_{xx}} & \frac{mgh - K_\phi}{I_{xx}} \\ 0 & 0 & 1 & 0 \end{bmatrix}, B = \begin{bmatrix} -\frac{F_{ya}}{m} \\ -\frac{M_{za}}{I_{zz}} \\ \frac{M_{xa}}{I_{xx}} \\ 0 \end{bmatrix}$$

Definition of parameters in eqs. (6) and (7) are given in eqs. (8) to (11)

$$\lambda = C_{y12} + C_{y34} \quad (8)$$

$$\tau = C_{y34}b - C_{y12}f \quad (9)$$

$$\sigma = C_{y12}f^2 + C_{y34}b^2 \quad (10)$$

$$I_{xeq} = I_{xx} + mh^2 \quad (11)$$

Corresponding values of the parameters in eqs. (6) to (11) can be found in Table 3.

Figure 10: Single track model with roll degree of freedom.

Table 3: Geometrical and mass properties of the GTS model employed in the study.

Vehicle's Parameter	Symbol	Data	Unit
Length	L	12.2	[m]
Height	h	3.6	[m]
Width	w	2.6	[m]
Track width	T	2.25	[m]
Length of the wheel base	L_{wb}	5.9	[m]
Distance between front axle to CG	f	3.7	[m]
Distance between rear axle to CG	b	2.2	[m]
Mass	m	13,650	[kg]
Linear tire stiffness for front tire	C_{y12}	250	[kN/rad]
Linear tire stiffness for rear tire	C_{y34}	450	[kN/rad]
Roll damping of suspension	C_ϕ	100	[kN/rad]
Roll stiffness of suspension	K_ϕ	1,000	[kNm/rad]
Yaw moment of inertia	I_{zz}	200,000	[kgm ² /rad]
Roll moment of inertia	I_{xx}	30,000	[kgm ² /rad]

264 The coupled computations are performed by using high performance com-
265 puting system at the PDC Center for High Performance Computing which
266 is hosted at KTH Royal Institute of Technology. The HPC system run on a
267 Cray XC40, based on Intel Haswell and Broadwell processors and Cray Aries
268 interconnect technology. In the present study, in general, 24 nodes with a
269 total of 768 cores are employed.

270 3. Results and Discussion

271 In this section, unsteady dynamic characteristics of the heavy vehicle
272 model GTS which is subjected to crosswind gust are presented and discussed
273 by using different coupling methods between aerodynamics and vehicle dy-

274 namics simulations. For that purpose, three different coupling methods are
 275 used, *i.e.* two-way coupled simulation, one-way coupled with moving vehicle
 276 simulation and one-way coupled with fixed vehicle simulation. Application
 277 details of the coupling methods are given previously in the Methods section.
 278 Comparison between results of the coupling methods are presented in detail
 279 in order to identify fidelity of each method for industrial applications.

Figure 11: Change of (a) lateral velocity V_y , (b) yaw rate $\dot{\psi}$, (c) lateral displacement y , (d) roll angle ϕ , and (e) roll rate $\dot{\phi}$, with different coupling methods.

280 3.1. Computational Efficiency of the Coupling Methods

281 The computational efficiency of the coupling methods can be evaluated
 282 in two perspectives, *i.e.* the computation time and the complexity of the
 283 computational setup needed.

284 The computation times of two-way and one-way coupling methods con-
 285 sidered in the present study are given in Table 4. The differences between the

Table 4: Computation times of each simulation.

Name of the coupling method	Computation time
Two-way coupled simulation	7:10:29
One-way coupled simulation with moving vehicle	5:54:07
One-way coupled simulation with fixed vehicle	6:51:50

computation times of the coupling methods are not large. The results of the two-way coupled simulation and one-way coupled simulation with moving vehicle show clear identification of the computation time difference between two methods because all settings of the simulations are the same except the way of coupling between aerodynamics and vehicle dynamics equations. However, although the one-way coupled simulation with fixed vehicle has low number of computational cells, its computation time is almost the same as the computation time of the two-way coupled simulation. The reason for this result is that the one-way coupled simulation with fixed vehicle needs more time step in order to prevent disturbed flow upstream of the GTS due to usage of moving boundary condition to simulate crosswind.

On the other hand, the complexity of the computational setup needed, which is the other factor in evaluating computational efficiency of the coupling methods, is lower in the one-way coupled simulation with fixed vehicle because there is no need to a computational setup for the communication between the simulations in every time steps and there is no need to use overset mesh in the aerodynamics simulation.

As a result, whereas the one-way coupling methods have no considerable advantage over the two-way coupling method in terms of computation

time, complexity in their computational setup is less than two-way coupling method.

3.2. Vehicle Dynamics

Results related to vehicle dynamics are presented in Fig. 11 by comparing three different simulations. In the figures, differences between the results of different coupling methods are directly given in a subplot. Crosswind profile is also plotted on each figure in order to better assessment of its effects on the dynamic characteristics of the GTS.

The results presented in Fig. 11 reveal that as soon as the GTS is subjected to the crosswind, its yaw rate $\dot{\psi}$, increases. Because of increase in its yaw rate, its lateral velocity V_y , starts to increase in negative y-direction immediately after it experiences a slight increase in positive y-direction. Similarly, roll angle ϕ , increases in negative direction, *i.e.* counter-clockwise direction, after being affected by the crosswind. Whereas the maximum values of the lateral velocity and the yaw rate are obtained at the end of the crosswind, the maximum value of the roll angle is obtained nearly at the mid-location of the crosswind. Finally, GTS starts to exhibit lateral displacement y , in the same direction with the application of the crosswind.

As presented in Fig. 11, results of the one-way coupled simulations have good harmony with results of the two-way coupled simulation until $t = 3.0s$, *i.e.* at the beginning of the crosswind. However, this good harmony between the results can not be kept further due to not responding of the one-way coupled simulations to highly unsteady effects of the crosswind. The results start to differ with each other, especially results of the lateral velocity and the yaw rate, after further movement of the GTS into the crosswind. In

330 general, the one-way coupled simulations overestimate the results. Absolute
 331 value of the differences between the results normalized by the absolute max-
 332 imum value of the results obtained by two-way coupled simulation are less
 333 than 20% in the results of lateral velocity, yaw rate, roll angle and roll rate.
 334 On the other hand, corresponding differences in lateral displacement between
 335 the results are relatively lower than the others, *i.e.* they are less than 3%.
 336 Furthermore, the maximum difference in lateral displacement of the vehicle
 337 is obtained between the two-way coupled simulation and the one-way coupled
 338 simulation with fixed vehicle, *i.e.* $\Delta y_{max} = 0.2$ m. In the studies of Win-
 339 kler et al. (2016), Carbonne et al. (2016) and Forbes et al. (2016), one-way
 340 coupled simulations also overestimate lateral displacement of the vehicle at
 341 slightly different levels. Winkler et al. (2016) find it as 3.9%, Carbonne et
 342 al. (2016) find it as maximum 1% and Forbes et al. (2016) find it close to
 343 zero. Differences in the results might be caused by using different vehicle
 344 models and different equations in their studies. For example, in the study
 345 of Winkler et al. (2016), roll motion of the vehicle is not considered in the
 346 simulations and in the studies of Carbonne et al. (2016) and Forbes et al.
 347 (2016), passenger car models are employed as the vehicle model.

348 The results of the one-way coupled with moving vehicle simulation (em-
 349 ploying overset mesh) are in general closer to the results of two-way coupled
 350 simulation than the results of one-way coupled simulation with fixed vehicle.
 351 Therefore, it can be concluded that simulation of the flow field by employing
 352 moving vehicle (overset mesh) rather than employing a fixed vehicle can im-
 353 prove obtained results. As a conclusion, there are differences between results
 354 of the one-way coupled simulations and the two-way coupled simulation at a

certain level in which the one-way coupled simulations overestimate absolute maximum values of the all results considered.

Figure 12: Change of (a) lateral force F_{ya} , (b) yaw moment M_{za} , and (c) roll moment M_{xa} with different coupling methods.

3.3. Aerodynamics

3.3.1. Force and Moment Results

Comparison of the computed aerodynamic force and moments exerted on the GTS by oncoming crosswind are given in Fig. 12. Because, in the present study, the main focus is on lateral, yaw and roll dynamics of the vehicle, only the results of the lateral force F_{ya} , the roll moment M_{xa} and the yaw moment M_{za} , are presented in the figure. In line with the results given in Fig. 11, the one-way coupled with fixed vehicle simulation overestimate force and moment results, especially the yaw moment. Absolute value of the differences between the results normalized by the maximum value of the results obtained in the two-way coupled simulation are less than 20 percent in all results presented in Fig. 12.

In order to understand reasons for the differences in the force and moment results given in Fig. 12, change of the force and moment coefficients, *i.e.* C_{side} , C_{yaw} and C_{roll} , on each surface of the GTS with time are investigated

Figure 13: Comparison of (a) the lateral force coefficient C_{side} , (b) the yaw moment coefficient C_{yaw} and (c) the roll moment coefficient C_{roll} , obtained by different coupling methods on each surface of the GTS (—represents two-way coupled simulation,represents one-way coupled with moving vehicle simulation, - - -represents one-way coupled with fixed vehicle simulation).

in Fig. 13. It can be explicitly understood from Fig. 13 that the front and the lateral surfaces have the main contribution to the lateral force, the yaw and the roll moments. Besides, contribution of the rear, the bottom and the top surfaces of the GTS to the corresponding force and the moments are little. The only exception is that the bottom and the top surfaces have considerable contribution to the roll moment of the GTS in opposite direction in which they cancel each other as a result. Before the crosswind starts, *i.e.* before $t=2.67$ s, total force and moment coefficient results obtained by using the one-way coupled with fixed vehicle simulation show some differences from results of the other simulations. That means, upstream flow field created by the crosswind in the one-way coupled with fixed vehicle simulation produces some lateral force, yaw and roll moments on the GTS before it hits on the GTS. However, as soon as the crosswind starts, results of all simulations overlap each other for a while. Then, they start to differ from each other while the GTS is fully immersed in the crosswind. According to the results presented in Fig. 13, differences on the left (leeward) surface of the GTS are

the main source of the differences between all force and moment results.

Figure 14: The pressure coefficient C_p , on the left (leeward) lateral surface of the GTS obtained by using three different coupling methods.

Figure 15: Skin friction coefficient C_f , on the left (leeward) lateral surface of the GTS obtained by using three different coupling methods.

Therefore, in Figs. 14 and 15, the pressure coefficient C_p , and skin friction coefficient C_f , results obtained in all simulations at three different instants,

391 *e.g.* $t = 2.67$ s, 3.89 s, 5.11 s, are investigated. At $t=2.67$ s, because the
 392 crosswind has just started, patterns of pressure coefficient contours are almost
 393 identical. However, after fully immersing of the GTS into the crosswind,
 394 *i.e.* $t = 3.89$ and 5.11 s, a massive reduction of the pressure coefficient
 395 which is resulted in a wake region on the front part of the left (leeward)
 396 lateral surface of the GTS is observed. Accordingly, the main difference
 397 between the results of the two-way and the one-way couplings is observed at
 398 $t=3.89$ s on the front part of the left lateral surface as presented by dashed
 399 ellipses in Fig 14. Additionally, traces of longitudinal vortices emerged from
 400 upper and lower part at the front of the GTS on the left lateral surface are
 401 indicated with dashed straight lines on each figures. Skin friction coefficient
 402 results, given in Fig. 15, present starting location of the upper and the lower
 403 longitudinal vortices at $t=2.67$ s in Fig. 15. At this instant, prediction of
 404 all simulations are rather close to each other since the GTS has a bluff body
 405 like geometry. Between these upper and lower longitudinal vortices, high
 406 pressure and skin friction coefficient region is observed in Figs. 14 and 15.
 407 This region corresponds to traces of hairpin vortices emerged from vertical
 408 front edge of the left (leeward) lateral surface of the GTS.

409 Pressure and skin friction coefficient results given on top surface of the
 410 GTS in Figs. 16 and 17 explain formation mechanism of the vortices further.
 411 At the beginning of the crosswind, *i.e.* $t=2.67$ s, pressure and skin friction
 412 coefficients show almost uniform change from the leading edge. However, as
 413 the GTS is fully immersed in the crosswind, a low pressure region appears
 414 on the top surface which shows trace of the vortex emerging on the right
 415 (windward) front edge and then crossing the top surface from right to left.

Figure 16: Pressure coefficient C_p on top surface of the GTS with different coupling methods.

Figure 17: Skin friction coefficient C_f on top surface of the GTS with different coupling methods.

416 As for the differences between the results on top surface of the GTS, one-
 417 way coupled simulations overestimate skin friction coefficient results at front
 418 left (leeward) part of the top surface at which secondary longitudinal vortex

419 emerge and interact other vortices on the left (leeward) surface of the GTS.
 420 Three dimensional interaction of theses vortices are presented in Fig. 22 and
 421 their detailed investigations are given in the next section.

422 3.3.2. Velocity Field Results

Figure 18: Contours of unsteady velocity magnitude U , at three different instants in the horizontal xz -plane at mid-height of the GTS, *e.g.* (a) $t = 2.67$ s starting point of the crosswind, (b) $t = 3.89$ s mid-point of the crosswind, (c) $t = 5.11$ s end-point of the crosswind.

423 Contour plots of unsteady velocity magnitudes obtained from three dif-
 424 ferent simulations are given in Fig. 18 at three different instants. At $t=2.67$
 425 s, because the GTS has just begun to be affected by the crosswind, the veloc-
 426 ity field around it looks similar to a characteristic one which is encountered
 427 around bluff bodies. It means that there are a stagnation flow region in the
 428 front and a wake flow region in the rear part of the GTS. At $t=3.89$ s, which is
 429 at the mid point of the crosswind, the velocity field around the GTS distorts

430 and new flow regions start to appear due to yawing effect of the incoming
 431 crosswind flow. For example, on the left (leeward) side of the GTS, a sep-
 432 arated flow region appear on the upstream part of the left (leeward) lateral
 433 surface and a secondary wake region appear in the wake flow downstream of
 434 the GTS. Besides, the stagnation region in the front part of the GTS shifts to
 435 right (windward) side of the front surface. Main differences observed at this
 436 instant between the results of the one-way and the two-way coupled simula-
 437 tions are dimensions of the stagnation region at the front part of the GTS.
 438 Two-way coupled simulation has the largest stagnation flow region because it
 439 rotates in positive yaw direction (counter clockwise) in response to the effects
 440 of the crosswind. At $t=5.11$ s, which is at the end point of the crosswind, flow
 441 features appearing in the previous instant keep their existence with enlarged
 442 dimensions.

443 Results of turbulent kinetic energy TKE, presented in Fig. 19 reveal the
 444 amount of the turbulence mixing around the GTS caused by the crosswind.
 445 TKE is directly related to the dynamics of the flow. In general, results of all
 446 simulations have the same patterns of TKE. Namely, high values of TKE are
 447 predicted in the shear layers developed around the GTS. Then, they dissipate
 448 gradually in the downstream flow direction. As it is expected, at the start of
 449 the crosswind *i.e.* $t = 2.67$ s, TKE is only high along the right and left shear
 450 layers emerged from lateral surfaces in the near wake region downstream of
 451 the GTS. However, after fully immersing of the GTS in the crosswind, *i.e.* at
 452 $t = 3.89$ s and 5.11 s, an additional region of high TKE appears on the front
 453 part of the left (leeward) lateral surface. Besides, concentrations of TKE
 454 contours increase on right (windward) shear layer in the near wake region

Figure 19: Contours of turbulent kinetic energy TKE, at three different instants in the horizontal xz-plane at mid-height of the GTS, *e.g.* (a) $t = 2.67$ s starting point of the crosswind, (b) $t = 3.89$ s mid-point of the crosswind, (c) $t = 5.11$ s end-point of the crosswind.

455 downstream of the GTS at $t = 3.89$ s. This increase is more pronounced
 456 in the results of the one-way coupled simulations than the two-way coupled
 457 simulation.

458 In Fig. 20, contours of unsteady vorticity ω_y , are presented at three
 459 different instants in the horizontal xz-plane at mid-height of the GTS. In
 460 this figure, blue and red colors correspond clockwise and counter clockwise
 461 rotation of the vorticity concentrations respectively. The most noticeable
 462 difference between the results at $t = 2.67$ s is in shedding frequency of the
 463 vorticity concentrations formed in the wake region downstream of the GTS.
 464 Comparing with the fixed vehicle simulation, longer shedding period of the
 465 vorticity concentrations is observed in the wake region of the simulations

Figure 20: Contours of vorticity ω_y , at three different instants in the horizontal xz-plane at mid-height of the GTS, *e.g.* (a) $t = 2.67$ s starting point of the crosswind, (b) $t = 3.89$ s mid-point of the crosswind and (c) $t = 5.11$ s end-point of the crosswind.

466 employing moving vehicle, *i.e.* overset mesh. At $t = 3.89$ s, because the
 467 vehicle is completely immersed into the crosswind, inline with the above
 468 mentioned results, a secondary wake region appears at front part of the left
 469 (leeward) lateral surface of the GTS in all simulations. Besides, an additional
 470 couple of vorticity concentrations appear on the left (leeward) side of the
 471 wake region in the downstream part of the GTS. This secondary couple of
 472 vorticity concentrations interact with main couple of vorticity concentrations
 473 in the wake region downstream of the GTS as presented in 20 at $t=3.89$ s and
 474 $t=5.11$ s. Starting location of this secondary vorticity concentration couple is
 475 closer to the GTS in the one-way coupled with fixed vehicle simulation than
 476 the corresponding starting location of the secondary vorticity concentrations

477 predicted in other simulations.

Figure 21: Formation of unsteady vortices around the GTS obtained from three different simulations at $t = 3.0$ s with the aid of Q criterion, $Q=10^6$.

478 Formation of the vortices developing around the GTS, which are com-
 479 puted by using Q criterion, are presented in Fig. 21. This figure give infor-
 480 mation about starting location and characteristics of the vortices emerging
 481 from the front part of the GTS after being effected by the crosswind. There
 482 are longitudinal vortices which emerge from each upper and lower corners at
 483 the front part of the GTS, *e.g.* $V_{L,11}$, $V_{L,21}$, $V_{L,3}$ as presented in Fig. 21.
 484 Besides them, there are secondary longitudinal vortices which are formed
 485 around upper edges connecting top and lateral surfaces, *e.g.* $V_{L,12}$ and $V_{L,22}$.
 486 These secondary vortices develop due to interaction between flow streams
 487 coming from neighbouring surfaces with the crosswind flow. In addition to
 488 the longitudinal vortices, there are hairpin vortices developing on the left
 489 (leeward) lateral surface, *e.g.* $V_{H,11}$ and $V_{H,12}$. These large scale hairpin
 490 vortices form at the front part with large scales and then they move on the
 491 left lateral surface in downstream direction with decreasing scales.

492 Finally, development of the above-mentioned vortices around the GTS

Figure 22: Development of vortices around the GTS at three different instants, *e.g.* (a) $t = 2.67$ s starting point of the crosswind, (b) $t = 3.89$ s mid-point of the crosswind, (c) $t = 5.11$ s end-point of the crosswind, with the aid of Q criterion, $Q=10^6$.

493 from beginning to end of the crosswind event are presented in Fig. 22. At the
 494 beginning of the crosswind *i.e.* $t = 2.67$ s, besides vortex structures observed
 495 in the wake downstream of the GTS, the longitudinal vortex emerging from
 496 bottom front part of the left (leeward) lateral surface and hairpin vortices
 497 on the rear part of the left lateral surface are observed. However, as the

498 GTS fully immerse in the crosswind, all vortices develop more and interact
 499 with each other resulting in a more complicated flow field around the GTS.
 500 Hairpin vortices $V_{H,11}$, disturb the longitudinal vortices $V_{L,21}$ and $V_{L,3}$ to
 501 make them unstabilized. Besides, secondary longitudinal vortices $V_{L,12}$ and
 502 $V_{L,22}$ interact with other longitudinal vortices $V_{L,11}$ and $V_{L,21}$, respectively.
 503 While, as soon as longitudinal vortex $V_{L,11}$ reaches to the rear end of the GTS,
 504 it breaks down into the wake region, the other longitudinal vortices $V_{L,21}$ and
 505 $V_{L,3}$ keeps their existence in the wake region. Therefore, Fig. 22 reveals the
 506 physical mechanism which produces secondary wake on the leeward side of
 507 the wake region downstream of the GTS. Interactions between the vortices
 508 $V_{L,12}$ and $V_{L,21}$ and flow stream coming from right (windward) side of the
 509 GTS generate the secondary wake region. Finally, when comparing obtained
 510 results between each other, one can observe that one-way coupled simulation
 511 with fixed vehicle estimates the strongest longitudinal vortices caused by
 512 crosswind which might also explains why one-way coupled with fixed vehicle
 513 simulation overestimates vehicle dynamics parameters presented in Fig. 11.

514 4. Conclusion

515 The aim of the present study is to understand effects of the coupling
 516 methods, *e.g.* one-way and two-way couplings, on the solution of the dynamic
 517 characteristics of heavy ground vehicles which are subjected to crosswind
 518 gusts. Therefore, the degree of the complexity required to obtain accurate
 519 solutions for industrial applications can be understood.

520 One-way coupled simulations, in general, overestimate the absolute max-
 521 imum values of the vehicle dynamics results. The lateral velocity followed

522 by the yaw rate present the highest differences between the results of the
 523 coupling methods. In lateral displacement results, the maximum difference
 524 between results of the two-way coupled simulation and one-way coupled with
 525 fixed vehicle simulation is $\Delta y_{max} = 0.2$ m. Because the vehicle dynamics re-
 526 sults of the one-way coupled with moving vehicle simulation are, in general,
 527 closer to the results of the two-way coupled simulation than the results of
 528 the one-way coupled with fixed vehicle simulation, It can be concluded that
 529 employing moving vehicle (overset mesh) improve results obtained.

530 In aerodynamics results, in line with the vehicle dynamics results, the
 531 one-way coupled with fixed vehicle simulation overestimate force and mo-
 532 ment results, especially the yaw moment. It is found that the front and the
 533 lateral surfaces have the main contribution to the lateral force, the yaw and
 534 the roll moments. The main difference in between the pressure and friction
 535 coefficient results of the simulations is observed at $t=3.89$ s on the front part
 536 of the left lateral surface. Therefore it can be concluded that the flow field
 537 resolved by the simulations on the left (leeward) surface of the GTS has the
 538 biggest contribution to differences between force and moment results. Ad-
 539 ditionally, velocity fields in the near wake region downstream of the GTS
 540 reveal some more differences between the results of the simulations. For
 541 example, increase in concentrations of the TKE contours on the right (wind-
 542 ward) shear layer in the near wake region at $t = 3.89$ s, is more pronounced
 543 in the results of the one-way coupled simulations than the two-way coupled
 544 simulation. Additionally, location of the secondary vorticity concentration
 545 couple developed in the near wake region due to the crosswind is closer to
 546 the GTS in the case of one-way coupled with fixed vehicle simulation than

547 the other simulations.

548 As a conclusion, two-way coupled simulations are necessary to compute
549 effects of the crosswind on ground vehicles accurately, especially for cases in
550 which high amount of yaw angles are expected. On the other hand, con-
551 sidering the differences between one-way and two-way coupled simulations,
552 one-way coupled simulations might provide a good alternative at initial stages
553 of design processes in industrial applications in which there is a lack of com-
554 putational facility and accuracy is not a priority.

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563 **References**

564 Carbonne, L., Winkler, N., Efraimsson, G.: Use of Full Coupling of Aerody-
565 namics and Vehicle Dynamics for Numerical Simulation of the Crosswind
566 Stability of Ground Vehicles. SAE Int. J. Commer. Veh., 9(2), 359-370,
567 2016. doi:10.4271/2016-01-8148

- 568 Cheli, F., Corradi, R., Sabbioni, E., Tomasini, G., 2011(a). Wind tunnel tests
569 on heavy road vehicles: Crosswind induced loads – Part 1. *J. Wind Eng.*
570 *Ind. Aerodyn.*, 99, 1000–1010. doi:10.1016/j.jweia.2011.07.009
- 571 Cheli, F., Ripamonti, F., Sabbioni, E., Tomasini, G., 2011(b). Wind tunnel
572 tests on heavy road vehicles: Crosswind induced loads – Part 2. *J. Wind*
573 *Eng. Ind. Aerodyn.*, 99, 1011–1024. doi:10.1016/j.jweia.2011.07.007
- 574 Choi, H., Lee, J., Park, H.: Aerodynamics of Heavy Vehicles. *Annual Review*
575 *of Fluid Mechanics*, 2014. 46:441–68. doi:10.1146/annurev-fluid-011212-
576 140616
- 577 Croll, R.H., Gutierrez, W.T., Hassan, B., Suazo, J.E., Riggins, A.J.: Experi-
578 mental Investigation of the Ground Transportation Systems (GTS) Project
579 for Heavy Vehicle Drag Reduction. In: 1996 SAE International Congress
580 and Exposition, Detroit, Michigan, February 26-29, 1996.
- 581 Favre, T., 2011. “Aerodynamics simulations of ground vehicles in unsteady
582 crosswind”, PhD thesis, KTH School of Engineering Sciences.
- 583 Forbes, D.C., Page, G.J., Passmore, M.A., Gaylard, A.P.: A Fully Coupled,
584 6Degree-of-Freedom, Aerodynamic and Vehicle Handling Crosswind Sim-
585 ulation using the DrivAer Model. *SAE Int. J. Passeng. Cars - Mech. Syst.*,
586 9(2): 710-722 (2016). doi:10.4271/2016-01-1601
- 587 Ghuge, H.: Detached Eddy Simulations of a simplified Tractor-Trailer Ge-
588 ometry. MSc Thesis, Auburn, Alabama May 10, 2007.
- 589 Guilmineau, E., Chikhaoui, O., Deng, G.B., Visonneau, M., 2013. Crosswind

590 effects on a simplified car model by a DES approach. *Computers and Flu-*
591 *ids*, 78, 29–40.

592 Gutierrez, W.T., Hassan, B., Croll, R.H., Rutledge, W.H.: Aerodynamics
593 overview of the ground transportation systems (GTS) project for heavy
594 vehicle drag reduction. In: 1996 SAE International Congress and Expositi-
595 tion, Detroit, Michigan, February 26-29, 1996.

596 Huang, T., Gu, Z., Feng, C.: "Transient Aerodynamics simulations
597 of a road vehicle in the crosswind condition coupled with the vehi-
598 cle's motion". *Proc IMechE Part D: J Automobile Engineering*, 1-16.
599 doi:10.1177/09.54407017704609

600 Huang, T.M., Gu, Z.Q., Feng, C.J.: Coupled Analysis of Unsteady Aero-
601 dynamics and Vehicle Motion of a Passenger Car in crosswind Con-
602 dition. *Journal of Applied Fluid Mechanics*, 10(2), 625-637 (2017).
603 doi:10.18869/acadpub.jafm.73.239.26639

604 Huang, T., Li, S., Wan, Z., Gu, C.: "Investigation of vehicle stability under
605 crosswind conditions based on coupling methods". *Proc IMechE Part D:*
606 *J Automobile Engineering*, 1-13. doi:10.1177/0954407018822424

607 Ishioka, H., Onishi, K., Nakasato, K., Nakashima, T., Tsubokura, M.: Cou-
608 pled 6Dof Motion and Aerodynamics Simulation of Road Vehicles in Cross-
609 wind Gusts. In: 33rd AIAA Applied Aerodynamics Conference, AIAA
610 AVIATION Forum 22-26 June 2015, American Institute of Aeronautics
611 and Astronautics, Dallas, TX (2015). doi: 10.2514/6.2015-3308

- 612 Lee, S., Kasahara, M., Mori, Y.: Roll Damping Control of a Heavy Ve-
613 hicle under the Strong Crosswind. In: 7th IFAC Symposium on Ad-
614 vances in Automotive Control, 4-7 September 2013, 219-224 The Inter-
615 national Federation of Automatic Control, Tokyo, Japan (2013). doi:
616 10.3182/20130904-4-JP-2042.00053
- 617 Li, S., Gu, Z., Huang, T., Chen, Z., Liu, J.: "Coupled analysis of vehicle
618 stability in crosswind on low adhesion road", International Journal of Nu-
619 merical Methods for Heat & Fluid Flow. doi:10.1108/HFF-01-2018-0013.
- 620 Kee, J.D., Rho, J.H., Kim, K.H., Lee, D.H, 2014: High Speed Driving Sta-
621 bility of Passenger Car Under Crosswind Effects. International Journal of
622 Automotive Technology, Vol. 15, No. 5, pp. 741-747.
- 623 Kim, K., Kim, B., Go, Y., Park, J., Park, J., Suh, I., Yi, K., 2014. "An
624 investigation on motor-driven power steering-based crosswind disturbance
625 compensation for the reduction of driver steering effort", Vehicle System
626 Dynamics: International Journal of Vehicle Mechanics and Mobility, 52:7,
627 922-947.
- 628 Mansor, S. and Passmore, M.A., 2008. Estimation of bluff body transient
629 aerodynamics using an oscillating model rig. Journal of Wind Engineering
630 and Industrial Aerodynamics, 96(6–7), pp. 1218–1231.
- 631 Nakasato, K., Tsubokura, M., Ikaeda, J., Onishi, K., Ota, S., Takase, H.,
632 Akasaka, K., Ihara, H., Oshima, M., Araki, T.: Coupled 6DoF Motion and
633 Aerodynamic Crosswind Simulation Incorporating Driver Model. SAE Int.
634 J. Passeng. Cars - Mech. Syst., 10(2), 662-670 (2017).

635 Nakashima, T., Tsubokura, M., Vazquez, M., Owen, H., Doi, Y.: Cou-
636 pled analysis of unsteady aerodynamics and vehicle motion of a road
637 vehicle in windy conditions. *Computers and Fluids*, 80: 1-9 (2013).
638 doi:10.1016/j.compfluid.2012.09.028

639 Schröck, D., Widdecke, N., Wiedemann, J., 2009. Aerodynamic Response of
640 a Vehicle Model to Turbulent Wind. FKFS Conference, Stuttgart.

641 Shur, M.L., Spalart, P.R., Strelets, M.Kh., Travin, A.K.: A hybrid RANS-
642 LES approach with delayed-DES and wall-modelled LES capabilities.
643 *International Journal of Heat and Fluid Flow* 29 (2008) 1638–1649.
644 doi:10.1016/j.ijheatfluidflow.2008.07.001

645 Sims-Williams, D. (2011). “Cross winds and transients: reality, simulation
646 and effects”, SAE Paper No. 2011-01-0172.

647 Storms, B.L., Ross, J.C., Heineck, J.T., Walker S.M., Driver, D.M., Zilliac,
648 G.G.: An experimental study of the ground transportation system (GTS)
649 model in the NASA Ames 7-by 10-ft wind tunnel. NASA TM-2001-209621
650 (2001) 2001.

651 Theissen, P., 2012. “Unsteady Vehicle Aerodynamics in Gusty Crosswind”,
652 PhD thesis, Technische Universität München.

653 Tunay, T., O’Reilly, C., Drugge, L.: ”The significance of roll on the dynamics
654 of ground vehicles subjected to crosswind gusts by two-way coupled simula-
655 tion of aero- and vehicle dynamics”, 26th IAVSD Symposium on Dynamics
656 of Vehicles on Roads and Tracks, 12-16 August 2019 Gothenburg, Sweden.

- 657 Unaune, S.V., Sovani, S.D., Kim, S.E., 2005. Aerodynamics of a Generic
658 Ground Transportation System: Detached Eddy Simulation. In: 2005 SAE
659 World Congress Detroit, Michigan April 11-14, 2005.
- 660 Volpe, R., Ferrand, V., DaSilva, A., LeMoyne, L., 2014. Forces and flow struc-
661 tures evolution on a car body in a sudden crosswind. *J. Wind Eng. Ind.*
662 *Aerodyn.* 128, 114–125. <http://dx.doi.org/10.1016/j.jweia.2014.03.006>.
- 663 Watkins, S., 1990. Wind-Tunnel Modelling of Vehicle Aerodynamics: With
664 Emphasis on Turbulent Wind Effects on Commercial Vehicle Drag. PhD
665 Thesis, Victorian University of Technology.
- 666 Watkins, S., Toksoy, S., Saunders, J., 1992. On the Generation of Tunnel
667 Turbulence for Road Vehicles. 11th AFMC, Hobart, Australia, December,
668 1992.
- 669 Winkler, N., Drugge, L., Trigell, A.S., Efraimsson, G.: Coupling
670 aerodynamics to vehicle dynamics in transient crosswinds includ-
671 ing a driver model. *Computers and Fluids*, 138: 26-34 (2016).
672 doi:10.1016/j.compfluid.2016.08.006
- 673 Wojciak J., 2012. “Quantitative analysis of vehicle aerodynamics during
674 crosswind gusts”, PhD thesis, Technische Universität München.