

# The energy consumption of a heavy-duty ground vehicle subjected to extreme crosswind

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## ABSTRACT

The road transport sector, a major consumer of global energy, relies predominantly on oil-based fuels and contributes significantly to greenhouse gas emissions. Enhancing fuel efficiency through improved vehicle aerodynamics is essential for sustainable mobility. However, crosswind disturbances compromise aerodynamic performance by increasing drag and rolling resistance, particularly for heavy-duty vehicles. This study investigates the impact of extreme crosswind on vehicle energy consumption and dynamic behaviour by considering driver steering response under extreme conditions at different delay times. A two-way coupled aerodynamic and vehicle dynamic simulations framework is employed to capture these interactions. The findings highlight the critical role of driver skills, i.e., prompt steering by driver effectively mitigates energy losses, whereas delayed or abrupt corrections exacerbate rolling resistance through pronounced tyre slip angles. For example, delayed steering response of the driver (e.g., 1.0 second delay) increases energy consumption by 77% when compared to 44% maximum increase for prompt steering of the driver. These results underscore the complex interplay between aerodynamic forces and driver-induced dynamic forces in shaping vehicle energy efficiency under crosswind conditions.

## 1. INTRODUCTION

The transportation of humans and goods using ground vehicles is one of the major consumers of the energy sources in the world that is accompanied by undesirable air pollution, safety issues, and other problems. According to the International Energy Agency (2024), the transportation sector consumes approximately 27% of global energy with around 90% of its energy consumption coming from oil-based fuels. Additionally, road transport accounts for approximately 75% of total transportation energy consumption, with passenger cars and heavy-duty trucks being the primary contributor.

According to the Jaramillo et al. (2022), the transportation sector contributes approximately 15% of total global greenhouse gas (GHG) emissions, making it a significant driver of climate change. Additionally, road transportation dominates among all transportation modes and accounts for nearly 74.5% of total transportation emissions. This is primarily due to the passenger vehicles such as cars and buses, which alone contribute around 45.1% of the sector's emissions, while freight trucks add another 29.4% (Ritchie, 2020). These figures underscore the urgent need to transition to cleaner transportation alternatives, such as electric vehicles, sustainable aviation fuels, and improved freight logistics, to mitigate the transportation sector's environmental impact (Jaramillo et al., 2022; Ritchie, 2020; U.S. Environmental Protection Agency, 2022).

Therefore, fuel efficiency of vehicles, in general, is crucial for multiple reasons, including economic, environmental, and performance-related factors. As fuel prices fluctuate and environmental concerns grow, the need for fuel efficient vehicles has become increasingly critical. Studies indicate that improving the vehicle aerodynamics can lead to savings of up to 25% in fuel costs for heavy-duty trucks, which often face high fuel consumption due to their size and load (Mohamed-Kassim and Filippone, 2010). Additionally, from environmental perspective, previous studies have shown that the relationship between fuel efficiency and CO<sub>2</sub> emissions is directly proportional. Thus, improvement in fuel efficiency can lead to a reduction in CO<sub>2</sub> emissions, making it a vital area of focus for both manufacturers and policymakers (Gao et al., 2023). Moreover, from the perspective of performance, fuel efficiency is closely linked to the vehicle design. Vehicles with improved aerodynamic performance experience less drag, which not only improves fuel efficiency but also enhances stability and handling, particularly at high speeds or in adverse weather conditions (Huang et al., 2017).

In designing fuel efficient vehicles, the impact of crosswinds is critical because crosswinds can significantly affect the aerodynamic performance of vehicles, for example the aerodynamic drag force acting on the vehicle can increase substantially (Zhang et al., 2020). Moreover, the stability of vehicles under crosswind conditions is crucial for maintaining fuel efficiency. Vehicles that are more stable in crosswinds can maintain a straighter path, thereby reducing the need for corrective steering inputs that can lead to reduced fuel consumption (Forbes et al., 2016; Salati et al., 2019).

The present study investigates the fuel consumption of a heavy-duty vehicle which is subjected to the crosswind by incorporating its drag force and tyre-slip angles into the driving resistances. The investigations are conducted using the ground transportation system, GTS, as the simplified heavy vehicle model together with the two-way coupled simulation between the vehicle dynamics and aerodynamics. Thus, a method for more realistic and accurate estimation of the fuel consumption of a vehicle in extreme crosswind conditions can be suggested.

## 2. METHODS

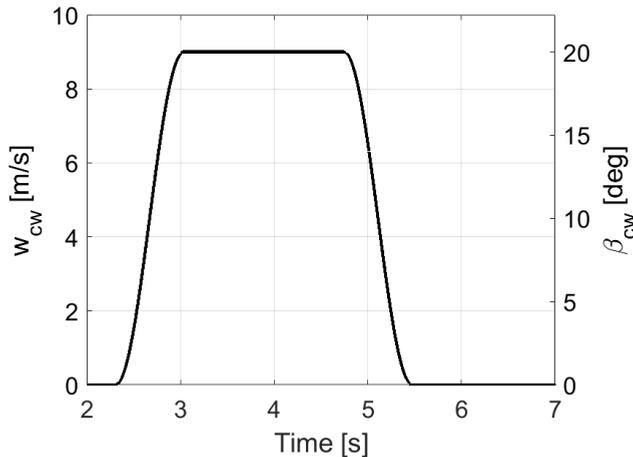


Figure 1: The extreme crosswind profile used in the investigations.

The single-track vehicle dynamics equation including roll degree-of-freedom was used to simulate the dynamics of the vehicle. Additionally, IDDES turbulence model was used for the calculation of the unsteady aerodynamic forces acting on the vehicle, e.g., drag and lift forces, due to the crosswind. The driver model used in the present study involved proportional gain

parameters on lateral displacement,  $k_y$ , yaw angle,  $k_\psi$  and the preview distance,  $k_l$ , i.e.,  $k_y = 2.0$ ,  $k_\psi = 50$ ,  $k_l = 1.5$ . The two-way coupled solution method of the vehicle dynamics and aerodynamics equations were employed in order to get an accurate and a realistic simulation of the crosswind-vehicle-driver interaction. The details of the dynamic, aerodynamic and driver models are given in (Tunay et al., 2021; Tunay, 2023; Tunay et al, 2024). The crosswind profile, shown in Figure 1, was used to simulate the extreme weather condition on roads, i.e., the maximum crosswind velocity,  $w_{cw} = 9$  m/s and the reduced frequency,  $k = \frac{2\pi fL}{u} = 1.3$  (Tunay et al, 2024). Here,  $f$  is the frequency of the crosswind (Hz) and  $u$  is the vehicle velocity (m/s) which was 25 m/s. The details of the geometrical and mass properties of the vehicle used in the present study are given in Table 1.

Table 1: Geometrical and mass properties of the vehicle employed in the study.

Vehicle's Parameter	Sym- bol	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 wheelbase	$L_{wb}$	5.9	[m]
Distance between front axle to CG	$L_f$	3.7	[m]
Distance between rear axle to CG	$L_r$	2.2	[m]
Mass	$m$	13,650	[kg]
Linear cornering stiff- ness for the front tyre	$C_{\alpha,f}$	250	[kN/rad]
Linear cornering stiff- ness for the rear tyre	$C_{\alpha,r}$	450	[kN/rad]
Roll damping of the sus- pension	$C_\phi$	100	[kN/rad]
Roll stiffness of the sus- pension	$K_\phi$	1,000	[kNm/rad]
Yaw moment of inertia	$I_{zz}$	200,000	[kgm <sup>2</sup> /rad]
Roll moment of inertia	$I_{xx}$	30,000	[kgm <sup>2</sup> /rad]

### 3. DRIVING RESISTANCES

The total driving resistance of a vehicle is calculated by summing the aerodynamic drag forces,  $F_D$ , rolling resistance forces,  $F_R$ , forces due to the grade resistance,  $F_H$ , and forces due to the acceleration,  $F_B$ , as given in Eq. (1).

$$F_T = F_D + F_R + F_H + F_B \quad (1)$$

In the present study,  $F_H$  and  $F_B$  forces were zero due to the zero-grade road condition and the constant velocity in the axial direction of the vehicle. The aerodynamic forces,  $F_D$ , were obtained directly from the results of the coupled simulation between the aerodynamics and vehicle dynamics of the vehicle. Finally, the rolling resistance,  $F_{R0}$ , of a vehicle can be calculated using Eq. (2) as suggested by (Schuetz, 2015).

$$F_{R0} = \mu_R (m \cdot g - F_{a,z}) \quad (2)$$

In Eq. (2),  $F_{R0}$  is the rolling resistance at zero sideslip angle,  $\mu_R$  is the rolling resistance coefficient, which was  $\mu_R = 0.005$  in the present study,  $m$  is the vehicle weight (in kg),  $g$  is the acceleration of gravity ( $9.81 \text{ m/s}^2$ ) and  $F_{a,z}$  is the aerodynamic lift force applied by wind on the vehicle.

Furthermore, the rolling resistance,  $F_{R\alpha}$ , in the case of the tyre slip angles,  $\alpha$ , can be calculated using the relation given in Eq. (3) as suggested by LaClair (2006).

$$F_{R\alpha} = F_{R0} + C_\alpha \cdot \alpha^2 \quad (3)$$

In Eq. (3),  $F_{R\alpha}$  is the rolling resistance at a certain tyre slip angle,  $\alpha$ , and  $C_\alpha$  is the cornering stiffness. Thus, the total  $F_R$  is calculated using Eq. (4).

$$F_{R\alpha} = \mu_R (m \cdot g - F_{a,z}) + C_\alpha \cdot \alpha^2 \quad (4)$$

Using Eqs. (2)-(4), one can obtain the Eq. (5) in which the effects of lift forces,  $F_{a,z}$ , front and rear tyre slip angles,  $\alpha_f$  and  $\alpha_r$ , contribute to the calculation of the rolling resistances,  $F_{R\alpha}$ .

$$F_{R\alpha} = \mu_R(m \cdot g - F_{a,z}) + C_{\alpha,f} \cdot \alpha_f^2 + C_{\alpha,r} \cdot \alpha_r^2 \quad (5)$$

Thus, the total power,  $P$ , needed to overcome the driving resistances of the vehicle when there is crosswind can be calculated by multiplying the total driving resistances with the vehicle velocity,  $u$ , as given in Eq. (6).

$$P = [F_{a,x} + \mu_R(m \cdot g - F_{a,z}) + C_{\alpha,f} \cdot \alpha_f^2 + C_{\alpha,r} \cdot \alpha_r^2]u \quad (6)$$

Additionally, the power needed to overcome the driving resistances of the vehicle when there is no crosswind is calculated by assuming the tyre slip angle,  $\alpha$ , is zero and the drag,  $F_{a,x}$ , and lift,  $F_{a,z}$ , forces were constant.

#### 4. RESULTS AND DISCUSSION

The present study investigates the energy consumption characteristics of a heavy-duty vehicle operating under the extreme crosswind condition. In particular, the influence of the driver's steering inputs on the vehicle's energy consumption is analysed for various delay times in the driver's steering response to the crosswind disturbances.

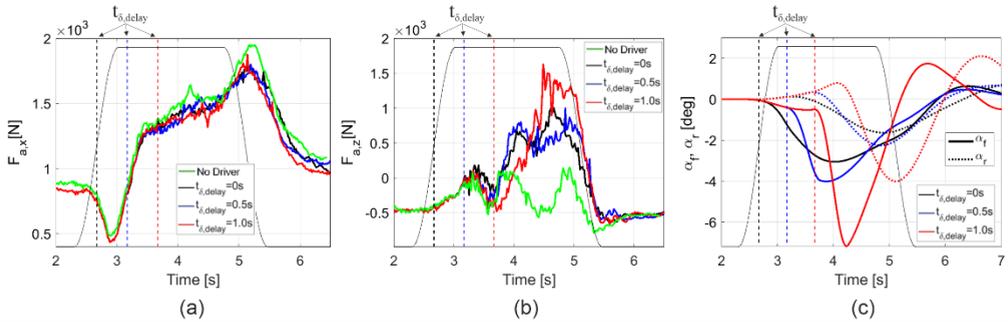


Figure 2: The aerodynamics forces (a) in the longitudinal direction (or drag forces),  $F_{a,x}$ , and (b) in the vertical direction (or lift forces),  $F_{a,z}$ , and (c) the tyre slip angles,  $\alpha_f$  and  $\alpha_r$ , at different delay times of driver's steering inputs.

Fig. 2 illustrates the longitudinal and vertical forces (i.e., drag,  $F_{a,x}$ , and lift,  $F_{a,z}$ , forces) acting on the vehicle at different delay times of driver's steering inputs aimed at counteracting extreme crosswind disturbances. The

corresponding vehicle dynamic responses, including the tyre slip angles at the front and rear axles (i.e.,  $\alpha_f$  and  $\alpha_r$ , respectively), are also presented. For comparative analysis, the figure includes results for a scenario without any steering input from the driver. Note that  $t_{\delta, \text{delay}}$  is the time at which the driver’s steering input starts after the crosswind hits the vehicle. As shown in Fig. 2(a), the peak drag forces,  $F_{a,x}$ , under different steering responses demonstrate only minor deviations from the no-steering case. Moreover, the temporal evolution of the drag force remains nearly indistinguishable across different delay times of driver inputs. In contrast, the lift force,  $F_{a,z}$ , profiles in Fig. 2(b) reveal a notable divergence. That means when steering corrections are applied, the lift force,  $F_{a,z}$ , assumes predominantly positive (upward) values, whereas it remains negative (downward) or approximately zero in the absence of steering intervention. This upward lift induced by steering in extreme crosswind conditions may be advantageous from an energy consumption perspective by reducing the normal load and thus rolling resistance. However, it also poses potential challenges to vehicle handling and stability due to reduced tyre contact forces. Fig. 2(c) shows that the peaks of all slip angles increase with the latency of the steering response. This effect is most pronounced when the steering input is delayed by  $t_{\delta, \text{delay}}=1.0$  second that highlights the strong interplay between reaction timing and control authority in mitigating crosswind-induced instabilities.

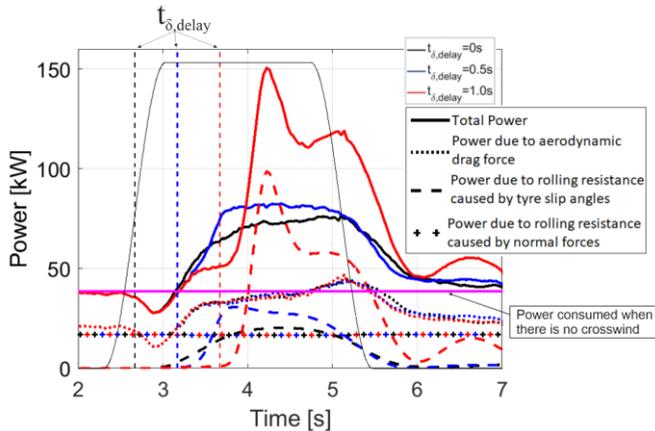


Figure 3: The power,  $P$ , consumed by the vehicle to overcome the driving resistance for various driver’s steering inputs against the extreme crosswind.

The results presented in Fig. 3 indicate that the power required by the vehicle to overcome the driving resistance under the extreme crosswind condition increases with longer delays in the initiation of steering input,  $t_{\delta, delay}$ . This trend can be attributed to the abrupt escalation in both front and rear tyre slip angles associated with the initiation of driver’s steering correction, as previously illustrated in Fig. 2(c). In contrast, the component of power demand, attributed to aerodynamic drag, exhibits comparatively lower sensitivity to the variations in steering delay time. This finding suggests that while aerodynamic resistance plays a consistent role, the dynamic tyre response induced by delayed or aggressive steering is a dominant contributor to the observed increases in power consumption.

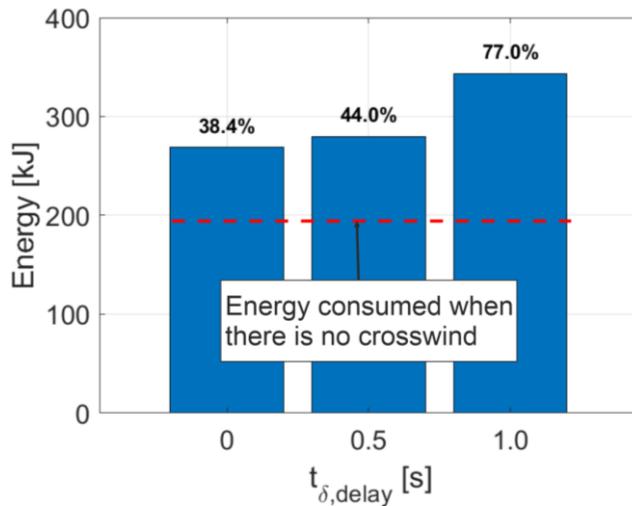


Figure 4: The energy consumed by the vehicle to overcome the driving resistance for various driver’s steering inputs.

The substantial increase in the vehicle’s energy consumption under extreme crosswind conditions is clearly illustrated in Fig. 4. For steering inputs initiated at  $t_{\delta, delay}=0$  s and 0.5 s, the energy consumption rises by maximum 44%. However, when the steering input is delayed to  $t_{\delta, delay}=1.0$  s, the increase in energy consumption reaches 77% which indicates a pronounced sensitivity to steering response timing. These findings emphasize the critical interplay between the driver skill and the steering response time in mitigating the energy inefficiency caused by the extreme crosswind disturbances.

## 5. CONCLUSION

The present study examined the impact of extreme crosswind scenario on the energy consumption and dynamic response of a heavy-duty vehicle. The results of study provided detailed insights into the energetic consequences of crosswind-vehicle-driver interactions by evaluating the delays in the driver's steering response.

The role of driver's steering input in the extreme crosswind conditions was investigated in detail using the representative extreme crosswind profile. The findings revealed that the delay in initiating a steering response play crucial roles in shaping the vehicle energy demand. While the prompt reaction of driver demonstrates more effective control thereby minimizing energy losses, the delayed response of the driver contributes to the highest energy penalty when the steering response is delayed. This is primarily due to the rapid onset of large slip angles which leads to the sharp increases in rolling resistance. In the extreme crosswind scenario studied, the energy consumption increased by 77% for a delayed steering response of 1.0 second, compared to the maximum 44% increase for a timely response by the driver.

In conclusion, the study underscores two main implications. First is that the crosswinds significantly deteriorate vehicle energy efficiency, with the extent of impact strongly dependent on the driver's behavioural response. The second is that the energy losses are not solely governed by aerodynamic drag; dynamic tyre responses and slip-induced resistances, particularly under delayed or abrupt steering actions, emerge as dominant contributors to power surges and cumulative energy demand.

Future research based on the motivations of present study could investigate the influence of variety of aerodynamic scenarios that have different maximum velocities and frequencies of the single crosswind events on the energy consumption of heavy-duty vehicles. Furthermore, future research could focus on evaluating the cumulative effects of prolonged crosswind exposure over extended driving distances. In particular, persistently windy environments may impose significant long-term impacts on overall system performance and durability, making this an important area for further investigation. For instance, in the context of electric vehicles, repeated crosswind-induced power surges may accelerate battery degradation, thereby shorten the service life, and reduce the operational efficiency.

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