

Vehicle motion matters for modelling the near-field dispersion of tailpipe emissions

Yu Zhang

yuzhang2020@sina.com

Hefei University of Technology

Junqi Chen

Hefei University of Technology

Bo Si

Hefei University of Technology

Chenfang Wang

Hefei University of Technology

Chunmei Wang

Hefei University of Technology

Yuhan Huang

University of Technology Sydney

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Abstract

The near-field dispersion of vehicle emissions is critical for the management of roadside air pollution and the development of non-intrusive tailpipe emission detection technologies (e.g., on-road remote sensing). Existing CFD studies mostly adopted the conventional wind-tunnel-like static mesh (i.e., the vehicle is fixed but the air flows at the vehicle speed in the opposite direction), which may fail to capture the airflows induced by vehicle motion and cause significant errors in the predicted exhaust plumes, particularly at high vehicle speeds. This study developed a dynamic mesh to represent the real vehicle motion and adopted the large eddy simulation (LES) with a wall-adaptive local vortex viscosity model to capture the airflow and emission dispersion processes. Two representative vehicle speeds of 30 and 90 km/h were considered, and the results were compared with the conventional static mesh method. Specially, the plume length was quantified by an innovative integral method based on the NO/CO₂ concentration ratio. The results showed that plume lengths predicted by dynamic and static meshes were comparable at 30 km/h, but static mesh over-estimated plume length by 29% at 90 km/h. The discrepancy stemmed from the inability of static mesh to resolve the dynamic balance between backward exhaust flow and forward-induced airflow, resulting in distorted vortex structures. In comparison, dynamic mesh produced quasi-parallel streamlines that match real driving conditions. This study demonstrated that dynamic mesh could substantially improve the modelling accuracy of near-field dispersion of vehicle emissions, providing important references for roadside air pollution modelling and remote sensing device optimisation.

Highlights

- Impact of static and dynamic meshes on near-field vehicle emission dispersion was assessed.
- An innovative integral method was used to quantify gas components and velocity plume lengths.
- Dynamic mesh captured the interactions between exhaust and vehicle-induced airflows.

1 Introduction

Vehicle emissions are the primary source of air pollution in our cities, posing a persistent and severe threat to the public health worldwide [1]. The roadside air pollution is usually much more serious than the ambient air pollution due to the proximity to tailpipes and the reduced air ventilation when deep urban street canyons are present [2]. Modelling the near-field dispersion of vehicle emissions is of great importance to a wide range of applications, such as roadside air pollution management [3], pedestrian exposure assessment [4], and the development of non-intrusive emission monitoring techniques such as on-road remote sensing (RS) and plume chasing [5]. In recent years, efforts have also been made to combine field measurements with dispersion models to derive real-world emission rates [6] and to evaluate how aggregate versus individual vehicle activity data affect emission estimates and subsequent air quality predictions [7]. These studies underscore the need for robust modelling

approaches that can accurately represent the complex interplay between vehicle movement, exhaust release, and atmospheric dilution.

In spite of a small proportion (~ 10%) of total fleet, diesel vehicles are the leading contributors of NO_x emissions making it critical to identify and target high emitters for effective pollution control [8, 9]. On-road remote sensing has emerged as a fast, non-intrusive, and cost-effective method for detecting real-world vehicle emissions. Two main configurations are commonly employed: horizontal and vertical beam setups. Hydrocarbon (HC), carbon monoxide (CO), and carbon dioxide (CO₂) are measured via infrared absorption, while NO is detected using ultraviolet beams [10]. Within half a second after the vehicle passes the measurement location, the ratios of pollutant concentrations (e.g., CO, HC, and NO) to CO₂ in the exhaust plume are recorded [11]. The horizontal beam configuration is currently the dominant RS method, which is only applicable to single lane traffic which limits its measurement efficiency and site selection. The vertical arrangement overcomes these limitations by placing measurement equipment at a high elevation. Moreover, the vertical configuration can provide detailed information on emission dispersion, as it uses a “whiskbroom” scanning approach to capture downward-facing images of passing vehicles and their exhaust plumes [12]. In addition, numerical studies have begun to explore the detailed structure of exhaust plumes specifically for remote sensing applications; for example, Plogmann et al. employed unsteady Reynolds-averaged Navier–Stokes (URANS) simulations to investigate the mixing and dilution of vehicle plumes [13], revealing that the characteristic emission signature is only preserved for a short distance downstream of the tailpipe—a finding directly relevant to the optimal placement of RS beams. The landmark study published in Environmental Pollution further refined plume modelling for light-duty and heavy-duty vehicles, highlighting discrepancies between simulated and measured effective RS detection lengths under fixed-vehicle wind tunnel-style setups [14]. For enforcement-oriented high-emitter identification, RS measurement accuracy relies entirely on capturing undistorted exhaust concentration ratio. Therefore, this work focuses on the vertical RS configuration due to its demonstrated advantages and promising performance.

For enforcement purposes, the identification of high-emitting vehicles must be highly accurate, which is a key challenge of RS devices. Computational fluid dynamics (CFD) is an effective tool to improve RS accuracy by visualising detailed information about the transport of pollutant emissions in turbulent fields behind a vehicle. The dispersion processes of pollutant emissions have been investigated when vehicles are traveling in tunnels [15], open spaces [16], idealised street canyons [17, 18], and complex urban streets [19]. The types of pollutant emissions include CO, CO₂, NO and particulate matter (PM) [20, 21]. SF₆ is a reasonable alternative for PM [22, 23]. Most turbulence models used the Reynolds Averaged Navier-Stokes (RANS) approach [24, 25], while an increasing number of studies used Large Eddy Simulation (LES) [26]. Beyond conventional pollutant species, recent CFD investigations have also addressed particulate dispersion from moving vehicles, such as the analysis of fine clay particles resuspended by trucks operating on unpaved roads [27]. Furthermore, the influence of roadside infrastructure on plume evolution has been quantified; for instance, studies have shown that noise barriers can modify the wake structure and enhance pollutant retention in the near-road environment

[28]. These findings highlight that both vehicle-induced turbulence and surrounding geometrical features play essential roles in plume dispersion, and that simplifications in the modelling setup may introduce non-negligible errors.

Despite these advances, the vast majority of existing CFD studies rely on a static-mesh, wind-tunnel-like setup, where the vehicle is fixed and a uniform opposing airflow is imposed to represent its forward motion. This equivalent boundary condition fundamentally fails to reproduce the dynamic balance between the backward exhaust jet and the forward vehicle-induced airflow, leading to distorted wake vortices and biased plume length predictions. Dynamic mesh techniques, which physically move the vehicle through static ambient air, offer a more faithful representation. A few studies have adopted this approach, including the Hong Kong University of Science and Technology team [29] for street canyon simulations, as well as Song [20] and Wang et al. [30] for tunnel and urban canyon studies. However, these dynamic-mesh investigations rarely conduct systematic, quantitative comparisons against static-mesh outputs, nor do they develop objective metrics for plume-length quantification. In the context of environmental fluid mechanics, the modelling of vehicle-induced turbulence remains challenging: while Kastner-Klein et al. [31] established the importance of traffic-induced turbulence for street-canyon dispersion over two decades ago, and recent EFM studies [32, 33] have continued to advance LES-based dispersion modelling in urban environments, the specific question of how mesh treatment — static versus dynamic — biases near-field plume predictions at different vehicle speeds has not been systematically addressed. However, these dynamic-mesh investigations rarely conduct systematic, quantitative comparisons against static-mesh outputs, nor do they develop objective metrics for plume-length quantification. More critically, to the best of our knowledge, few studies have systematically the effects of low-speed urban versus high-speed highway conditions to evaluate how vehicle speed amplifies static-mesh modelling errors, nor examined the implications for vertical remote sensing (RS) systems.

To fill this gap, this study establishes a systematic comparative framework to quantify disparities between static and dynamic mesh simulations at representative urban (30 km/h) and highway (90 km/h) speeds. Specifically, we develop a dynamic mesh domain partitioning strategy paired with wall-adaptive LES (WALE) to resolve transient wake vortex evolution. Based on this, we propose a vertical line integral method to objectively quantify both pollutant plume length and the effective measurement window for vertical RS devices. This integrated approach allows us to reveal the physical mechanism behind static-mesh overestimation of plume extent at high speeds, and to provide practical engineering guidelines for both CFD setup and RS hardware optimisation. Comparative results demonstrate that static mesh produces minimal deviation at low vehicle speeds but overpredicts plume length by nearly 29% at 90 km/h, stemming from its inability to capture the counterbalance between exhaust outflow and vehicle-induced incoming airflow. Beyond advancing fundamental CFD modelling accuracy for traffic pollution, this research delivers practical engineering references: it provides clear recommendations for mesh selection in future roadside dispersion simulations, and offers optimised beam layout and sampling time strategies for vertical remote sensing equipment to reduce measurement dilution bias and improve high-emitting vehicle identification precision.

2 Numerical models

2.1 Conservation equations

The simulations were conducted using ANSYS Fluent. Eqs. (1)-(4) are mass, momentum, energy, and species conservation equations. Chemical reactions are ignored because of the short time scale considered in this work. Except for nitrogen (N₂) and oxygen (O₂) in the air, only CO₂, NO and water vapor (H₂O) are considered in this work because CO and HC emissions are relatively low in a diesel vehicle. Large eddy simulation (LES) with a wall-adaptive local vortex viscosity (WALE) model is employed to capture transient turbulent flows. The pressure-velocity coupling is solved using the Pressure-Implicit with Splitting of Operators (PISO). The absolute criteria for conservation equations are 10⁻⁶.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0$$

1

$$\frac{\partial}{\partial t}(\rho \vec{u}) + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot (\bar{\tau}) + \rho \vec{g}$$

2

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\vec{u}(\rho E + p)) = \nabla \cdot \left(k_{eff} \nabla T - \sum_i h_i \vec{J}_i \right)$$

3

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho \vec{u} Y_i) = -\nabla \cdot \vec{J}_i$$

4

2.2 Computational meshes and boundary conditions

In this work, pollutant dispersion is modelled using both static and dynamic meshes. For the static mesh, the vehicle is fixed at a specific location and its motion is simulated by setting an air flow at the vehicle speed in the opposite direction. For the dynamic mesh, the vehicle moves at a constant speed in a static ambient air environment. A Toyota Hiace vehicle (Fig. 1a) with a 3.0 L turbocharged diesel engine is investigated in this work, whose length, width, and height 4695, 1695, and 1980 mm, respectively. The exhaust tailpipe is on the vehicle's left hand and its diameter is 104 mm.

1. Static mesh

The computational domain for the static mesh (the region B in Fig. 1b) is a rectangular box with 20, 6 and 5 m in length, width and height, respectively. The vehicle is placed on the centerline at a location of 4 m from the front of the computational domain. The mesh is generated by ICEM and it is composed of hexahedral structured meshes. The meshes around the exhaust tailpipe, vehicle surface and ground are refined to capture the flow characteristics with dramatic changes.

The vehicle is stationary and the vehicle speed is considered by setting an inlet air velocity. Therefore, the domain front is set as a velocity inlet. The inlet velocities are 0.0, 8.3 and 25.0 m/s which correspond to the vehicle speeds of 0, 30 and 90 km/h, respectively. Air (79% N₂, 21% O₂) enters the inlet at 300 K. The outlet of the exhaust tailpipe is also set as a velocity inlet. The exhaust velocity, temperature and component concentration under different driving speeds are set based on the experimental measurements [14]. Both the rear and top faces are set as pressure outlets. The no-slip wall is applied to the ground and vehicle surfaces. Both the left and right faces are periodic boundaries and they are associated with each other. **Table S1** shows detailed boundary conditions for the static mesh.

2. Dynamic mesh

Compared to static mesh, dynamic mesh better represents the actual driving environment [16]. In this study, the dynamic mesh is generated based on the static mesh, which is divided into three regions of A, B, and C (Fig. 1b). The vehicle is placed in region B, whose setting is the same as the static mesh. The vehicle is relatively stationary in region B, both the whole region B moves forward at the driving speed. Regions A and C are before and behind the region B, respectively. The initial lengths of regions A and C are 200 and 2 m, respectively. With the movement of region B, region A gradually disappears and region C appears.

The main advantage of the dynamic mesh is a decoupling analysis of the effects of inlet and vehicle velocities. The vehicle velocity is considered by setting a velocity for region B. Furthermore, an interface boundary is needed to establish a relationship between different regions. For example, interface A-B is set by coupling the rear in region A and the front in region B. Similar to the static mesh, the left and right faces in regions A, B and C are coupled by setting a periodic boundary. **Table S2** shows detailed boundary conditions for the dynamic mesh.

2.3 Data processing method

To obtain generalised results, the data processing method is similar to that of remote sensing measurement, which concerns the relative pollutant concentration changes relative to the CO₂ concentration (a bulk gas in the exhaust plume), rather than the absolute pollutant changes. In remote sensing, the light source emits ultraviolet and infrared beams which are absorbed by CO₂, CO, NO_x, and HC in the exhaust gas. Then, the light passing through the exhaust gas is received by the detection equipment. The integration of emission concentration along the light path is determined by the attenuation of light intensity based on Lambert Beer's law (Eq. (5)). I is light intensity and dI is the weakened light intensity due to the absorption of gas molecules. k is a proportionality coefficient. $C(y)$ is

the local molar concentration and dy is the tiny change of vertical distance. Eq. (6) can be obtained by integrating Eq. (5). I_1 and I_2 are the intensities of input and output lights, respectively. It is necessary to calculate the integration of molar concentration along a light path. This paper simulates the working process of the remote sensing measurement, whose light direction is vertical.

$$\frac{dI}{I} = -kC(y) dy$$

5

$$\int_1^2 \frac{dI}{I} = \ln\left(\frac{I_2}{I_1}\right) = -k \int_1^2 C(y) dy$$

6

To simulate the working process of the remote sensing measurement in the vertical direction, the vertical lines have to be distributed uniformly in the vehicle wake area (Fig. 1b). The process of integrating the data over the vertical lines is divided into five steps. Firstly, the molar concentration and mesh height of a specific mesh need to be abstracted to calculate the integration. Secondly, a product is obtained by multiplying the molar concentration and mesh height in the same mesh. Thirdly, these products are summed along each vertical line. Fourthly, the integral value is averaged in the range of 3.0–8.0 s to eliminate the impact of temporal fluctuation. The 3.0–8.0 s interval is chosen because the vehicle wake develops into a statistically quasi-steady state after 3.0 s, and all boundary conditions remain unchanged before 8.0 s, avoiding the influence of initial startup transients..Finally, a contour map is generated in the x-z plane.

2.4 Sensitivity analysis and model verification

Figure 2 shows sensitivity analysis and model verification for the static mesh when the vehicle speed is 0 m/s. Sensitivity analysis is a critical issue for CFD simulations, including both mesh density and timestep. To achieve mesh independence, two different densities for the static mesh are tested in this study, namely coarse (662,672 nodes) and fine (2,057,149 nodes) meshes. The mesh size in the area near the tailpipe is refined to 0.04 m in the coarse mesh and 0.02 m in the fine one. A five-second average data (from 3 to 8 s) is plotted in Fig. 2 because the flow is unstable in the initial period (from 0 to 3 s). Figure 2 shows the changing trends of the mole fraction of CO_2 and gas temperature along the tailpipe center. The computational time for the fine mesh is about 70% longer than that for the coarse one. Therefore, the coarse mesh is selected due to low computational cost and reasonable accuracy. Furthermore, the gas temperature and mole fraction of CO_2 along the tailpipe centerline are also experimentally measured by a K-type thermocouple and a gas analyser [14]. The model is considered valid because the numerical curves agree very well with the experimental data. In addition, two timesteps (0.1 and 0.01 s) are also compared in Fig. 2. The timestep of 0.1 s is chosen because the curves of the two timesteps coincide with each other. Since region B of the dynamic mesh is the same as that of the static mesh, there is no need for additional sensitivity analysis and model verification.

Sensitivity analyses are also conducted on the time step and the density of vertical lines using the integration method introduced in Fig. 3. Two line densities are adopted as follows, namely 110 and 399 vertical lines. These lines are evenly laid out after the vehicle (4 m in x-direction $\times$ 1.695 m in y-direction). For 110 vertical lines, 11 and 10 lines are placed along the x- and y- directions, respectively. For 399 vertical lines, 21 and 19 lines are placed along the x- and y- directions, respectively. Comparisons are made for the integral values along the tailpipe's centerline for 110 (Fig. 1b) and 399 vertical lines, and for two different time steps of 0.1 and 0.01 s. Insignificant dependences on time step and line density are observed. Therefore, 110 lines (11 $\times$ 10) and 0.1 s are selected to conduct the integration method.

3 Results and discussion

This study focuses on comparing the effect of dynamic and static meshes on the near-wake dispersion process of exhaust emissions. The main research parameters are the CO₂ integral molar concentration, the velocity streamlines and the NO/CO₂ ratio. Figure 4 compares the integral CO₂ molar concentrations using dynamic and static meshes at of 30 and 90 km/h. For each speed, the integral molar concentration is divided into 10 levels. The top three levels represent the high-concentration region and the black dashed lines are drawn in Fig. 4 to describe the boundary of high-concentration regions. The largest x-coordinate on the high-concentration boundary defines the plume length. The plume length of dynamic mesh is slightly shorter than that of static mesh at 30 km/h (Fig. 4a and 4b). The difference in plume length between dynamic and static meshes is further increased at 90 km/h (Fig. 4c and 4d). For the dynamic mesh, the plume length is significantly shortened as the vehicle speed increases. However, the shortening of the plume length with increasing vehicle speed is not significant for the static mesh. The distribution of integral CO₂ molar concentrations on the center line of the tailpipe and velocity streamlines behind the vehicle can explain these phenomena. A similar phenomenon is also found in the contour plot of integral NO molar concentrations.

Figure 5 compares integral CO₂ molar concentrations on the tailpipe's centerline between static and dynamic meshes at vehicle speeds of 30 and 90 km/h. Four phenomena can be observed in Fig. 5. First, the two curves approximately coincide with each other for static and dynamic meshes at 30 km/h (Fig. 5a). Second, the curve of static mesh is higher than that of dynamic mesh from 0 to 4 m at 90 km/h (Fig. 5b). The first two phenomena can explain that the plume lengths are similar for static and dynamic meshes at 30 km/h (Fig. 4a and 4b). The plume length of dynamic mesh is shorter than that of static mesh at 90 km/h (Fig. 4c and 4d). Third, the integral CO₂ concentration of static mesh is higher than that of dynamic mesh at the outlet of the exhaust pipe (x = 0.0 m) for both speeds. Finally, the maximum difference in CO₂ concentration is at the location of x = 1.2 m behind the exhaust pipe.

Figure 6 compares the distribution of CO₂ molar concentration at the locations of x = 0 and 1.2 m, where showed an obvious difference between static and dynamic meshes in Fig. 5. At 0–3 m above the ground (y = 0–3 m), the region can be divided into five sub-domains, including $\square$ under the vehicle bottom, $\square$ from the vehicle bottom to the tailpipe bottom, $\square$ the tailpipe, $\square$ from the tailpipe top to the vehicle top, and $\square$

above the vehicle top. As shown in the partially enlarged drawing in Fig. 6a and 6b, the molar concentration of CO_2 in the static mesh is higher than that of the dynamic mesh in the fourth sub-domain. In the other four sub-domains, the distribution of CO_2 concentrations is the same for static and dynamic meshes. The results can explain the third phenomenon in Fig. 5. For the static mesh in Fig. 6c and 6d, the CO_2 emissions concentrate in a region of $y = 0.50\text{--}0.80\text{ m}$, which corresponds to the height of the exhaust pipe. The CO_2 concentration of static mesh is significantly higher than that of dynamic mesh in this region of the exhaust pipe. In other regions, the CO_2 concentration is similar for the two mesh technologies. This can explain the **fourth phenomenon** in Fig. 5.

The distribution of CO_2 concentration is flat for the dynamic mesh in Fig. 6. This phenomenon can be explained by the velocity streamlines in Fig. 7. The vehicle motion creates a negative pressure zone behind the vehicle. The flow of exhaust gases from the tailpipe is likely to be hindered by the forward airflow, which is induced by this negative pressure zone. Finally, the CO_2 concentration spreads in a wide region for the dynamic mesh.

For the dynamic mesh, the velocity streamlines are quasi-parallel and their direction is the same as the direction of vehicle movement. For the static mesh, multiple vortices are formed behind the vehicle. These vortices carry CO_2 emissions from the third subdomain to the fourth subdomain. This explains that the integral concentration of static mesh is higher than that of dynamic mesh in the fourth subdomain (Fig. 6a and 6b).

The 0-velocity contour (Fig. 8) is the velocity equilibrium position between the exhaust gas and the induced air flows. The velocity plume length is defined by the largest x-coordinate of 0-velocity contours. The velocity plume length shortens with increasing vehicle speed. From Fig. 9, although the exhaust gas velocity increases with increasing vehicle speed, the increased magnitude of induced velocity significantly exceeds the increase of the exhaust gas velocity. This phenomenon can explain why the plume length shortens with increasing vehicle speed for the dynamic mesh.

The analysis of characteristic speed can also explain that the plume length of static mesh is significantly longer than that of dynamic mesh at 90 km/h. On one hand, the exhaust-gas velocity of static mesh is higher than that of dynamic mesh and their difference equals the vehicle speed (Fig. 9). On the other hand, the exhaust gas is inhibited by the induced air for the dynamic mesh. However, the inhibiting effect is not found in the static mesh.

The RS technology can only determine the ratio of NO/CO_2 concentration and cannot ascertain their absolute concentrations. A key assumption in RS technology is that the NO/CO_2 concentration ratio remains constant within a given plume length. From Fig. 10, NO/CO_2 is almost unchanged ($\text{NO}/\text{CO}_2 \approx 0.005$) in the region near the exhaust pipe because the emission dispersion is controlled by the high velocity of exhaust gas. In the downstream region, the ratio of NO/CO_2 concentration rapidly decreased because molecular diffusion is dominant. In this work, the binary diffusion coefficient D_{AB} of

any two components is calculated using Eq. (7), where σ_{AB} is the characteristic length and Ω_D is the diffusion collision integral. The relationship between D_{AB} and temperature can be fitted as a second-order function, which is input into Fluent. Then, the diffusion coefficient of component i in the mixture ($D_{i,m}$) is calculated by Eq. (8) to improve the simulation accuracy. X_i is the mole fraction of component i . **Table S3** shows the fitting function for the mass diffusivity coefficient.

$$D_{AB} = \frac{0.00266T^{3/2}}{PM_{AB}^{1/2}\sigma_{AB}^2\Omega_D}$$

7

$$D_{i,m} = \frac{1 - X_i}{\sum_{j,j \neq i} (X_j / D_{ij})}$$

8

From Fig. 10, the effective measurement region of RS technology for dynamic mesh is shorter than that for static mesh. For one measurement of RS, it lasts for 0.5 seconds at 200 Hz as the vehicle passes through the measurement site. If the vehicle speed is 30 km/h, the working length is equivalent to 4.2 meters. In this study, the effective measurement length is defined as the maximum horizontal downstream distance where the local NO/CO₂ molar ratio remains within a tolerable deviation compared with the undiluted exhaust NO/CO₂ ratio at the tailpipe outlet. In a region of effective measurement, its NO/CO₂ ratio is similar to that at the outlet of the exhaust pipe. The effective measurement length of dynamic and static meshes is only approximately 1.10 and 1.21 m, respectively. Beyond this effective length, the NO/CO₂ ratio will differ significantly from the un-diluted ratio at the engine tailpipe, and thus will not be able to represent the real combustion performance of an engine.

The dynamic mesh better represents the actual vehicle driving situation. Significant deviations of characteristic length can be observed when comparing static and dynamic meshes. When the vehicle speed is 30 km/h, the plume length of dynamic mesh is about 9.6% shorter than that of static mesh. The relative deviation of plume length will increase to 28.7% if the vehicle speed rises to 90 km/h. Furthermore, the relative deviation is about 5–10% for the effective measurement length, which is obtained based on NO/CO₂ ratio. An increase in vehicle speed will reduce the relative deviation of the effective measurement length based on the NO/CO₂ ratio.

These findings have important practical implications for the design and calibration of vertical remote sensing devices. Specifically, the effective measurement length of ~ 1.1 m indicates that the infrared/ultraviolet beams should be installed within 0.5–1.0 m horizontally downstream of the tailpipe outlet to ensure that the measurement is performed in the region where the NO/CO₂ ratio remains stable. Additionally, the sampling time window should be concentrated in the first 0.2 s as the vehicle passes

the measurement beam, rather than using the full 0.5 s nominal working window. This optimised sampling strategy can effectively reduce the dilution effect of ambient air and significantly improve the accuracy of emission concentration ratio measurements.

4 Conclusions

In this study, static and dynamic mesh methods are employed to systematically investigate the dispersion characteristics of vehicle exhaust emissions in the near-wake region, with a focus on quantifying the differences in pollutant plume evolution. The results demonstrate that significant discrepancies exist in plume lengths, flow structures, and pollutant concentration distributions between static and dynamic meshes. By accounting for the relative motion between the vehicle and ambient flow under real driving conditions, the dynamic mesh setup reproduces the kinematic boundary condition consistent with on-road scenarios. Therefore, it exhibits distinguishable near-wake features compared with static mesh simulations, particularly at higher vehicle speeds (e.g., 90 km/h). The static mesh configuration corresponds to the typical wind-tunnel setup with fixed vehicle geometry, which tends to predict longer pollutant plumes and alter near-wake recirculation characteristics under the tested driving speeds. These findings highlight the critical importance of mesh treatment strategies in accurately modeling vehicle emission dispersion, providing valuable guidance for numerical simulations of vehicular pollution in road environments. The main results are summarised as follows:

- (1) The plume length predicted by the dynamic mesh is slightly shorter than that of the static mesh at 30 km/h, and the discrepancy becomes considerably greater at 90 km/h. Correspondingly, the integrated CO₂ concentration curves from static and dynamic mesh cases show reasonable agreement at 30 km/h, while obvious deviations are observed under the 90 km/h condition.
- (2) Mesh treatment strategies lead to fundamentally different wake response characteristics with rising vehicle speed. For dynamic mesh simulations, plume length decreases markedly as travelling speed increases, which arises from the competing effect between backward exhaust jet and forward airflow induced by vehicle motion. By contrast, plume length barely varies with speed in static mesh cases, since the exhaust plume is not constrained by vehicle-induced convective flow.
- (3) The NO/CO₂ ratio is almost unchanged in the region near the exhaust pipe because the emission dispersion is controlled by the high velocity of exhaust gas. The longest distance of this region is defined by an effective measurement length, which is shorter than the working length of remote sensing technology. In the downstream region, the NO/CO₂ ratio rapidly decreases because molecular diffusion is dominant.
- (4) Overall, this study demonstrates that the induced flow field behind the vehicle is different for static and dynamic meshes. Obvious vortices are observed for the static mesh, whereas the directions of induced flow and vehicle movement are similar for the dynamic mesh. Because of the different induced flow fields, the characteristic lengths of dynamic mesh are shorter than those of static mesh. We

advocate using dynamic mesh for simulating traffic-related air pollution problems in near-wake and roadside side regions.

Declarations

Author Contribution

Y.Z. conceptualized the study, developed the methodology, supervised the project, acquired funding, and wrote the original draft. J.C. performed the numerical simulations, conducted the formal analysis, and created the visualizations. B.S. contributed to the model validation and data curation. C.F.W. contributed to the software implementation and investigation. C.M.W. contributed to the interpretation of results and manuscript preparation. Y.H. contributed to conceptualization, methodology, and critically reviewed and edited the manuscript. All authors reviewed and approved the final manuscript.

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Data Availability

All data generated or analyzed during this study are included in this published article [and its supplementary information files].

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Figures

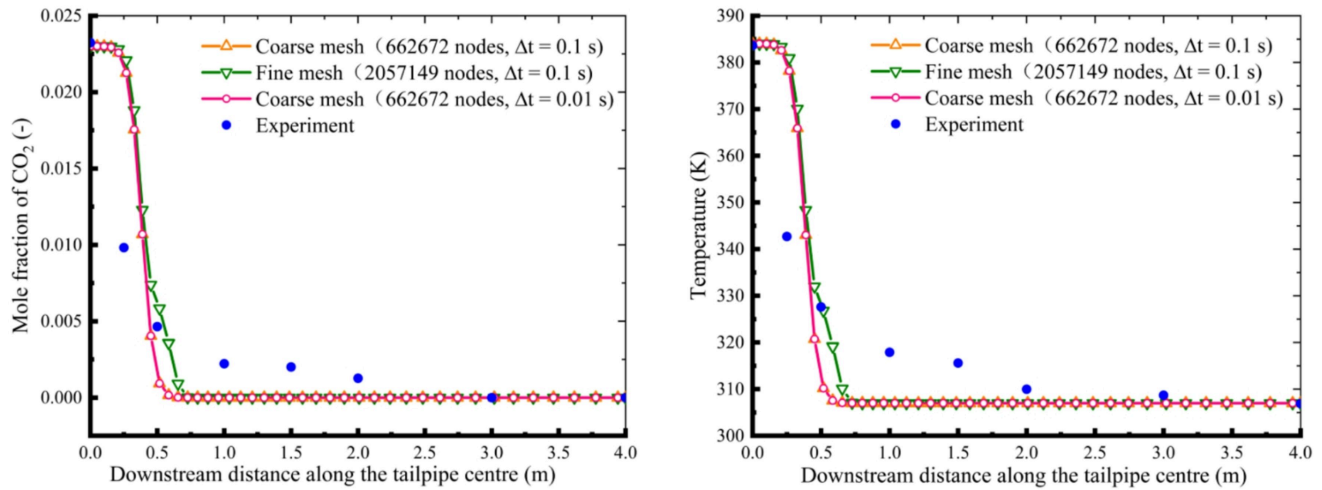


Figure 2

Sensitivity analysis and model verification for the static mesh.

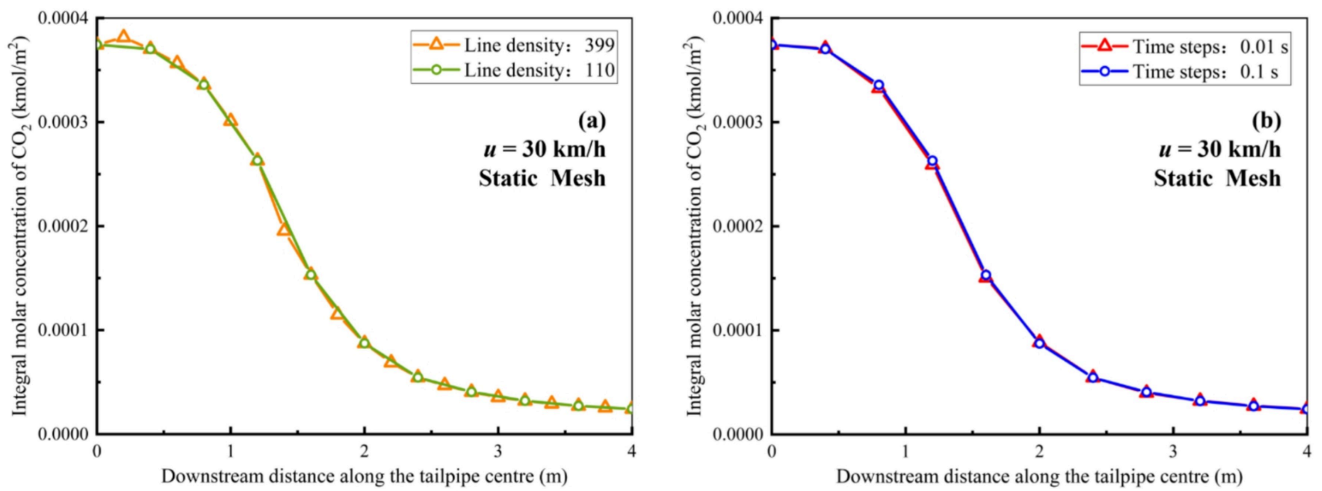


Figure 3

Sensitivity analysis of line density (a) and time step (b).

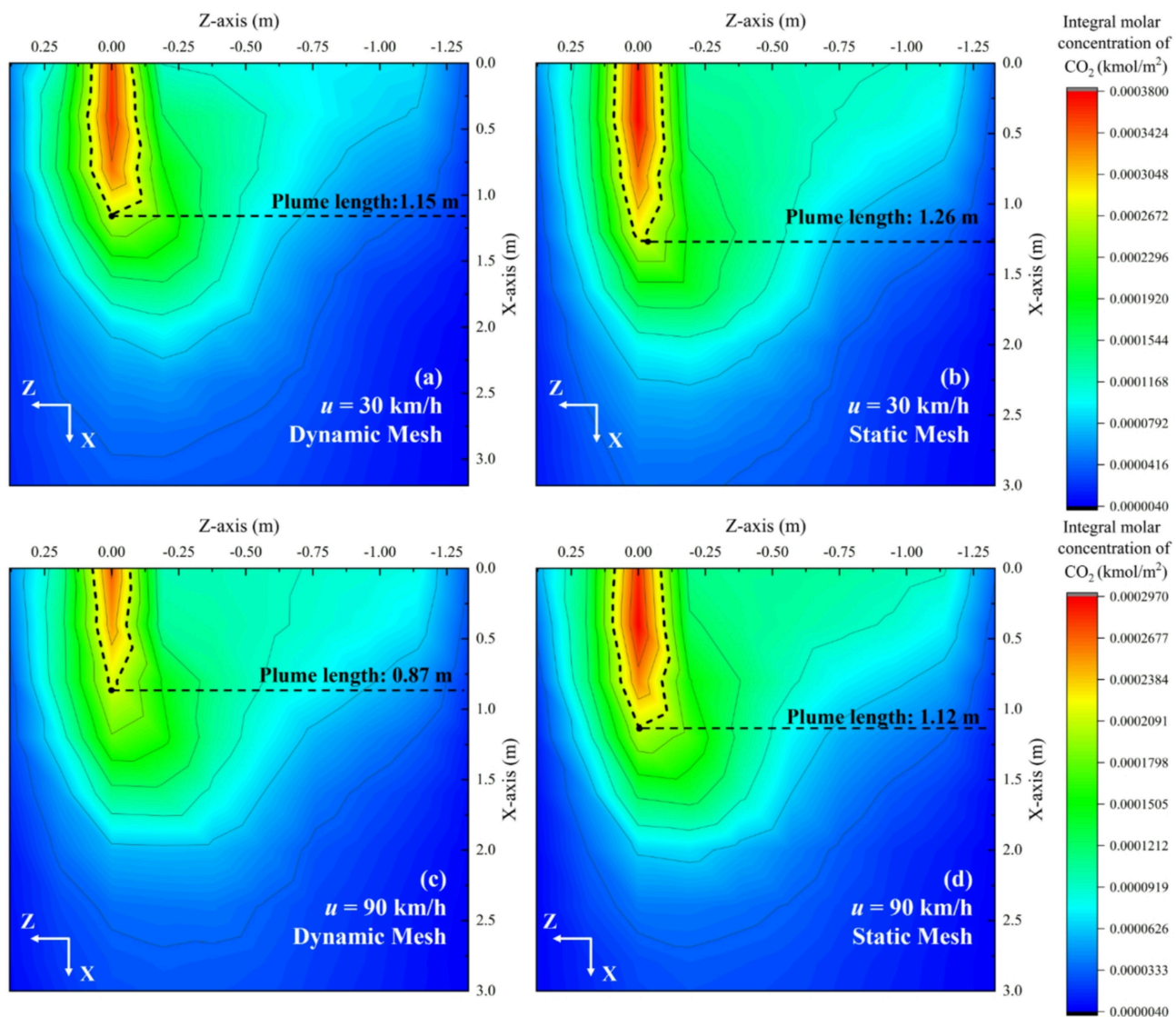


Figure 4

Comparison of CO_2 integral molar concentrations at 30 and 90 km/h for dynamic and static meshes.

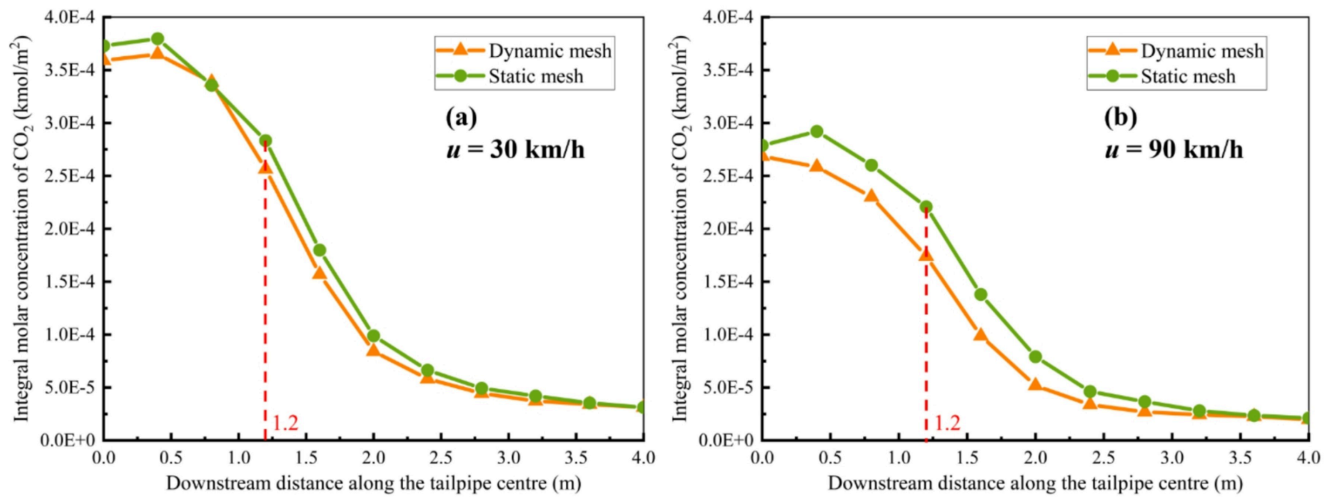


Figure 5

Comparison of CO₂ Integral Molar Concentration along the tailpipe centerline between static and dynamic meshes at 30 and 90 km/h.

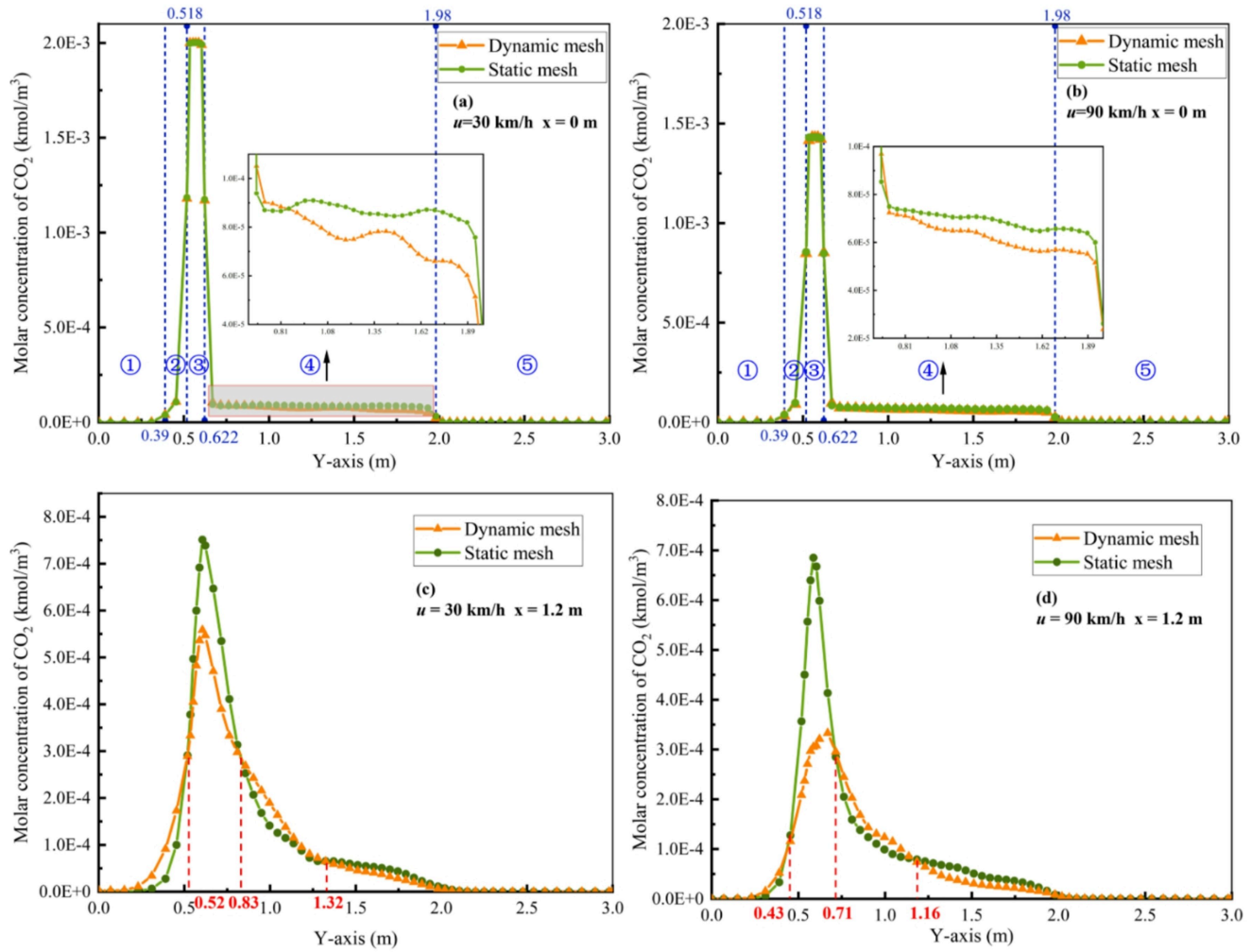


Figure 6

Comparison of molar concentrations along the Y-axis at the tailpipe outlet (**a-b**) and 1.2 m behind the tailpipe (**c-d**).

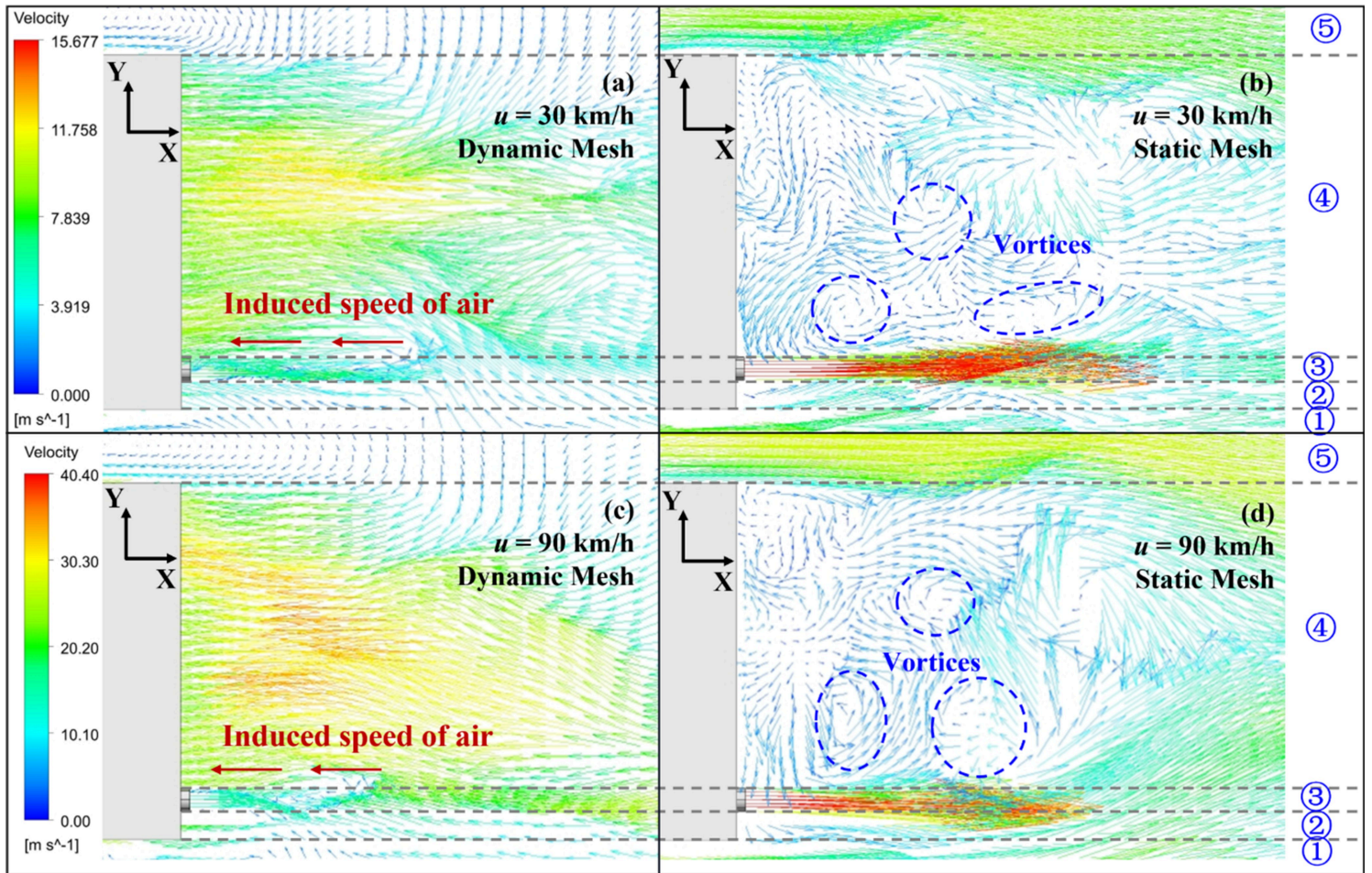


Figure 7

Velocity streamlines of dynamic and static meshes behind the vehicle at 30 and 90 km/h.

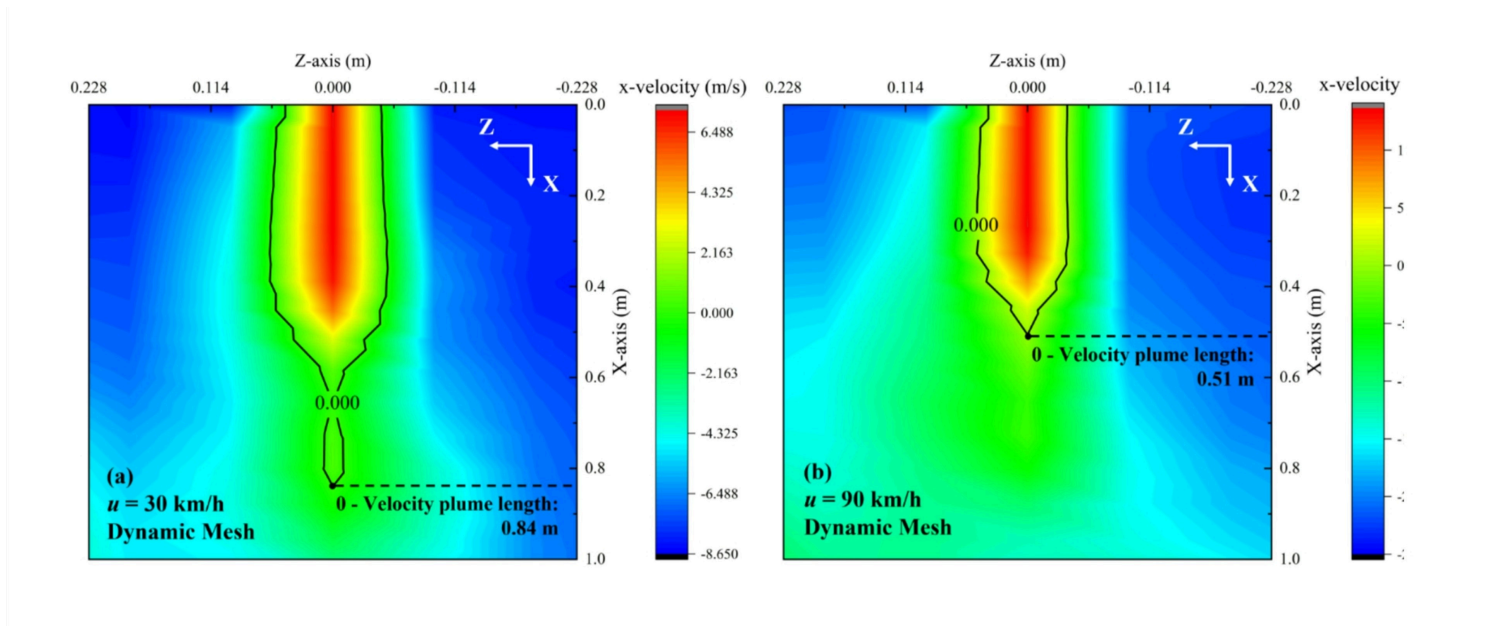


Figure 8

0-velocity contours of dynamic mesh behind the vehicle at 30 and 90 km/h.

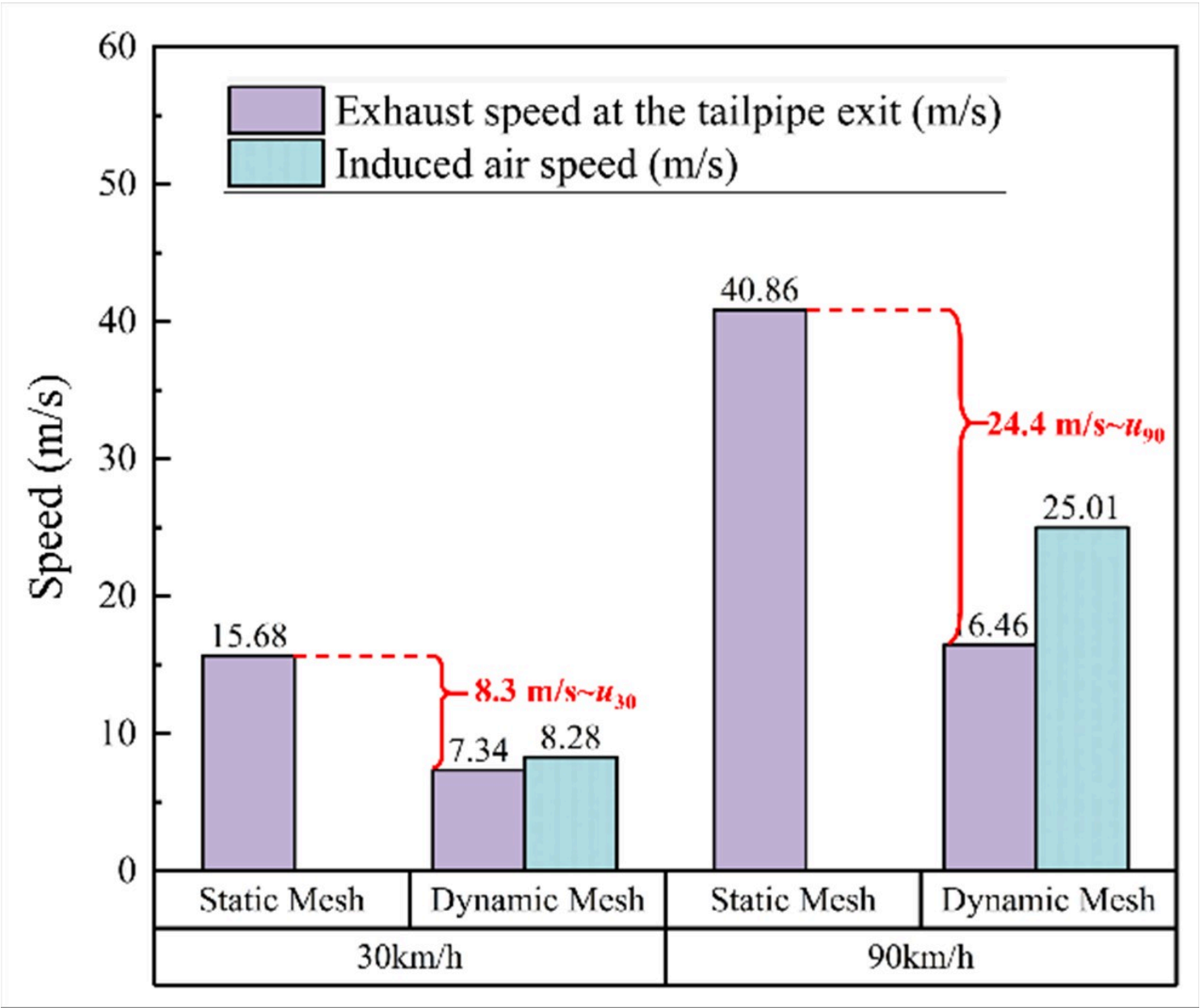


Figure 9

Characteristic speeds for static and dynamic meshes at 30 and 90 km/h.

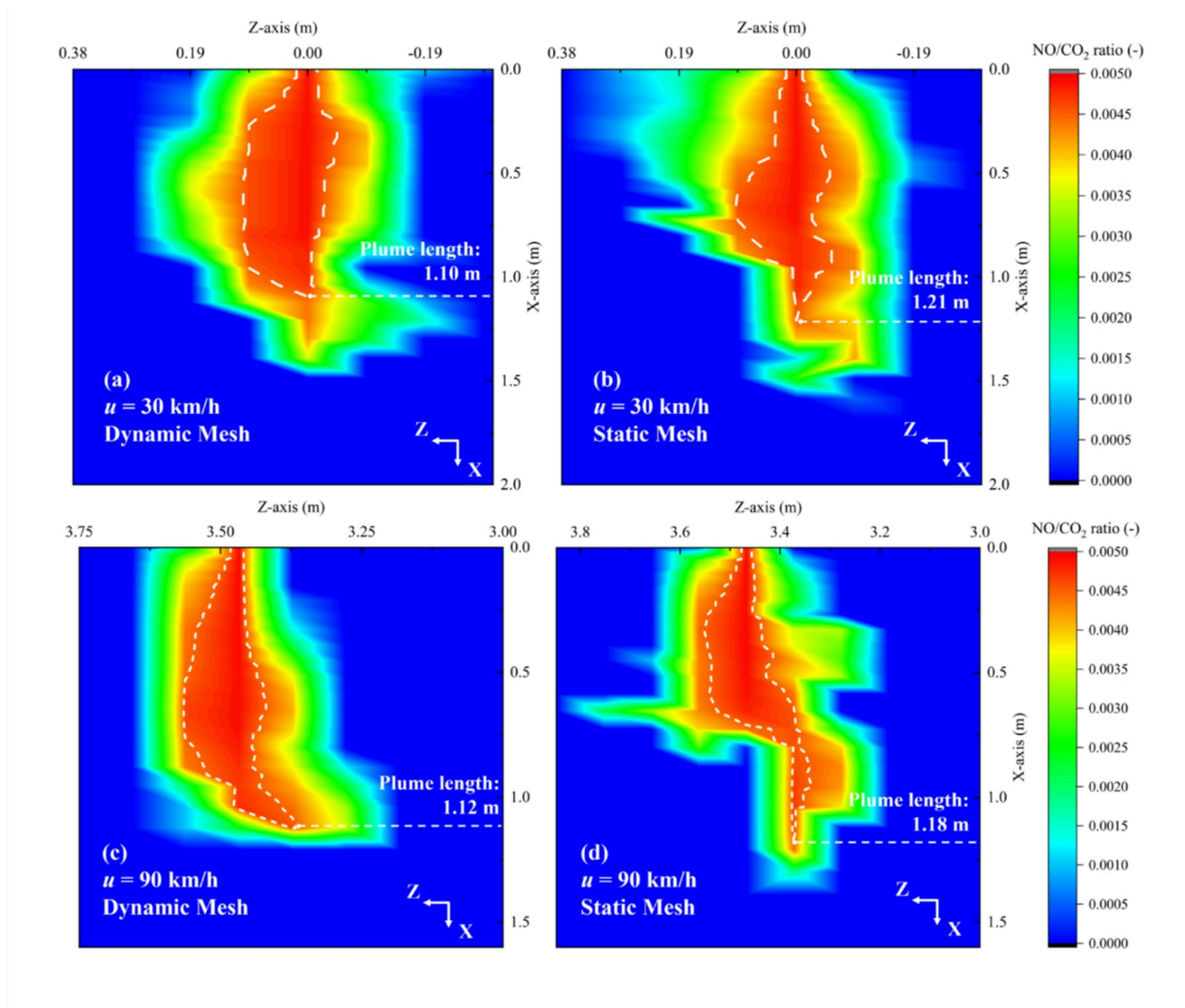


Figure 10

NO/CO₂ ratios of dynamic and static meshes at 30 km/h (**a-b**) and 90 km/h (**c-d**).

Supplementary Files

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