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Investigation of the aerodynamic phenomena associated with a long lorry platoon running through a tunnel

Xiao-Tian Zhang^{a,b,c}, Francis H. Robertson^a, David Soper^a, Hassan Hemida^{a,*}, Shi-Di Huang^{b,c,*}

^a*School of Engineering, University of Birmingham, Birmingham, B15 2TT, Edgbaston, UK*

^b*Center for Complex Flows and Soft Matter Research and Department of Mechanics and Aerospace Engineering, Southern University of Science and Technology, Shenzhen, 518055, Guangdong, China*

^c*Guangdong Provincial Key Laboratory of Turbulence Research and Applications, Southern University of Science and Technology, Shenzhen, 518055, Guangdong, China*

Abstract

In recent years, the concept of vehicle platooning has gained widespread attention for its highly efficient road usage and lower fuel consumption. However, the aerodynamics of vehicle platoons travelling in a tunnel are not well understood, even though more and more road tunnels have been built to alleviate the traffic congestion problem. This paper presents a detailed study of the aerodynamic flow created by a long lorry platoon running through a tunnel, conducted via a combination of model-scale experiments and Improved Delayed Detached Eddy Simulations (IDDES). The slipstream velocity and pressure, the lorry surface pressure, as well as the drag coefficient, were investigated systematically and compared with the results obtained in the open air. The results show greater pressure variations when the platoon is running through the tunnel. The piston effect in the tunnel leads to a lower approaching velocity and a weaker flow separation compared to the case in the open air. All vehicles, in both the tunnel and the open air, experience a drag reduction due to platooning. Interestingly, the drag reduction in the tunnel is 20% greater than that in the open air, implying a greater potential in fuel saving.

Keywords: Vehicle aerodynamics, Lorry platoon, Road tunnel, Model-scale experiment, IDDES, Drag reduction

1. Introduction

Road traffic has been continuously increasing over the years. For example,

* Corresponding authors

Email addresses: h.hemida@bham.ac.uk (Hassan Hemida), huangsd@sustech.edu.cn (Shi-Di Huang)

30 passenger transport in Europe increased by 8% from 2005 to 2015. To deal with the
31 growing traffic demand and the consequent environmental problem due to
32 increasing pollutant emissions, the concept of platooning has long been proposed as
33 a potential solution (Shladover et al., 1991). Platooning, or vehicle convoys, refers
34 to the case where several vehicles form a road-train, with relatively small gaps
35 between vehicles that are maintained autonomously. Thanks to the recent fast
36 development of autonomous road vehicles, the platooning strategy has once again
37 become an important topic in both academic and industrial fields.

38 To date, most studies of the aerodynamics of vehicle platoons were conducted in
39 the environment of open air (Alam et al., 2010; Armagan et al., 2015; Bonnet and
40 Fritz, 2000; Browand et al., 2004; Davila et al., 2013; Humphreys and Bevely, 2016;
41 Lammert et al., 2014; Le Good et al., 2018; Liang et al., 2016; McAuliffe and
42 Ahmadi-Baloutaki, 2018; Pagliarella, 2009; Robertson et al., 2021, 2019; Schito and
43 Braghin, 2012; Tsuei and Savaş, 2001; Watkins and Vino, 2008; Zabat et al., 1995).
44 Based on these studies, it is now generally accepted that platooning can not only
45 increase the efficiency of road utilisation but also bring other benefits, such as
46 decreasing the drag coefficient and thus reducing the fuel consumption. For
47 example, considerable drag reduction was identified by (McAuliffe and Ahmadi-
48 Baloutaki, 2018) in their wind tunnel experiments of a two-truck platoon with
49 various inter-vehicle separation distances. They also investigated the effect of
50 crosswinds, vehicle configuration and vehicle stagger on the truck platoon.
51 However, very few studies have focused on platoons with more than four vehicles,
52 mainly due to the length limitation of wind tunnels and the high requirement of
53 computational resources. It is not known *a priori* whether long platoons would
54 behave similarly as the short ones. (Davila et al., 2013) conducted numerical
55 simulations for a five-vehicle platoon with mixed vehicle shapes and confirmed that
56 the aerodynamic drag coefficient is reduced for all the vehicles in that platoon
57 configuration. (Le Good et al., 2018) investigated platoons of up to 5 cars and found
58 an increase in drag under certain conditions, suggesting that the optimisation
59 techniques for low-drag styles of vehicles depend on the platoon formation.
60 Nevertheless, studies on platoons of bluff vehicles with square backs, such as lorries
61 (albeit often conducted with fewer vehicles), seem to consistently show a reduction
62 in drag due to platooning. More recently, (Robertson et al., 2019) carried out model-
63 scale experiments to investigate the aerodynamics of a long platoon with eight
64 lorries. It was found that the downwind lorries were shielded effectively, and they
65 all experienced significant drag reductions. Their experimental work was also
66 complemented with numerical simulations, which showed excellent agreement
67 regarding the drag coefficients (He et al., 2019).

68 On the other hand, increasing numbers of road tunnels have been built in recent
69 years to alleviate the urban traffic congestion problem (Chung and Chung, 2007).
70 When vehicles are travelling in a tunnel, the presence of tunnel walls restricts the

71 airflow motions and additional aerodynamic forces act on the vehicles, which are
72 likely to influence the drag coefficient and even the stability of the vehicles.
73 Therefore, studying the aerodynamic phenomena associated with vehicles moving
74 in a tunnel is crucial in the design and operation of road tunnels. Early studies of
75 this issue mainly came from field measurements (Jang and Chen, 2002, 2000) and
76 model-scale experiments (Chen et al., 1998; Sambolek, 2004). Due to the cost and
77 limitations of experimental techniques, these studies generally focused on how time-
78 averaged flow quantities, such as the mean drag coefficient, vary with the size,
79 speed and number of the vehicles. The complete picture of the velocity and pressure
80 fields, especially the transient aerodynamics when vehicles entering and leaving the
81 tunnel, has largely been overlooked.

82 With the rapidly growing ability of computational methods to reliably and
83 affordably simulate complex flows, Computational Fluid Dynamics (CFD) has
84 become a powerful tool to reveal detailed flow dynamics around moving vehicles.
85 Of the many different simulation approaches available, the Reynolds Averaged
86 Navier Stokes (RANS) equations with the $k - \varepsilon$ model is the most widely used in
87 the academic literature, largely due to its comparatively low cost. (Li et al., 2009)
88 used dynamic mesh techniques to numerically simulate the aerodynamics of one van
89 running into a tunnel. They found that the drag coefficient increased sharply near
90 the tunnel entrance, about 13% more than that in the open air. They later adopted
91 the renormalisation group method (Yakhot and Orszag, 1986) to study the process
92 of two vans running in a tunnel (Li et al., 2010). It was found that the aerodynamic
93 characteristics around the first van were similar to that of a single van, and the
94 aerodynamic forces on the truck behind did not have an obvious change. By
95 performing a numerical study combining a one-dimensional mathematical model
96 and a RANS simulation, (Wang et al., 2014) obtained similar results for the case of
97 a two-vehicle platoon moving in a curved tunnel. They further found that the
98 effective drag coefficient increased with increasing the inter-vehicle spacing but
99 decreased with an increase in the vehicle speed, which was attributed to the
100 influence of vehicle wake on the airflow. (Song and Zhao, 2019) also conducted
101 RANS simulations to investigate the flow patterns induced by a fleet of vehicles
102 inside a road tunnel. Their results showed that the drag coefficient fluctuated
103 dramatically during the vehicle passing period, which could be attributed to the
104 unstable traffic wind during the transient movement process.

105 However, many authors reported that while the predicted drag coefficients in
106 vehicle aerodynamics are acceptable, the pressure distributions are often inaccurate.
107 For example, (Humphreys and Bevely, 2016) pointed out that RANS modelling was
108 only valid in predicting drag reduction for short platoons (with less than four
109 vehicles), and its description of the flow field was far from satisfactory and
110 sometimes non-physical. In addition, the one-dimensional model could result in
111 either underestimating or overestimating the drag forces, depending on the traffic

112 conditions, e.g., the speed and number of the vehicles (Eftekharian et al., 2015). In
113 this context, Detached Eddy Simulation (DES) is a more suitable numerical
114 approach (Spalart et al., 1997). Indeed, some researchers have used DES to study
115 platoon aerodynamics and obtained good agreement with experiments at a low
116 computational cost compared to Large Eddy Simulation (LES) (He et al., 2019;
117 Humphreys and Bevly, 2016). Nevertheless, previous simulation works pertaining
118 to the phenomena of vehicle platoons in a tunnel have mostly been based on RANS
119 in the academic literature, despite its deficiencies. Furthermore, as is the case in the
120 open air, these studies were limited to relatively short platoons. Moreover, the
121 traffic wind induced by vehicle platoons running in the tunnel ~~have~~has been rarely
122 studied. These limitations of the previous research form the motivation of the
123 present study.

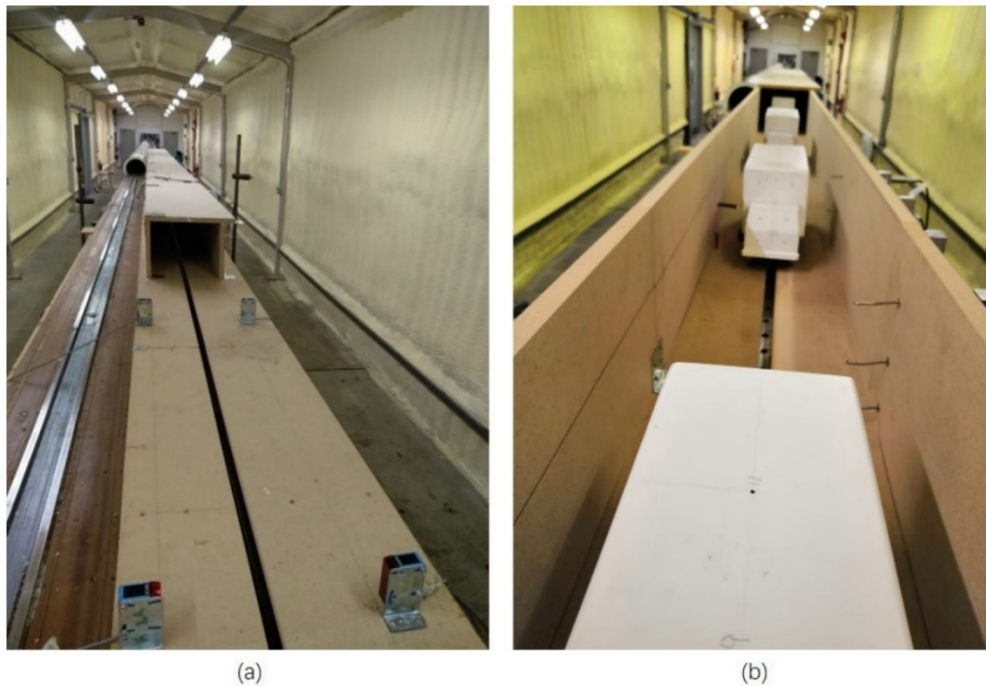
124 This paper aims to improve our understanding of the aerodynamic phenomena
125 associated with a long vehicle platoon running through a tunnel. To achieve this
126 goal, both model-scale experiments and numerical simulations were conducted, and
127 the results are compared to a similar study conducted in the open air. The model-
128 scale experiments were performed with novel moving models at the University of
129 Birmingham Transient Aerodynamic Investigation (TRAIN) rig facility (Robertson
130 et al., 2019). The slipstream properties and vehicle surface pressure were measured
131 to provide a benchmark for validating the CFD results. For the numerical
132 simulations, a sophisticated DES method (Gritskevich et al., 2012) was utilised ~~here~~
133 to obtain high-quality information of the unsteady flow. These results enable us for
134 the first time to have a full understanding of the aerodynamic behaviour of a long
135 platoon travelling through a tunnel. The rest of the paper is organised as follows.
136 The TRAIN rig facility and the moving vehicle models are described in section 2.1,
137 followed by the data analysis methodology in section 2.2. The numerical methods
138 are specified in section 3. Section 4 presents a detailed analysis of the velocity and
139 pressure fields, the vehicle surface pressure, and the drag coefficient. A
140 comprehensive comparison between the behaviours of a vehicle platoon in the
141 tunnel and in the open air will also be made in this section. Finally, the conclusions
142 are presented in section 5.

144 **2. Experiment methodology**

145 *2.1. Experimental set-up*

146 A series of novel moving model-scale experiments were performed at the
147 University of Birmingham TRAIN rig facility. The TRAIN rig facility is a purpose-
148 built facility to examine transient aerodynamics of vehicles (Baker et al., 2001).
149 The reduced-scale vehicle models can be propelled along a series of 150 m long
150 tracks at speeds up to 75 m/s. They are fired by pre-tensioned elastic bungee ropes

151 without additional propulsion and then run at a relatively constant specified speed
152 before decelerating by a friction device. More detail about the rig facility can be
153 found in (Soper, 2016). In this work, eight lorry models in a platoon formation were
154 supported by a long spine type system. Therefore, they can run as a single unit at the
155 same speed and at a fixed inter-lorry spacing (Robertson et al., 2019). The ground
156 plane was composed of two suspended plane halves with a minimised gap of 10 mm
157 in width. The scaled tunnel with a rectangular cross-section in shape was built on
158 the plane, with the length, width and height being 10 m, 0.26 m and 0.215 m,
159 respectively. Figure 1 shows the photographs of the platform and the lorry platoon
160 on the rig. Note that in Figure 1(b), the roof of the tunnel was temporarily removed
161 to show the lorries and cobra probes inside. **Note that the choice of a single-lane
162 tunnel in the present study was largely due to the experimental constraints of the
163 present TRAIN rig. From the viewpoint of applied aerodynamics application, the
164 lateral dynamics induced by a platoon running through the tunnel are of more
165 interest, especially when the platoon enters/leaves the tunnel and passes other
166 vehicles. However, such kind of experiments requires to conduct in a multi-lane
167 tunnel, which is technically inaccessible at this stage. Some two-lane test will be
168 conducted in future after improving the present TRAIN rig facility.**

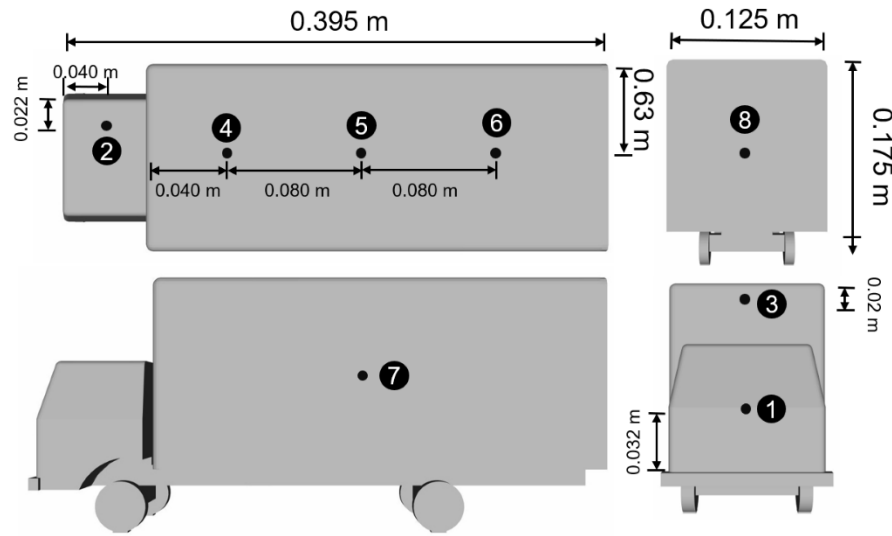


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Figure 1: Photographs of the platform and the lorry platoon on the train rig.

171 The vehicle model was a 1/20th scale commercial box-type lorry (see Figure 2),
172 with the length(L), width(W) and height(H) being 0.395 m, 0.125 m and 0.175 m,
173 respectively. This lorry model was simplified from a typical commercial vehicle
174 Leyland DAF 45-130, which has been extensively investigated either as a single-
175 vehicle (Cheli et al., 2011; Patel et al., 2019; Quinn et al., 2007) or in a platoon
176 formation (He et al., 2019; Robertson et al., 2019). Therefore, there are abundant

177 results to offer useful references and necessary validations of the present
 178 experiments and numerical simulations. Furthermore, by using the same vehicle
 179 shape as in previous studies by the same research group (He et al., 2019; Robertson
 180 et al., 2019), we can make direct comparisons of the results obtained in the tunnel
 181 and in the open air, which is the focus of the present study. Note that some detailed
 182 features of the original lorry, such as side mirrors and windshield overhangs, were
 183 removed or simplified in the present lorry model. This simplification is related to
 184 the simulation efforts, as including these features has a negligible effect on the
 185 aerodynamic performance, but it would require intensive meshing design and result
 186 in an exponential growth in the number of mesh cells.



187
 188 Figure 2; The shape and dimensions of the reduced-scale lorry model. The positions of the pressure
 189 taps for surface pressure measurements are indicated by the numbers on the lorry.

190 The chosen number of eight lorries in the platoon was based on the requirement
 191 for a fully developed boundary layer (Robertson et al., 2019; Soper et al., 2014). In
 192 the present study, the inter-lorry distance was fixed at $1.5L$ for all the experiments.
 193 Note that this separation distance can reflect typical road conditions more
 194 appropriately. It is not uncommon for lorries to travel at a separation comparable to
 195 this distance, while smaller separations could only be achieved through autonomous
 196 vehicle technology. It is also worth mentioning that the aerodynamics of platoons in
 197 the open air were qualitatively similar for different separation distances from $0.5L$ to
 198 $1.5L$ (Robertson et al., 2019). Therefore, the selection of the separation distance
 199 ~~has~~ was not ~~been~~ a major concerned factor in the present study. The focus of this
 200 study is to compare different behaviours of lorry platoons in the tunnel and in the
 201 open air. The lorry platoon was propelled at a speed of $V_{plat} = 25 \pm 1$ m/s,
 202 corresponding to a Reynolds number of 2.96×10^5 based on the lorry's height H .
 203 The actual speed was monitored with an accuracy of ± 0.10 m/s by a series of
 204 position finders and reflectors mounted on the suspended ground plane. **Because of**
 205 **the aerodynamic drag on the lorry models and the friction between the vehicle**

206 mounting point and the rig, there is a slight decrease in the speed (1.17 m/s) of the
207 lorry platoon when it left the tunnel.

208

Probe number	Height from the ground level (y/H)	Distance from the lorry body side (z/H)
A	0.86	0.14
B	0.45	0.14
C	0.11	0.14
D	0.86	0.28

209 Table 1: The positions of the multi-hole probes for measuring the slipstream properties. Here, H is
210 the height of the lorry model.

211 A coordinate system was defined such that the x -axis was aligned in the direction
212 of platoon motion; the y -axis was in the vertical direction measured from the ground
213 plane; the z -axis was on the horizontal plane and perpendicular to the direction of
214 platoon motion. The slipstream velocities and pressures were measured by multi-
215 hole probes (Turbulent Flow Instrumentation Series 100 Cobra probes). This kind of
216 probe can measure three velocity components of the airflow and also the static
217 pressure, with the accuracies being 0.3 m/s and ± 5 Pa for velocity and pressure
218 measurements, respectively. All data were recorded at a sampling frequency of
219 5kHz and filtered using a 650 Hz low-pass filter to reflect the maximum frequency
220 response of the probe. The multi-hole probe has a ± 45 degree cone of acceptance,
221 which is sufficient to capture the majority flow around the lorries (Robertson et al.,
222 2019). The slipstream data were measured at a series of positions as shown in Table
223 1. The surface pressure on each lorry was measured by an on-board pressure
224 monitoring system as described by (Robertson et al., 2019). Metal tubing adaptors,
225 acting as pressure taps, were glued into the lorry walls and connected to the pressure
226 transducer (manufactured by FirstSensor) via silicon tubes. The data was sampled
227 by a stand-alone data logger as a series of voltages and then converted to pressure
228 with an accuracy of ± 15 Pa with careful calibration. The surface pressure
229 measurements were made at eight different locations as indicated in Figure 2. Note
230 that both the platoon configuration and the data acquisition details in the present
231 work were in line with previous studies of a lorry platoon in the open air (He et al.,
232 2019; Robertson et al., 2019), so that a direct comparison between the behaviours in
233 the tunnel and in the open air can be made.

234

235

236 *2.2. Data analysis methodology*

237 Due to the highly temporal variations in velocity and pressure obtained from
 238 individual measurement, multiple runs (of the order of 10~20) are required to
 239 ~~conduct such~~ ensure that the standard deviation of the ensemble average is
 240 comparable to the turbulence level (Baker et al., 2001). Therefore, 20 runs of the
 241 experiment were conducted in the present study to ensure statistically converged
 242 ensemble averages (Robertson et al., 2019; Sterling et al., 2008). In addition, as the
 243 sampling rate was constant but the platoon speed varied between runs, the positions
 244 of the lorries where the measurements were taken were unique for each run. To
 245 eliminate this problem, all the data ~~was-were~~ re-sampled to a nominal speed of 25
 246 m/s. The raw data ~~was-were~~ re-aligned with the sample points when the first lorry
 247 entered the tunnel. The slipstream velocity and pressure are presented in
 248 dimensionless form.

$$U(\tau) = \frac{u(\tau)}{V_{plat}} \quad (1)$$

$$V(\tau) = \frac{v(\tau)}{V_{plat}} \quad (2)$$

$$W(\tau) = \frac{w(\tau)}{V_{plat}} \quad (3)$$

$$U_{res}(\tau) = \sqrt{\left(\frac{u(\tau)}{V_{plat}}\right)^2 + \left(\frac{v(\tau)}{V_{plat}}\right)^2} \quad (4)$$

$$C_p(\tau) = \frac{p(\tau) - p_0}{1/2\rho V_{plat}^2} \quad (5)$$

249 Here, $\tau = V_{plat}t/L$ is the normalised time in terms of the nominal platoon speed
 250 V_{plat} and the lorry model's length L . Note that τ is taken as zero when the first lorry
 251 enters the tunnel for presenting the slipstream properties of the platoon, or when
 252 each lorry enters the tunnel for presenting their surface pressures and drag
 253 properties. U , V and W represent the normalised velocity for the longitudinal, lateral
 254 and vertical components, respectively. U_{res} is the overall normalised horizontal
 255 velocity. The pressure coefficient C_p is calculated with respect to an ambient
 256 reference pressure p_0 and the air density ρ . The atmospheric pressure was measured
 257 by a GBP3300 Digital Barometer with an accuracy of ± 200 Pa. The temperature
 258 and humidity were measured by an Oregon Scientific BAR208HGA weather station.
 259 The surface pressure of each lorry is presented in term of pressure coefficient as
 260 well. The uncertainty in C_p for surface pressure measurements (see, for example, the
 261 error bars in Figure 18), is calculated as the sum of the bias limit (which accounts

262 for the performance limits of the equipment) and random uncertainty (which
263 | accounts for run-to-run variability due to the unsteadiness in the airflow).

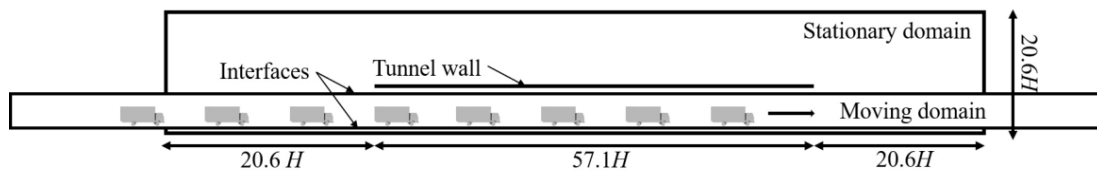
264

265 **3. Numerical set-up**

266 *3.1. Simulation methodology and numerical schemes*

267 | The simulation approach adopted in the present study was IDDES, Improved
268 Delayed Detached Eddy Simulation. This approach was originated from the
269 Detached Eddy Simulation (DES) proposed by (Spalart et al., 1997). DES can
270 reduce the high computational cost for high Reynolds number flows, but it has
271 disadvantages in certain aspects such as modelling stress depletion and grid-induced
272 separation. IDDES solves these problems nicely, thus it is particularly suitable for
273 studying mixed flows with both attached and separated regions.

274 The simulations were performed by commercial CFD software ANSYS 18.2
275 using a pressure-based solver with the finite volume method. The SIMPLE (Semi-
276 Implicit Method for Pressure-Linked Equations) algorithm was used to handle the
277 pressure and velocity coupling equations. The IDDES approach, based on the model
278 by (Gritskevich et al., 2012)), was adopted and the bounded central differencing
279 was applied to the momentum equations. An implicit scheme with second-order
280 accuracy was applied to the time term. The time step was set to 1×10^{-4} s (Hemida
281 and Krajnović, 2009; Niu et al., 2017) and there were 50 iterations in each time step.



282

283

Figure 3: Computational domain for lorries in platoon travelling through a tunnel.

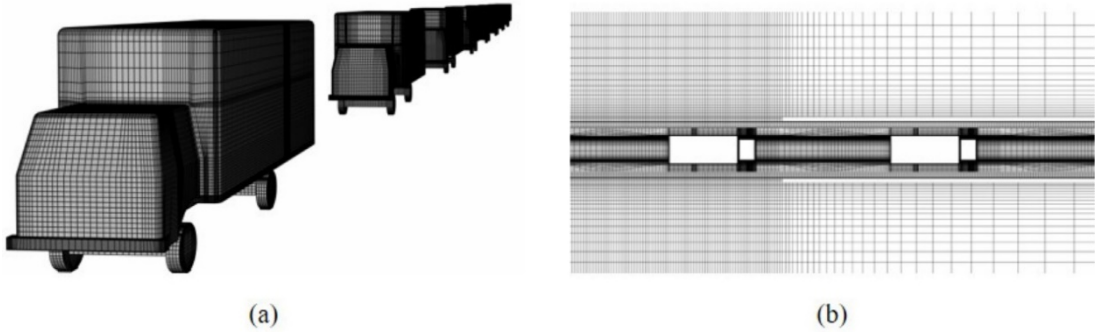
284 *3.2. Computational domain and boundary condition*

285 The computational domain consists of both stationary and moving sub-domains
286 | with the width being $41.14H$. For the other dimensions of the domain, please refer
287 to Figure 3. In order to accurately simulate the relative motion between the vehicles
288 and the tunnel, the sliding mesh technique was adopted. This technique is promising
289 in solving the problems similar to the present study (Chen et al., 2017; Chu et al.,
290 2014; Liu et al., 2014; Niu et al., 2017). To be specific, during the simulation, the
291 moving sub-domain slides relative to stationary sub-domain along the interfaces
292 without mesh generation at every time step, and thus the nodes do not need to be re-
293 aligned at the interfaces. In each time step, the fluxes across each grid point inside
294 the non-conformal interface zones were computed.

295 The initial conditions were set to zero gauge pressure and zero velocity in both
 296 moving and stationary sub-domains. The top and side faces of the stationary sub-
 297 domain were set to zero static pressure. A non-slip boundary condition was applied
 298 to the lorry surface, tunnel walls and the ground of the stationary sub-domain. In
 299 order to ensure that the flow field is fully developed and to avoid the impact of the
 300 boundary conditions, the simulation started when the first lorry was outside the
 301 tunnel at a distance of $20.6H$ away from the entrance and stopped when the last
 302 lorry was outside the tunnel at a distance of $20.6H$ away from the exit.

303 3.3. Mesh generation scheme

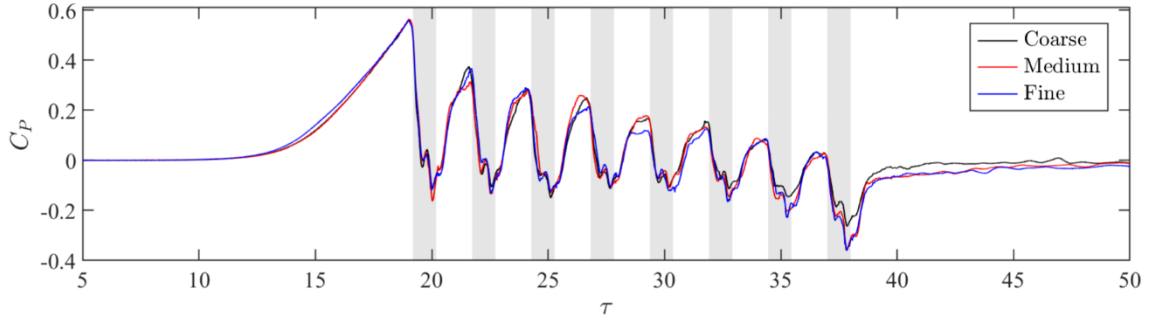
304 Figure 4 shows the computational meshes used in this study. The structured
 305 meshing method was employed for the entire computational domain by the
 306 commercial software Ansys ICEM-CFD. The total number of mesh cells used in
 307 this study was 34.9 million. Another two meshes with different numbers of cells
 308 (17.4 million and 24.2 million) were used to test the mesh sensitivity (see Table 2).
 309 The Courant-Friedrichs-Lewy number ($CFL = U_{\infty} \Delta t / \Delta x$, where Δx is the length of
 310 cells and Δt is the time step) remained below 1 with a small number of localised
 311 exceptions. (Xia et al., 2017)) and (Wang et al., 2017)) have shown that this minor
 312 infringement on the CFL requirement is unlikely to affect the simulation results.



313
 314 Figure 4: Computational meshes used in this study: (a) lorry surface; (b) horizontal cross-section of
 315 the whole domain at $y/H = 0.57$.

	Coarse	Medium	Fine
Averaged y^+	49	45	33
Number of mesh cells used in the moving domain (million)	12.2	14.7	20.3
Number of mesh cells used in the stationary domain (million)	5.2	9.5	14.6
Total number of mesh cells (million)	17.4	24.2	34.9

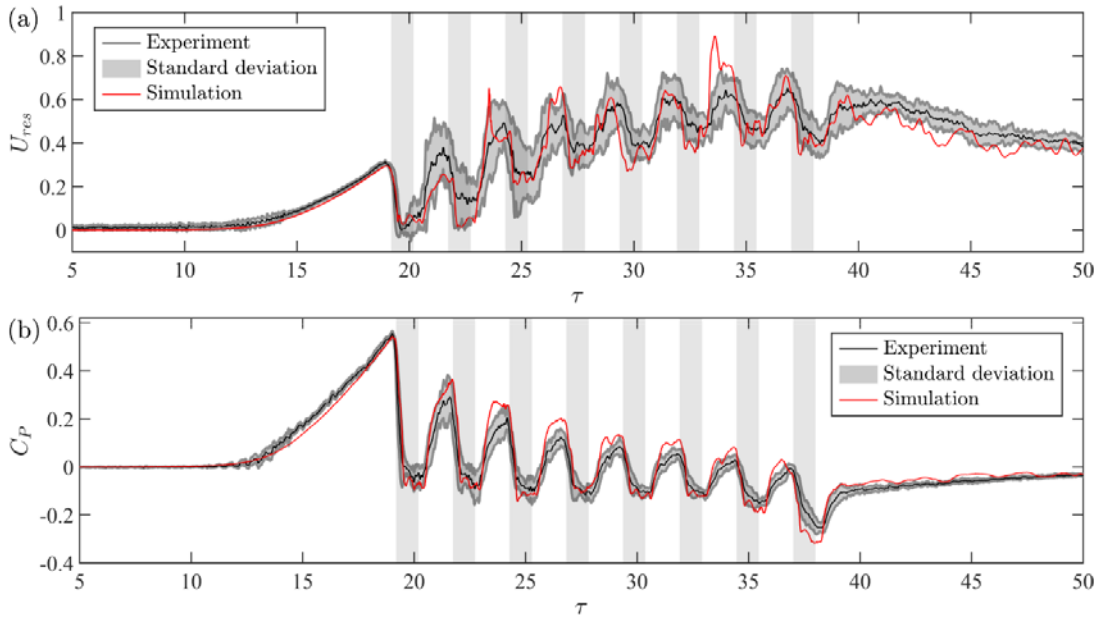
316 Table 2: The parameters for the grid sensitivity testing in the simulations.



317
 318 Figure 5: Pressure coefficients for different mesh densities. The shaded rectangles indicate the time
 319 duration for each lorry to pass the probes.

320 The pressure coefficients C_p of the IDDES simulations based on three different
 321 numbers of cells are shown in Figure 5. The testing point is located at a position of
 322 $0.45H$ above the ground and $0.14H$ away from the lorry body. The differences in the
 323 positive pressure peaks between the fine and middle meshes are relatively small.
 324 However, the results using coarse mesh have relatively large deviations, especially
 325 at $37 < \tau < 38$. Therefore, the fine mesh was used in this study.

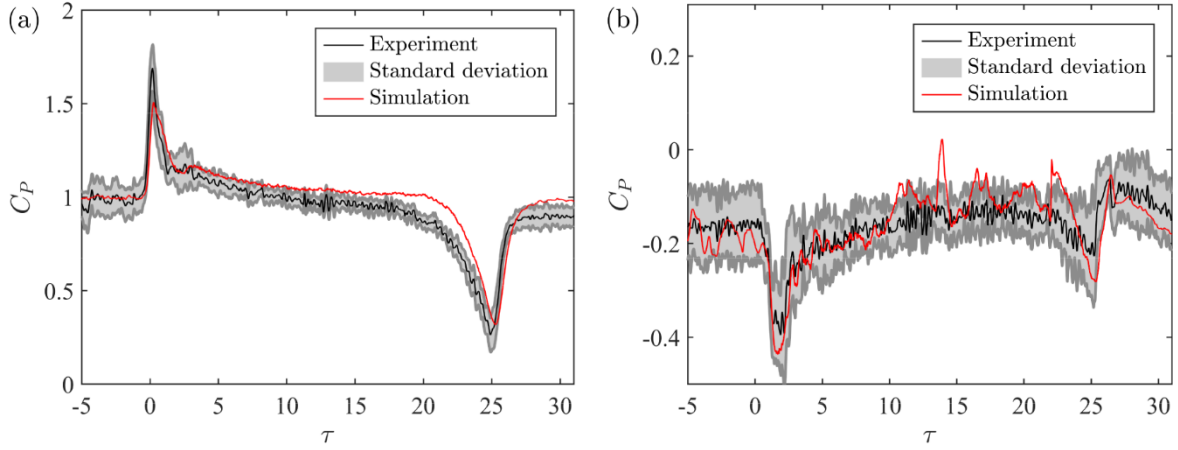
326 3.4. Validation of simulation results



327
 328 Figure 6: Comparison between the experiments and numerical simulations measured at the position
 329 of the multi-hole probe B (see Table 1): (a) normalised horizontal velocity; (b) pressure coefficient.
 330 The shaded rectangles indicate the time duration for each lorry to pass the probes.

331 To validate the CFD results, we show in Figure 6 the simulated normalised
 332 velocities and pressure coefficients at the position of multi-hole probe B (see Table
 333 1) together with the experimental data. The trends of the pressure data obtained
 334 from the numerical simulations are consistent with the experimental results. Whilst
 335 the velocity data deviate a lot in detail, the numerical data mostly fall within one
 336 standard deviation of the experimental values. To understand the discrepancy in

337 velocity data, we note that although the gap in the ground plane has been modelled
 338 in the simulations, the exact boundary conditions for this region are difficult to
 339 define. In addition, the tunnel is assumed to be fully sealed in the simulations, which
 340 is impossible in the experiments. Another possible reason could come from the
 341 multi-hole probe. The velocity component in the direction of platoon motion is
 342 sensitive to the alignment of the probe. The ± 45 degree cone of acceptance of the
 343 probe might also restrict the detection of air flows (Soper, 2016; Soper et al., 2017).



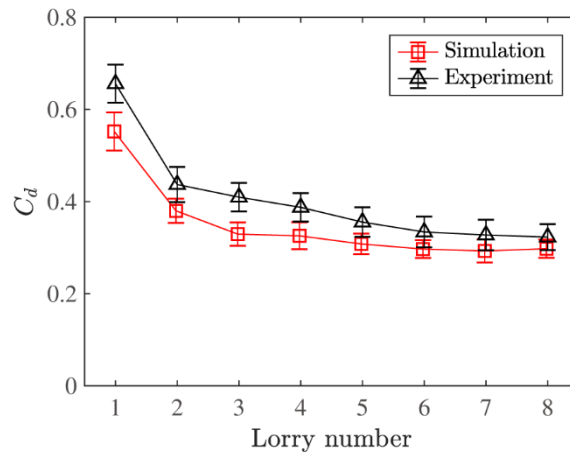
344
 345 Figure 7: The surface pressure coefficients from the experiments and simulations. The monitoring
 346 positions are at (a) point No.1 and (b) point No.8 as indicated in Figure 2.

347 Figure 7 compares the surface pressure coefficients between the simulations and
 348 the experiments. Figure 7(a) and (b) represent the data at the cab front and rear
 349 points of the leading lorry, respectively. It is seen in Figure 7(a) that the data from
 350 the numerical simulations compare well with the experimental results. When the
 351 lorry is running inside the tunnel, the simulated frontal surface pressure decreases
 352 slower than the experimental cases. This can be ascribed to a gradual decrease in the
 353 speed of the platoon in the experiments (as a result of the rig friction and the
 354 aerodynamic drag aforementioned), in contrast to the constant speed used in the
 355 simulations. The experimentally measured C_p drops from around 1 prior to the inlet
 356 to around 0.9 after leaving the tunnel (beyond $\tau = 27$), suggesting that the platoon
 357 speed at the exit is 95% of that at the entry. Indeed, direct measurement with laser
 358 sensors shows that the platoon speed reduces by 4.6%, which provides a support for
 359 the conclusion that the lower C_p of the experiments is due to the slowing down of
 360 the lorry model when running through the tunnel. For the rear region of the lorry
 361 where separated flow exists (Figure 7(b)), the simulation data are also in good
 362 agreement with the experimental values (typically within one standard deviation).

363 The last important quantity to be validated is the mean drag coefficient as
 364 defined below:

$$C_d = \frac{F}{0.5\rho V_{plat}^2 A_f} \quad (6)$$

365 Here, F is the effective drag force, and A_f is the reference area derived from the
 366 projected area of the lorry. V_{plat} is the nominal platoon speed aforementioned. Note
 367 that the calculation of mean drag coefficient requires integrating pressure over a
 368 discrete geometry of the lorry surface and thus sufficient data should be acquired to
 369 make the integration (Dorigatti et al., 2015). In this work, the pressures along the
 370 lorry surface were experimentally measured at eight positions only. This low
 371 resolution of pressure data prevents us from obtaining a reliable drag coefficient.
 372 Therefore, we validate the numerical model here by comparing the drag coefficient
 373 simulated in the open air with the experimental results obtained by (Robertson et al.,
 374 2019)). The error bars in Figure 8 indicate the root-mean-square (rms) magnitudes for the simulations, while for the experiments they are uncertainties calculated by applying the uncertainty transfer formula based on the uncertainties of the pressure coefficients at all the locations. It is seen that there is a discrepancy between the experimental and numerical results, which may be due to the relatively low resolution of surface pressure taps in the experiments. As noted by (Robertson et al., 2019)), the experimental data only provides an estimated drag coefficient and the uncertainty may be less than the true error, because the assumption of uniform pressure across the discretised area might be inaccurate. Nevertheless, it will be shown in Section 4.3 that there is a good agreement between the experimental and IDDES values in the surface pressure coefficients for lorries both inside the tunnel and in the open air (see, for example, Figure 18). This gives us confidence in the reliability of the present results.



387
 388 Figure 8: Mean drag coefficient in the open air from the experiments and simulations. The
 389 experimental results were obtained by (Robertson et al., 2019).

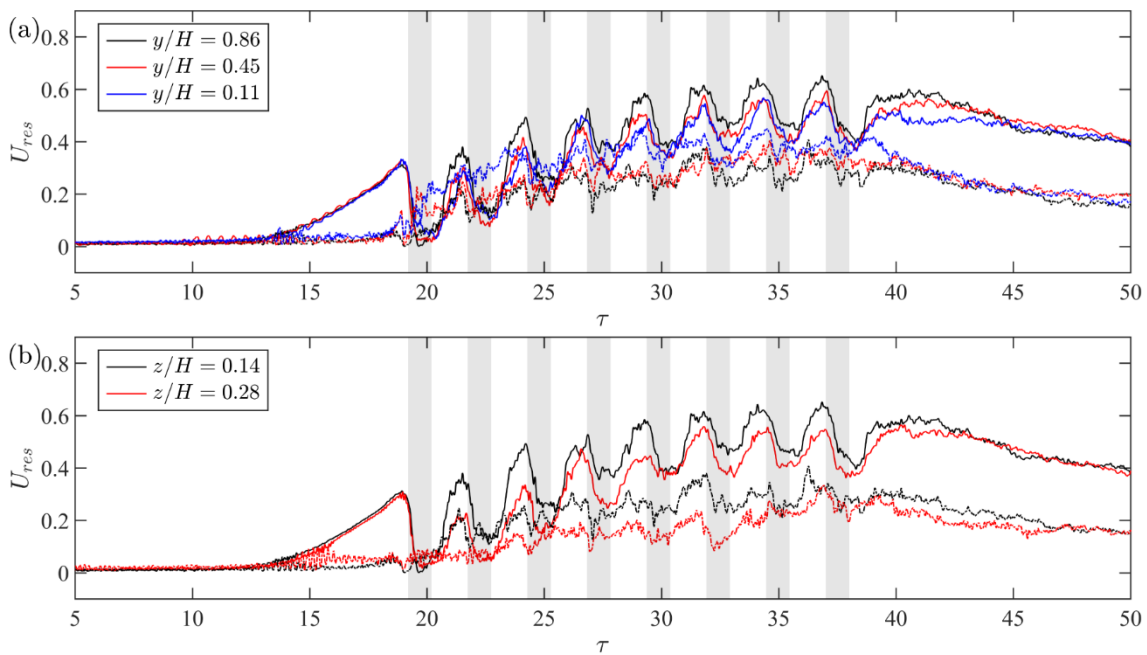
390

391 4. Results and discussion

392 4.1. Slipstream properties

393 We first show in Figure 9 the aerodynamic flow around the lorry platoon, in
 394 terms of the normalised horizontal velocity in the slipstream. The data measured in

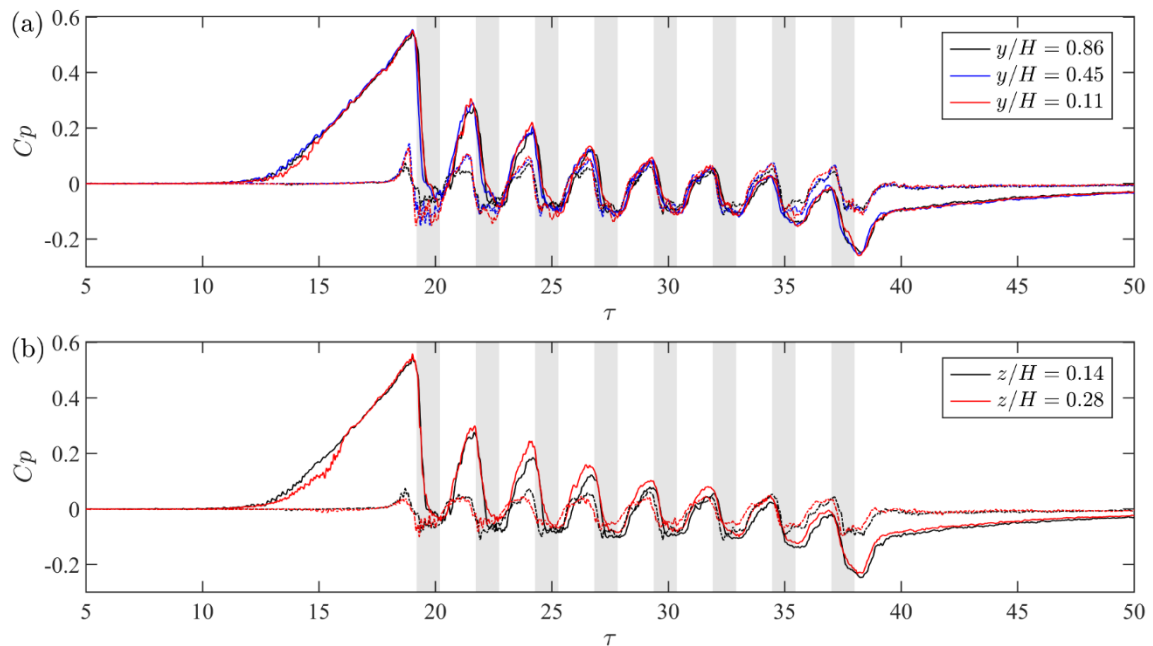
395 the tunnel and in the open air are plotted together for comparison. In the open air,
 396 the flow created by the moving platoon is characterised by a continually growing
 397 boundary layer punctuated with pulse peaks near the front of each lorry (Robertson
 398 et al., 2019). While in the tunnel, the piston effect induced by the movement of the
 399 lorry platoon causes the bulk flow through the tunnel. Therefore, the horizontal
 400 velocity starts rising long before the arrival of the first lorry. The bulk flow in the
 401 tunnel also leads to a smaller approach flow velocity for the platoon. Fluctuations
 402 are recorded due to the complex flow patterns. The peaks associated with the lorries
 403 are more obvious in the tunnel than in the open air. It is further seen that the
 404 horizontal velocity does not approach the maximum value until the sixth lorry
 405 passes, suggesting that at least this number of vehicles are needed to study the
 406 aerodynamic phenomena of a long platoon in the tunnel.



407
 408 Figure 9: The experimentally measured normalised horizontal velocity as a function of the
 409 normalised time: (a) at various heights from the ground level with the same location of $z/H = 0.14$
 410 away from the lorry side; (b) at different locations away from the lorry side with the same height of
 411 $y/H = 0.86$ from the ground level. The solid lines denote the results obtained in the tunnel and the
 412 dotted lines denote the results obtained in the open air (Robertson et al., 2019). The shaded
 413 rectangles indicate the time duration for each lorry to pass the probes.

414 Figure 10 presents the experimental pressure coefficients at different heights
 415 from the ground level and at different distances away from the lorry. Also shown in
 416 the figure are the experimental data for the same platoon configuration running in
 417 the open air. The pressure coefficients for different positions have a similar trend as
 418 time evolves. To be specific, the pressure coefficients rise until the first lorry arrives
 419 at the positions where the cobra probes were installed. When the first lorry passes
 420 by the cobra probes, the slipstream pressures due to the so-created turbulent flow
 421 have lower values than the ambient fluid. The pressure coefficients therefore drop
 422 drastically after the first lorry leaves the location of the probes. As the platoon

423 moves forward, all the lorries induce similar variations in the local pressure. Thus,
 424 there are eight peaks as seen in the figure, corresponding to eight lorries in the
 425 platoon. These phenomena are the same in both the tunnel and the open air.

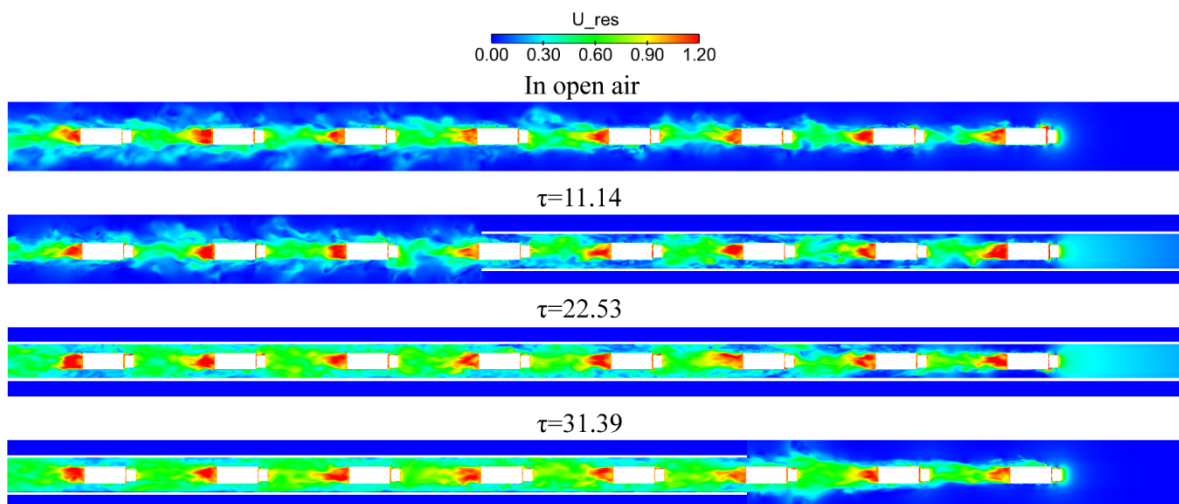


426
 427 Figure 10: The temporal variations of the experimentally measured pressure coefficients: (a)
 428 at different heights from the ground level with the same location of $z/H = 0.14$ away from the lorry side;
 429 (b) at different locations away from the lorry side with the same height of $y/H = 0.86$ from the
 430 ground level. The solid lines denote the results obtained in the tunnel and the dotted lines denote the
 431 results obtained in the open air (Robertson et al., 2019). The shaded rectangles indicate the time
 432 duration for each lorry to pass the probes.

433 However, when considering the magnitude of the pressure coefficient, significant
 434 differences are observed between the data in the tunnel and in the open air. When
 435 the platoon runs in the tunnel, the air around the lorries is largely forced to flow
 436 parallel to the travelling direction of the platoon because of the spatial confinement.
 437 This results in a slower dissipation in the frontal pressure. Therefore, the first peak
 438 of pressure coefficient reaches a value as large as 0.55 in the tunnel, while the value
 439 in the open air is about four times lower. This difference gets progressively smaller
 440 for the following lorries and the pressure coefficients for different situations become
 441 almost identical for the fifth to seventh lorries in the platoon. On the other hand,
 442 as less airflow is able to penetrate into the rear region of the platoon in the tunnel,
 443 the low-pressure behind the last lorry is strongly intensified, leading to a great fall in the
 444 value of pressure coefficient (as low as -0.25). This is in strong contrast to the
 445 almost constant value (around -0.1) of the negative peaks for the platoon in the open
 446 air. Note that the above differences in the pressure coefficient are observed for all
 447 the positions shown in Figure 10. These much larger pressure variations in the
 448 tunnel indicate that additional aerodynamic forces exist when the platoon passes by.

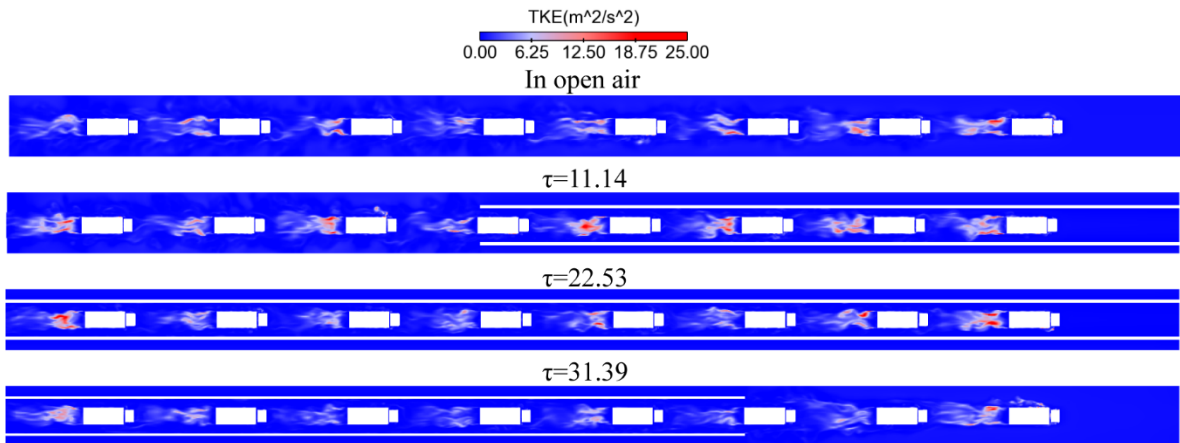
449

450 To have a better understanding of the aerodynamic flow created by the lorry
 451 platoon in the tunnel, we now turn to the numerical results for detail. Figure 11
 452 presents the top view of the horizontal velocity at the height $y/H = 0.57$ above the
 453 ground. The transient velocity fields at three distinct times during the platoon
 454 passing through the tunnel are shown, together with the stationary results in the
 455 open air. The highest speed appears in the rear regions of all the lorries, regardless
 456 of in the tunnel or in the open air. However, when the platoon is running inside the
 457 tunnel, stronger flows are induced in the frontal and rear regions of the platoon. The
 458 velocity in the regions between each lorry is also larger than that in the open air. For
 459 the lateral sides of the platoon, the influenced regions expand gradually as the
 460 platoon moves forward. While the sides of the first two lorries have a relatively
 461 weak airflow, the horizontal velocity around the last four lorries increases to a
 462 constant value of 0.6 inside the tunnel. These findings are in good agreement with
 463 the experimental results as shown in Figure 9.



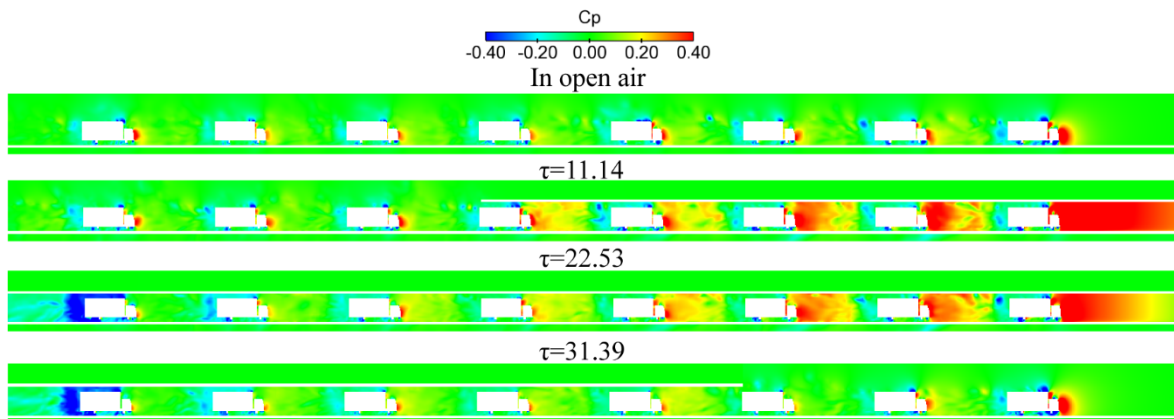
464
 465 Figure 11: The simulated velocity fields during the lorry platoon passing through the tunnel at three
 466 distinct times on the horizontal plane of $y/H = 0.57$. The top panel shows the data in the open air for
 467 comparison.

468 Figure 12 shows the corresponding turbulent kinetic energy (TKE) of the
 469 velocity fields in Figure 11. It is seen that intense turbulent kinetic energy is
 470 concentrated in the rear regions of all the lorries. This is originated from small-scale
 471 turbulent structures due to the large-scale flow separations in these regions.
 472 Interestingly, the TKE seems to be weaker for some intermediate lorries in the
 473 tunnel than in the open air, suggesting that the transient flow created by these lorries
 474 is less fluctuating.



475
 476 Figure 12: The instantaneous turbulent kinetic energy during the lorry platoon passing through the
 477 tunnel at three distinct times on the horizontal plane of $y/H = 0.57$. The top panel shows the data in
 478 the open air for comparison.

479 Figure 13 shows the side view of the pressure distribution at $z/H = 0.076$
 480 during the platoon running through the tunnel and in the open air. The results reveal
 481 a significant piston effect induced by the movements of the lorry platoon inside the
 482 tunnel. As the platoon enters the tunnel, the pressures at the cab front of the leading
 483 lorries increase greatly, especially for the first one. When the whole lorry platoon is
 484 inside the tunnel, the frontal positive pressure continuously decreases from the
 485 leading lorry to the last one, which is consistent with the experimental results shown
 486 in Figure 10. Moreover, the experimentally-observed smaller positive pressure at
 487 the front region and larger negative pressure at the rear region of the last lorry are
 488 more clear here. As the platoon begins to leave the tunnel, the pressures around the
 489 lorries reduce again quickly, with the frontal positive pressures of some lorries (e.g.,
 490 the second and the third ones) even smaller than those in the open air.



491
 492 Figure 13: The pressure distribution during the lorry platoon passing through the tunnel at three
 493 distinct times on the vertical plane of $z/H = 0.076$. The top panel shows the data in the open air for
 494 comparison.

495

496

497 4.2. *Flow structures*

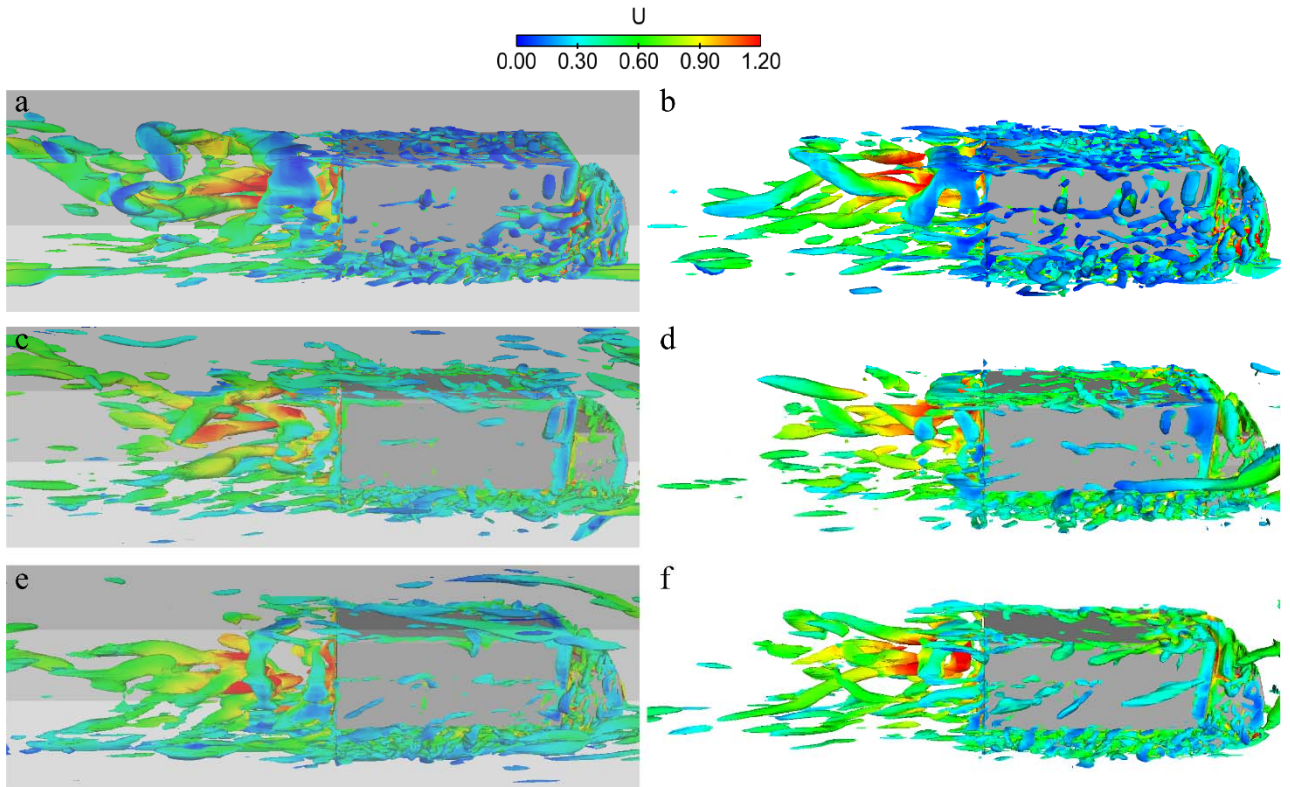
498 To have a closer look at the aerodynamic flow created by the platoon, we use the
499 iso-surfaces of the second invariant Q to extract the flow structures around the
500 lorries. The second invariant Q is defined as below,

$$Q = -\frac{1}{2}(\bar{S}_{ij}\bar{S}_{ij} - \bar{\Omega}_{ij}\bar{\Omega}_{ij}) \quad (7)$$

501 where \bar{S}_{ij} and $\bar{\Omega}_{ij}$ are the symmetric and anti-symmetric parts of the velocity
502 gradient tensor. Iso-surfaces with positive Q represent locations where the strength
503 of the rotation overcomes the strain, thus indicating vortical structures (Jeong and
504 Hussain, 1995).

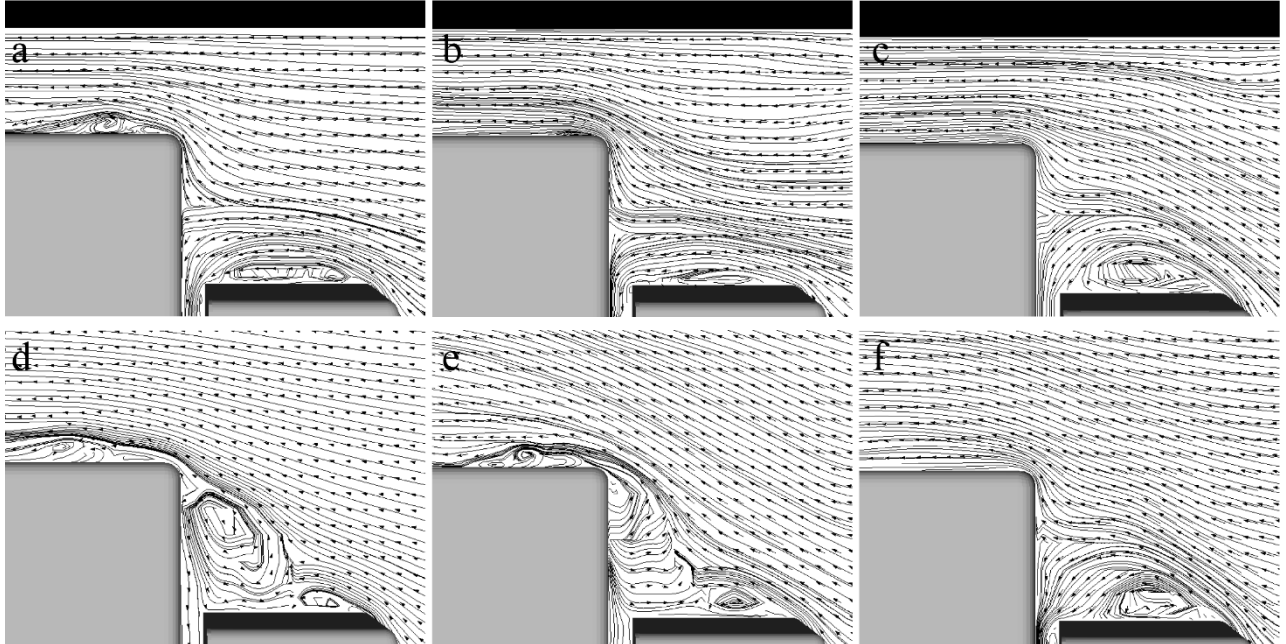
505 Figure 14 compares the instantaneous flow structures around the first, the fifth
506 and the last lorries running in the middle of the tunnel and in the open air. The
507 distributions of the vortices around the leading lorries are similar in these two cases.
508 As shown in Figure 14 (a) and (b), a large number of vortices are generated around
509 the cab, box side and rear regions, due to the bluff nature of the box lorries.
510 However, some differences in the vortical structures can be found for the platoon in
511 the tunnel: fewer vortices are appearing at the lorry sides. This difference is also
512 observed but less obvious for the fifth and the last lorries as shown in Figure 14 (c)
513 to (f). As mentioned in Section 4.1, the piston effect induced by the movement of
514 the platoon leads to a lower approach velocity, which results in weaker flow
515 separations. **Thanks to the shielding effect, there are fewer vortices around the fifth
516 and the last lorries compared to those around the leading lorries in both the tunnel
517 and the open air.**

518 Figure 15 compares the streamlines at the centreline plane in the frontal region of
519 three representative lorries in the platoon. Note that each lorry is in the middle of
520 the tunnel and travelling at the corresponding time in the open air. As clearly
521 indicated in Figure 15 (a) and (d), the recirculation region close to the frontal edge
522 of the lorry box is obviously larger in the open air than in the tunnel. This
523 phenomenon is also identified ~~on~~in the same region of the fifth lorry (see Figure 15
524 (b) and (e)). When it comes to the last lorry, the separation almost disappears
525 compared to the leading lorries due to the shielding effect in both the tunnel and the
526 open air. Figure 16 compares the corresponding streamlines in the rear region. The
527 figure shows two counter-rotating recirculation vortices in the near_wake region.
528 The most noticeable difference in the flow structures between the lorries travelling
529 in the tunnel and in the open air is the size of the bottom vortex and the upper vortex.
530 It is clear that the presence of the tunnel enlarges the upper vortices for all the
531 lorries in the tunnel. **As will be shown in next section, these differences in flow
532 structures provide direct support for interpreting the surface pressure results.**



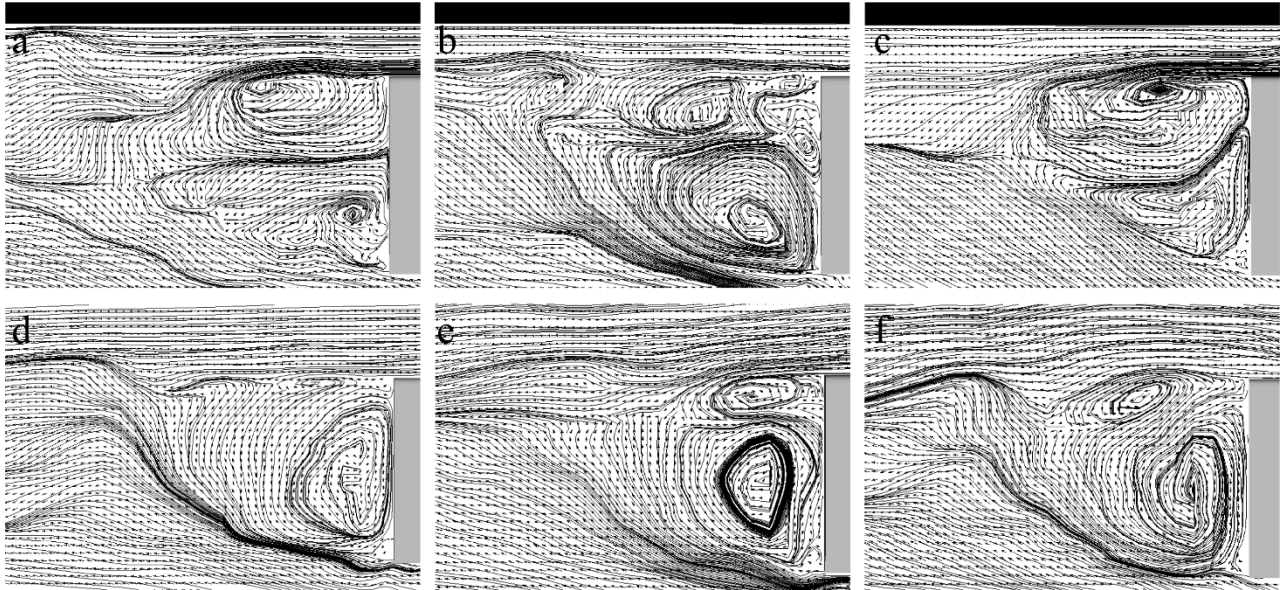
533
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Figure 14: The instantaneous iso-surfaces of the second invariant Q . Left panel: (a), (c) and (e) are the lorries 1, 5 and 8 in the tunnel. Right panel: (b), (d) and (f) are the lorries 1, 5 and 8 in the open air. Here, Q is set to be 50000 s^{-2} and coloured by the normalised velocity.



537
538
539
540

Figure 15: Illustrations of the frontal flow structures of three representative lorries in the platoon at $z/H=0$. Top panel: (a), (b) and (c) are the lorries 1, 5 and 8 in the tunnel. Bottom panel: (d), (e) and (f) are the lorries 1, 5 and 8 in the open air.



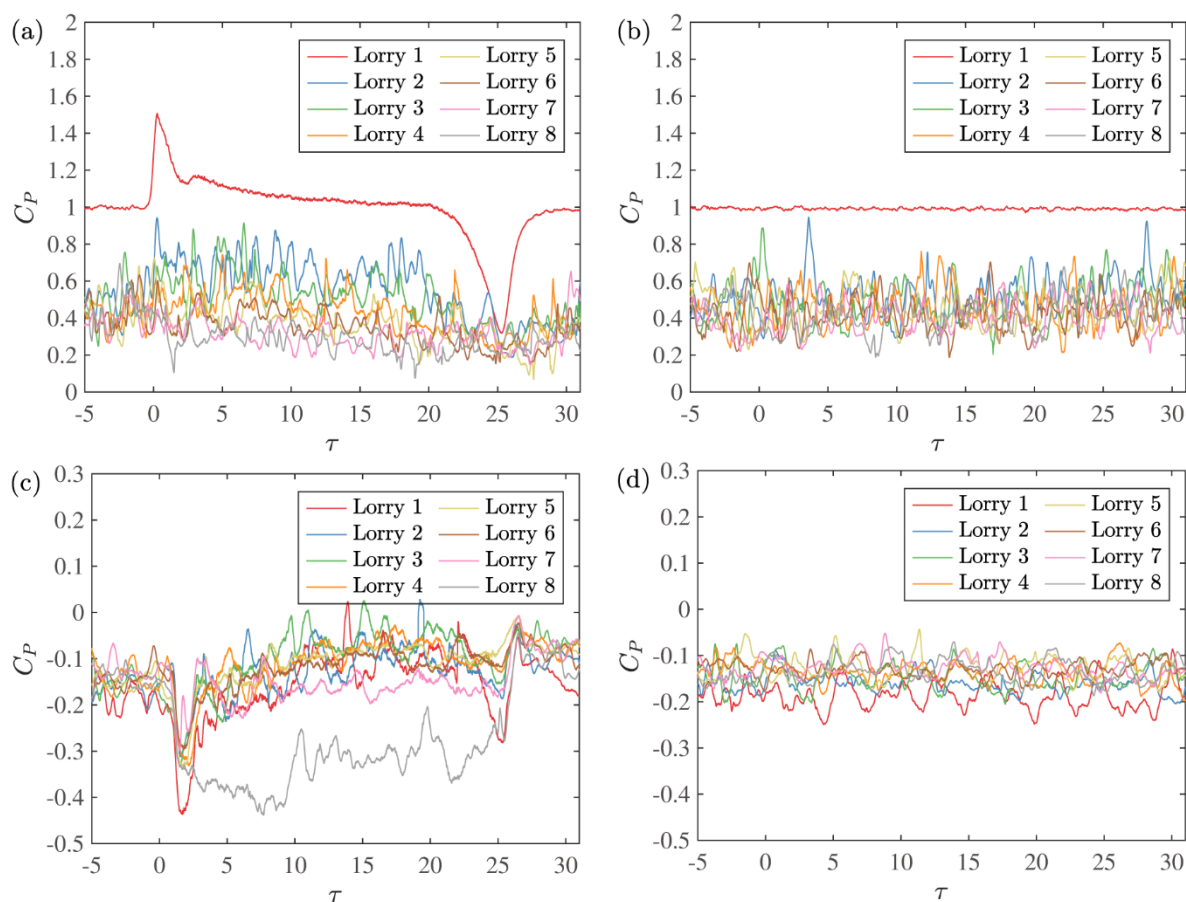
541
 542 Figure 16: Illustrations of the wake flow structures of three representative lorries in the platoon at
 543 $z/H=0$. Top panel: (a), (b) and (c) are lorries 1, 5 and 8 in the tunnel. Bottom panel: (d), (e) and (f)
 544 are lorries 1, 5 and 8 in the open air.

545 **4.3. Surface pressure analysis**

546 As the aerodynamic flow created by the platoon running in the tunnel is
 547 pronouncedly different from that in the open air, it is natural to expect that the
 548 pressure distributions on the lorries' surfaces are also different. However, in contrast
 549 to the case in the open air, the flow field around the platoon is strongly unsteady,
 550 and the positions of the lorries relative to the tunnel change with time. In order to
 551 study the surface pressure variation, a user-defined function was added to the CFD
 552 code to simulate the surface pressures on the moving lorries.

553 Figure 17 presents the time series of the simulated surface pressure coefficient
 554 C_p at two typical surface positions of each lorry in the tunnel and in the open air.
 555 Note that the data is aligned with respect to the time when each lorry arrives at the
 556 entrance of the tunnel. The shielding effect is obvious for the results shown in
 557 Figure 17(a) and (b). In the tunnel, the surface pressure on the cab front decreases
 558 for the first four lorries, with the largest drop occurring at the second one, and then
 559 keeps relatively constant for the last four lorries. Also thanks to the shielding effect,
 560 the pressure variations for the trailing lorries in the tunnel are not as drastic as
 561 those at for the leading lorries during entering and leaving the tunnel. However,
 562 frequent and small fluctuations are observed for the trailing lorries in both the tunnel
 563 and the open air, which are induced by the separated flow structures from the
 564 upwind stream as shown in Figure 14. When it comes to the box rear regions of the
 565 lorries in the tunnel (see Figure 17(c)), almost all the lorries experience larger
 566 surface pressure fluctuations when entering the tunnel, but only the first and the last
 567 lorries have obvious changes in the surface pressure when leaving the tunnel. The
 568 last lorry has the lowest rear pressure coefficient in the tunnel, which is consistent

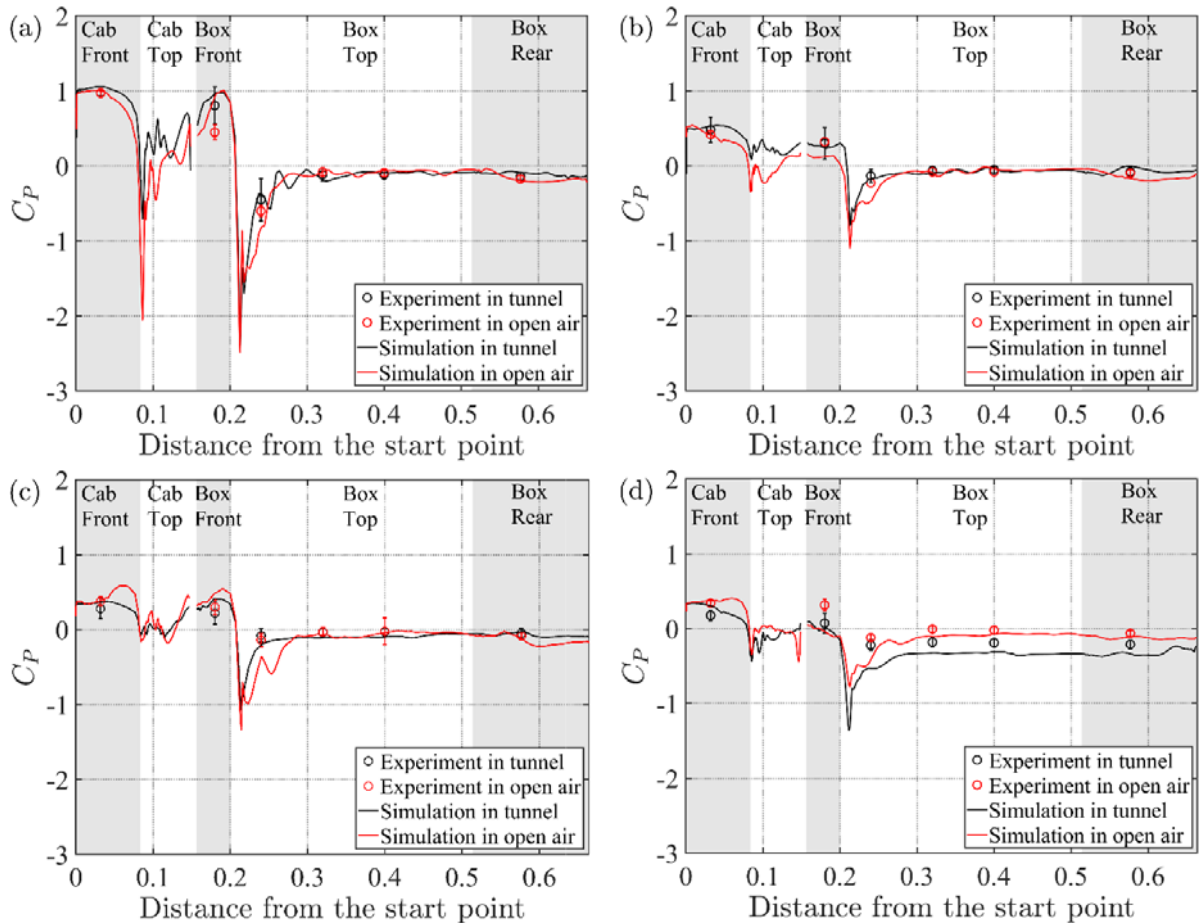
569 with pressure distribution as shown in Figure 13. In addition, except for the last
 570 lorry, which has the lowest pressure coefficient in the tunnel, the pressures on the
 571 box rear fluctuate at similar levels for the other lorries.



572
 573 Figure 17: The simulated surface pressure coefficients of all the lorries as a function of the
 574 normalised time: (a) cab front in the tunnel; (b) cab front in the open air; (c) box rear in the tunnel; (d)
 575 box rear in the open air.

576 Figure 18 shows the time-averaged surface pressure coefficients of four
 577 representative lorries along the central line in the platoon. Both experimental and
 578 numerical results are plotted together, and a comparison is made between the data in
 579 the tunnel and in the open air (Robertson et al., 2019). Note that the surface pressure
 580 coefficient in the tunnel is averaged over the intermediate 4-meters when each lorry
 581 is travelling inside the tunnel. The shaded areas are employed to distinguish
 582 different regions along the lorry's surface. It is seen that the data predicted by the
 583 simulations are generally in good agreement with the experimental data. The mean
 584 surface pressure coefficients have a similar trend for different lorries both inside and
 585 outside the tunnel. To be specific, the surface pressure along the central line of each
 586 lorry drops significantly in the regions where the strongest flow separations occur
 587 (see Figures 14-16), as indicated by the negative peaks, and then becomes almost
 588 unchanged for the box top and rear regions. Moreover, for both data in the tunnel
 589 and in the open air, the trailing lorries have much smaller frontal pressures than the

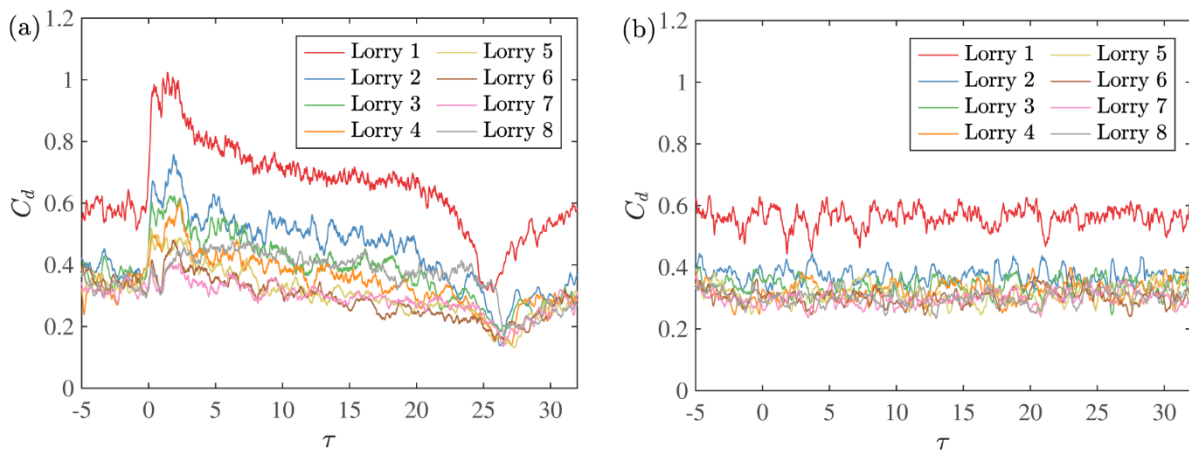
590 leading one, and their rear pressures are almost the same. As indicated in section 4.2,
 591 the piston effect in the tunnel leads to a lower approach velocity and a weaker flow
 592 separation near the box front edge, as compared to the case in the open air. This is
 593 evident by the pressure values of the negative peaks: the lowest C_p at the box front
 594 edge of Lorry 1 is -2.14 in the tunnel, compared to the value of -3.0 in the open air.
 595 C_p at the cab front edge of Lorry 1 is also lower in the open air than that in the
 596 tunnel. This difference in the negative pressure peak becomes smaller for the
 597 trailing lorries, as a result of shielding. Another appreciative difference that can be
 598 found is the surface pressure coefficients of Lorry 8. Their values are systematically
 599 lower in the tunnel than in the open air, supported by both the experiments and
 600 simulations. However, the difference between the two cases is generally more
 601 pronounced at the rear region of the lorry than it is at the front. This suggests that
 602 the mean drag coefficient for Lorry 8 will be significantly higher inside the tunnel,
 603 as we will show in next section.



604
 605 Figure 18: The mean surface pressure coefficients of different lorries along the central line of the
 606 platoon: (a) Lorry 1; (b) Lorry 3; (c) Lorry 5; (d) Lorry 8. Both experimental and numerical results
 607 are shown for the cases in the tunnel and in the open air. The shaded area is used to help to
 608 distinguish different regions along the lorry's surface.

610 4.4. Drag analysis

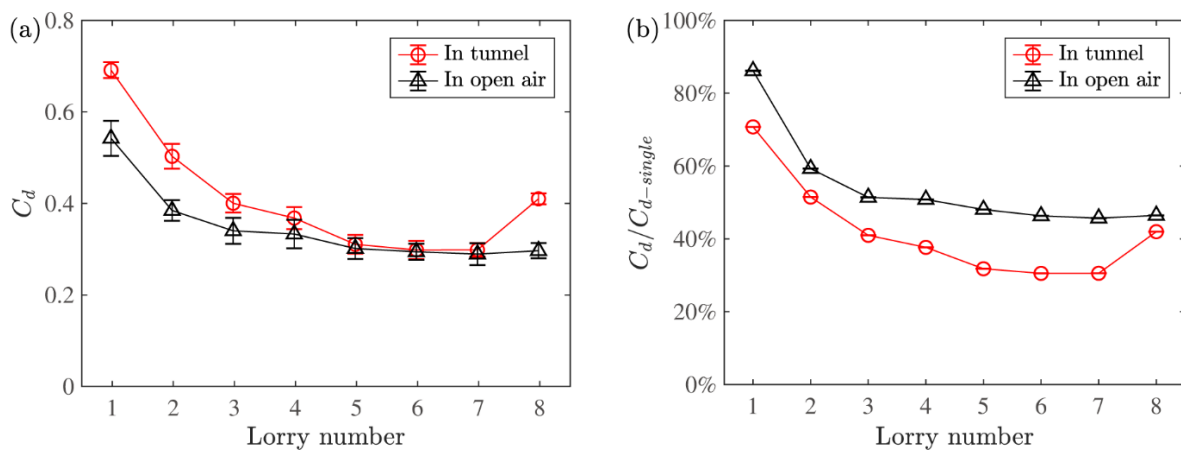
611 Now we consider the aerodynamic drag coefficient. Figure 19 illustrates the time
612 series of drag coefficients of each lorry running through the tunnel and in the open
613 air. It is clearly seen in Figure 19(a) that the drag coefficients of all the lorries first
614 rise sharply when entering the tunnel, and then decrease slowly inside the tunnel
615 before a sudden drop at the exit. The variation in the drag coefficients can be up to
616 70% for the leading lorry in the tunnel, which is absent for the case in the open air
617 (Figure 19(b)). As a benefit from the shielding effect, the trailing lorries in the
618 tunnel experience ~~less~~ smaller drag variation in the drag coefficients, but they still
619 experience larger fluctuations than those in the open air. A similar result was
620 obtained previously by (Li et al., 2010), who simulated a two-vehicle platoon
621 running into a tunnel. Their work showed that the drag coefficient of the trailing
622 vehicle did not change significantly while the drag coefficient of the leading vehicle
623 increased during the process of entering the tunnel. In addition, It is further seen in
624 Figure 19(a) that the drag coefficient continuously decreases from Lorry 1 to Lorry
625 5, with the largest drop occurring at the second lorry. Note that the drag coefficient
626 of Lorry 8 in the tunnel is much higher than the other lorries, in contrast to the case
627 in the open air. This is largely due to the strongly negative rear pressure when the
628 lorry travels through the tunnel, as shown in Figures 17(c) and 18(d).



629 Figure 19: The time series of drag coefficients of different lorries in the platoon: (a) in the tunnel and
630 (b) in the open air.
631

632 In order to compare the drag coefficients in the tunnel and in the open air directly,
633 we show in Figure 20(a) the corresponding mean values. Note that the drag
634 coefficients in the tunnel are averaged for the intermediate duration when the whole
635 platoon is travelling inside the tunnel. It is seen that while the mean drag coefficient
636 in the open air only changes significantly for the first three lorries and approaches a
637 plateau after that, C_d in the tunnel continues to decrease appreciably until the fifth
638 lorry. For the first four lorries, the presence of the tunnel tends to increase the drag
639 coefficient due to the much higher frontal pressure, thus the C_d values in the tunnel
640 are larger than those in the open air. The drag coefficients from the fifth to the

641 seventh lorries are almost identical for different situations. However, for the last
642 lorry in the tunnel, there is a large increase in the drag coefficient due to the strongly
643 negative rear pressures. It is worth noting that whilst the drag coefficient is typically
644 higher for a platoon travelling inside a tunnel than it is in the open air, the same is
645 also true for vehicles travelling in isolation. The drag coefficient of an isolated lorry
646 $C_{d-single}$ is 0.98 inside the tunnel and 0.64 in the open air. Therefore, to compare
647 the benefits of platooning inside the tunnel and in the open air, it is instructive to
648 normalise the drag coefficient by that of an isolated vehicle in their respective cases,
649 as shown in Figure 20(b). It is seen that platooning provides a drag-reduction
650 benefit for all the lorries in both the tunnel and the open air. Interestingly, there is a
651 much larger drag reduction due to platooning for the lorries inside the tunnel than
652 those in the open air. This difference is as large as 20% for the lorries towards the
653 middle of the platoon. Furthermore, the absolute difference between drag
654 coefficients for a lorry in the platoon and in isolation is always higher in the tunnel
655 than it is in the open air. ~~in the tunnel and in the open air is higher for a single-~~
656 ~~vehicle than it is for all the vehicles in the platoon.~~ This suggestsing that platooning
657 has a greater potential for reducing fuel consumption in the tunnel than in the open
658 air.



659
660 Figure 20: A comparison of (a) the mean drag coefficients and (b) the drag reduction ratio $C_d/C_{d-single}$
661 $C_{d-single}$ between the lorries in platoon in the tunnel and in the open air.

662

663 5. Conclusion

664 This paper presents a detailed experimental and numerical study of the
665 aerodynamic phenomena of a long lorry platoon running through a tunnel. The
666 slipstream properties, surface pressure and drag force are discussed and compared to
667 the data obtained in the open air. The main findings of this study are as follow.

- 668 ● Due to the piston effect, stronger flows are induced in the frontal and rear
669 regions of the platoon in the tunnel than in the open air. The influenced
670 regions expand faster when the platoon is travelling inside the tunnel.

671 Both experimental and numerical results reveal greater static pressure
672 variations near the frontal regions of the leading lorries and the rear
673 region of the last lorry in the tunnel.

674 ● The flow structures around the lorry platoon are altered due to the tunnel
675 walls: Fewer vortices are generated from the front edge of the lorry, and
676 larger upper vortices are observed in the rear region. A weaker flow
677 separation leads to a smaller drop in the surface pressure near the box
678 front edge, as compared to the case in the open air.

679 ● The variations of the drag coefficients show similar behaviours with the
680 surface pressure, exhibiting great variations while entering and leaving
681 the tunnel. In contrast to the case in the open air, the mean drag
682 coefficient in the tunnel is no longer monotonically decreasing from the
683 first to the last lorry in the platoon. Rather, it significantly decreases to a
684 plateau at the fifth lorry and then increases again greatly at the last lorry
685 due to strongly negative rear pressures.

686 ● All vehicles, in both the tunnel and the open air, experience a reduction in
687 drag due to platooning. The drag is consistently higher in the tunnel than
688 in the open air for both isolated vehicles and platoons. However, the drag
689 reduction due to platooning is consistently greater in the tunnel than ~~it is~~
690 in the open air. This implies a greater potential to reduce fuel
691 consumption in the tunnel than in the open air.

692 Finally, we would like to highlight three issues for future study of vehicle
693 platoons in a tunnel. The first one is the inter-vehicle separation distance, which was
694 fixed at 1.5 vehicle-length in the present study. However, autonomous vehicle
695 technologies allow smaller separation distances. Therefore, examining platoons with
696 different separation distances is definitely an important issue to explore. The second
697 one is the vehicle shape. The vehicle model used in the present study is a
698 representative of regional delivery trucks. For long-haul transportation trucks, they
699 are often longer with taller cabs and can be expected to behave differently in a
700 tunnel. So studying the tunnel effects on platoons with different vehicle shapes is
701 also desirable. The third one is the tunnel geometry. **Due to experimental constraints,
702 the present study was conducted in a single-lane tunnel. However, tunnels with
703 multiple lanes are of more interest for aerodynamics applications. Platoons
704 travelling through such tunnels would produce different flow fields from the one
705 encountered here. Therefore, studying platoons travelling through a multi-lane
706 tunnel is also an important issue and should be conducted in future.**

707

708

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718

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