1 Wind tunnel measurements for dispersion modelling of vehicle wakes

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7 Abstract

8 Wind tunnel measurements downwind of reduced scale car models have been made to study the
9 wake regions in detail, test the usefulness of existing vehicle wake models, and draw key
10 information needed for dispersion modelling in vehicle wakes. The experiments simulated a car
11 moving in still air. This is achieved by (i) the experimental characterisation of the flow, turbulence
12 and concentration fields in both the near and far wake regions, (ii) the preliminary assessment of
13 existing wake models using the experimental database, and (iii) the comparison of previous field
14 measurements in the wake of a real diesel car with the wind tunnel measurements. The experiments
15 highlighted very large gradients of velocities and concentrations existing, in particular, in the near-
16 wake. Of course, the measured fields are strongly dependent on the geometry of the modelled
17 vehicle and a generalisation for other vehicles may prove to be difficult. The methodology applied
18 in the present study, although improvable, could constitute a first step towards the development of
19 mathematical parameterisations. Experimental results were also compared with estimates from two
20 wake models. It was found that they can adequately describe the far-wake of a vehicle in terms of
21 velocities, but a better characterisation in terms of turbulence and pollutant dispersion is needed.
22 Parameterised models able to predict velocity and concentrations with fine enough details at the
23 near-wake scale do not exist.

24 **Keywords:** Dispersion modelling; Near and far wake; Vehicle wake dispersion; Wind tunnel
25 measurements; Mixing processes

26 1. Introduction

27 Exposure to both short-term transient and long term mean concentrations of gas and
28 particles emitted by ground vehicles in cities can cause severe damage to human health (Brugge et
29 al., 2007; Atkinson et al., 2010; Kumar et al., 2011a). Transport of relatively inert gases and coarse

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30 particles has been well studied in the past (see, e.g., Vardoulakis et al., 2003), however physical and
31 chemical processes involved in nanoparticles dispersion modelling are still poorly understood
32 (Kumar et al., 2010, 2011b), especially at fine spatial and temporal scales, where the impact of a
33 single vehicle wake on the dispersion process can become important (Baker, 2001). Vehicle wakes,
34 for example, can strongly affect the turbulence field in street canyons (Di Sabatino et al., 2003), and
35 their influence on pollutant dilution cause complex interactions with other transformation processes
36 affecting nanoparticles (Carpentieri et al., 2011). Operational dispersion models rarely acknowledge
37 these effects.

38 The vehicle wake is usually divided in two separate regions (Hucho, 1987): the *near-wake* and the
39 *main* or *far-wake*. The near-wake consists of two components: a large scale recirculation region
40 immediately behind the vehicle and a system of longitudinal trailing vortices with unsteady
41 fluctuations caused by a variety of effects such as the instability of the separated shear layer and
42 wake pumping (Ahmed, 1981; Hucho, 1987; Baker, 2001). Studies related to the characterisation of
43 dispersion behaviour in the near wake are much rarer than those related to the far-wake regions.
44 Baker (1996) describes a model based on the assumption that the pollutant emitted by the vehicle is
45 spread uniformly in the near-wake, using a Gaussian puff approach to calculate the concentrations
46 further downwind. This approach might be acceptable for passive gaseous pollutants, but not for
47 nanoparticles that experience transformations on very short time scales (Pohjola et al., 2003; Ketzel
48 and Berkowicz, 2004; Carpentieri and Kumar, 2011) and a more detailed characterisation of the
49 near wake may therefore be necessary (Kumar et al., 2011b). Computational fluid dynamics (CFD)
50 has recently been applied to the near-wake dispersion of pollutants (Richards, 2002; Dong and
51 Chan, 2006; Albriet et al., 2010). The usefulness of the output from these simulations is however
52 limited due to the lack of experimental studies specifically aimed at deriving suitable boundary
53 conditions for the numerical calculations.

54 As far as the far-wake is concerned, the most well known and documented vehicle wake theory is
55 that of Eskridge and Hunt (1979), hereafter referred to as E&H model. Based on the perturbation
56 analysis of the equations of motion the theory describes the velocity field far downstream of a
57 single vehicle moving through still air. Expressions were developed for the velocity deficit far
58 downwind of a vehicle, assuming constant vehicle velocity, flat terrain and no wind. A more recent
59 study by Hider et al. (1997) reported the derivation of the same expression using a different method.
60 They also derived expressions for the lateral and vertical velocity components. Dispersion in the
61 far-wake is usually represented by a standard Gaussian plume (Baker, 1996, 2001; Richards, 2002).

62 Very few models take into account the effect of the vehicle wake in the dispersion process. Clearly,

63 further research is needed for the adequate characterisation of vehicle wakes in dispersion models.
64 In particular, almost no information can be found on the mixing process in the near-wake, though
65 this is the key region where the main nanoparticle evolution processes occur (Carpentieri and
66 Kumar, 2011; Kumar et al., 2009).

67 Wind tunnel experiments have been used extensively for determining the flow characteristics of the
68 wake behind vehicles, as in Eskridge and Thompson (1982), Hackett et al. (1987), and Shaw et al.
69 (2000), but studies for pollutant dispersion are relatively rare. For the development of the
70 ROADWAY model, Eskridge and Rao (1986) determined the optimal turbulence scales in the far-
71 wake region of a moving vehicle. This was obtained by measuring concentrations of inert gaseous
72 tracer in the far-wake (30 to 60 car heights downstream) of a full scale model of a passenger car in
73 a wind tunnel. The near-wake was not the focus of their study, though. More relevant to the near-
74 wake was the study conducted by Clifford et al. (1997). They used three passenger car models in a
75 row in a wind tunnel, separated by half a car length from each other, and measured the distribution
76 of the concentration of emitted tracer on the car surface, including the air inlet positions. Results of
77 their study highlighted the strong influence on the mixing processes of the car immediately behind
78 the emitting vehicle. The focus of their study, however, was on internal air quality rather than
79 dispersion processes in the near-wake.

80 Richards (2002) and Baker (2001) analysed flow and dispersion characteristics in the near-wake of
81 a vehicle model with no cross-wind. Results from these wind tunnel studies highlighted the close
82 relationship between the inert tracer concentration field and the velocity and turbulence fields.
83 Concentration fluctuations, measured by a flame ionisation detector (FID), were consistent with the
84 fluctuations in the velocity field (obtained through a combination of particle image velocimetry,
85 PIV, hot-wire anemometry, HWA, and flow visualisation methods). The time histories of
86 concentration had a “peaky”, intermittent nature. Kanda et al. (2006a) measured the flow
87 characteristics in the near-wake of small-scale models of a car and a lorry emitting a thermally
88 buoyant plume. They used PIV and laser Doppler anemometry (LDA) to measure velocity and
89 turbulence fields in the wind tunnel, and an FID to measure tracer gas concentrations. They found
90 that the buoyancy of the exhaust had generally a minor effect on the dispersion behaviour. The
91 results from this study were then used as a basis for studying multi-vehicle configurations (Kanda
92 et al., 2006b), with an approach similar to the one adopted by Clifford et al. (1997) in the wind
93 tunnel. Chang et al. (2009a; 2009b) also investigated the dilution properties of gas released in the
94 wake of several vehicles in the wind tunnel. While the measurement grid had a lower resolution,
95 compared to the present study, they highlighted the influence of the vehicle shape on flow and
96 dispersion in the near and far wakes.

97 Traffic produced turbulence and its effects on the flow and mixing processes have been the main
98 focus of a number of wind tunnel studies. For instance, Kastner–Klein et al. (2000a,b, 2001a,b)
99 studied different traffic configurations (one–way and two–way) simulated by small metal plates
100 moving on two belts along the street in a wind tunnel model. Their main interest was in the
101 interactions between traffic– and wind–induced flows in a street canyon. The presence of traffic and
102 its arrangement were also shown to affect the concentration distribution along the leeward canyon
103 wall (Kastner–Klein et al., 2001b). The results were then used to derive parameterisations for traffic
104 induced turbulence in street canyon models (Kastner–Klein et al., 2003; Di Sabatino et al., 2003).
105 Khare et al. (2002) and Ahmad et al. (2002) used a similar approach, consisting of moving belts
106 carrying model vehicles, in their wind tunnel experiments. The system was placed in a number of
107 different simulated atmospheric boundary layers, and the effect of the traffic condition and the wind
108 direction on the vertical spread of the exhaust gas was examined. Since the main concern was the
109 effect of traffic as a whole on the general flow and mixing processes in the urban environment, the
110 above mentioned studies did not analyse in detail the characteristics of the wake behind a single
111 moving element. None of them studied the near–wake region of the vehicles in any great detail.

112 The present study involves a series of experiments performed in the wind tunnel laboratory at the
113 University of Surrey, UK. Flow and dispersion characteristics were investigated both in the near–
114 and far–wake regions downwind of reduced scale car models, simulating a vehicle moving in still
115 air. The aims included the experimental characterisation of the flow, turbulence and concentration
116 fields in both wake regions, and the preliminary assessment of existing wake models using the
117 experimental data base. The analysis of previous literature clearly showed that dilution is the main
118 driver for many transformation processes affecting nanoparticles once emitted from the tailpipe
119 (Carpentieri et al., 2011; Chang et al., 2009a). While the present study is mainly focussed with
120 understanding and characterising dilution and mixing processes in a vehicle wake using a passive
121 tracer, the results are relevant to nanoparticle dispersion because of the primary role of dilution and
122 mixing. This approach is similar to the one proposed by Chang et al. (2009a). Compared to previous
123 studies, the research presented here benefits from the integrated approach used, which includes
124 previous field measurements. The comparison between field measurements of nanoparticle
125 concentrations and wind tunnel results on passive tracers, in particular, can help in better assessing
126 and quantifying the role of dilution in nanoparticle transformations.

127 The work presented in this paper is part of a wider effort aimed at characterising the dispersion of
128 nanoparticles in the wake of moving vehicles through field measurements and laboratory
129 experiments, in order to derive simple mathematical parameterisations (Carpentieri et al., 2011;
130 Carpentieri and Kumar, 2011).

131   **2.   Wind tunnel tests**

132   **2.1   Experimental setup**

133   The core of the experimental work was carried out at the boundary layer wind tunnel of the
134   Environmental Flow Research Centre (EnFlo) at the University of Surrey, UK (referred to hereafter
135   as the ‘EnFlo tunnel’). It is an open circuit, ‘suck-down’ wind tunnel having a 20 m long, 3.5 m
136   wide and 1.5 m high working section. The wind speed range is from 0.3 to 3.5 m s⁻¹, and the facility
137   is capable of simulating both stable and unstable atmospheric conditions, although these features
138   were not used in this study. Reference flow conditions were measured by an ultrasonic anemometer
139   held at a fixed location at 1 m from the ground, and two propeller anemometers mounted on either
140   side of the traverse carriage. Temperature conditions were monitored by thermocouple rakes in the
141   flow and individual thermocouples in each tunnel wall panel. The wind tunnel and the associated
142   instrumentation are fully automated and controlled using ‘virtual instrument’ software created in
143   LabVIEW by the EnFlo research staff.

144   The geometrical characteristics of the reduced-scale models were derived from the diesel car used
145   (2004 Vauxhall AstraVan) during related field measurements (Carpentieri and Kumar, 2011). Two
146   different scales were investigated: a 1:5 model focusing on the near-wake characterisation, and a
147   smaller 1:20 model extending our measurements well into the far-wake. The wind tunnel models
148   which are simplified representations of the actual diesel car are shown in Fig. 1.

149   Models were installed approximately 11 m from the inlet to the wind tunnel working section, where
150   a relatively deep boundary layer would develop on the smooth tunnel floor, even without the use of
151   turbulence generators or roughness elements. In order to remove the unrealistic effects of such a
152   boundary layer, all models were placed near the edge of a raised false floor, which is a common
153   practice in wind tunnel measurements (see, for example, Kanda et al., 2006a, 2006b, and Chang et
154   al., 2009a, 2009b). In fact, we are simulating a vehicle moving in still air, where turbulence levels
155   must be as small as possible. A schematic representation of the experimental set-up is reported in
156   Fig. 2.

157   The false floor was 4150 mm long, 90 mm wide and 20 mm thick. It was placed at a height of 220
158   mm from the wind tunnel floor. For reference, the model dimensions were approximately: 860 mm
159   × 380 mm × 300 mm (1:5 model; length × width × height), and 215 mm × 95 mm × 75 mm (1:20
160   model). The wind tunnel dimensions implied that the blockage factor was about 2.1% for the 1:5
161   model, and 0.5% for the 1:20 model.

162   Velocity and turbulence fields in the wake of the models were measured by means of a two
163   component LDA. A fibre-optic system was used, with the final optical head being a 20 mm

164 diameter cylinder, 150 mm long and the measurement volume located at 50 mm in front of the head.
165 Concentration measurements were obtained by using a Fast response Flame Ionisation Detector
166 (FFID, Cambustion HR400), sampled at a frequency of 200 Hz. A passive tracer gas (propane in
167 air) was released from the vehicle tailpipe, with an exit velocity (V) equal to 0.33 or 0.66 m s⁻¹ for
168 the 1:5 and 1:20 scale model, respectively. The exit velocities were kept as low as possible in order
169 to provide a passive release, while still having the ability to control the flow rate with the laboratory
170 instrumentation. The choice of using a passive tracer is of course a simplification. As highlighted,
171 for example, by Chang et al. (2009b), the exit velocity from the tailpipe is an important factor when
172 assessing near wake dispersion. Buoyancy could also affect the exhaust plume in real emissions.
173 However, the analysis of these parameters is outside the scope of the present study and a simplified
174 approach has been applied (see, e.g., the similar approach chosen by Baker and Hargreaves, 2001;
175 Baker, 2001). The choice of using a passive tracer also simplifies the scaling properties of our
176 models, because only the similarity of the external flow must be ensured (see Section 3.1) for this
177 experimental setup. Since the EnFlo experiments were conducted with a reference wind speed of
178 2.5 m s⁻¹, the ratio between exit velocity and car speed (V/U_{ref}) were 0.13 and 0.27 for the 1:5 and
179 1:20 scale model, respectively. These values are comparable to those used by Kanda et al. (2006a).

180 Three-dimensional LDA measurements were performed over most of the false floor using a
181 reference wind speed of 2.5 m s⁻¹. Initial evaluations were carried out without the vehicle model to
182 assess the development of the boundary layer above the floor. To further assess this particular
183 aspect, additional FFID tests were also carried out in a smaller closed-circuit wind tunnel designed
184 for aerodynamic tests on ground vehicles. This wind tunnel (hereafter referred to as the ‘Aero
185 tunnel’) has a 9.8 m long, 1.065 m wide and 1.37 m high working section, and has a rolling road
186 section with a boundary layer suction system. The maximum achievable wind speed for this wind
187 tunnel is 40 m s⁻¹. Unrealistic boundary layer effects were removed by running the rolling road at
188 the same speed as the wind flow and adjusting the boundary layer suction fans speed accordingly.

189 The preliminary tests in the Aero tunnel were conducted on the 1:20 model, as the 1:5 model was
190 too large to fit the wind tunnel without causing excessive blockage effects. In order to measure
191 tracer concentrations at a high resolution within the near wake, an intermediate size model (i.e. 1:8
192 scale) was constructed and used. The rolling road belt was 1.47 m long and 0.60 m wide, sufficient
193 to cover at least the near wake of the 1:20 scale model, and the recirculation region of the wake of
194 the 1:8 scale model. A wind speed of 10 m s⁻¹ was set for these tests as this was the lowest
195 operating speed at which the rolling road could be used satisfactorily. The exit velocity of the tracer
196 gas released from the tailpipe of the 1:8 scale model was 0.29 m s⁻¹.

197 2.2 Experimental strategy

198 A right-handed Cartesian coordinate system was used during all the experiments, both in the
199 EnFlo and Aero tunnels, with the x axis along the wind tunnel centre line (i.e. along the flow
200 direction), the y axis across the floor surface, and a vertical z axis. Coordinate origins were located
201 with $x = 0$ at the rear of the vehicle model, $y = 0$ on the centre line, and $z = 0$ at ground level. In
202 order to compare the results from measurements taken in different experiments using different
203 models, dimensionless coordinates were used: $X = x/h$, $Y = y/h$, and $Z = z/h$, where h is the vehicle
204 height. The area covered by the LDA measurements was the region $0.40 < X < 10.47$, $-1.33 < Y <$
205 1.33 and $0.07 < Z < 2.00$, for the 1:5 model, and $0.44 < X < 47.80$, $-2.67 < Y < 2.67$ and $0.20 < Z <$
206 4.00 , for the 1:20 model. Two non-uniform measurement grids were used during the experiments
207 with the 1:5 model, a high resolution grid closer to the model, up to $X = 5.47$ ($10 \times 15 \times 9$ points),
208 and a low resolution grid further away from the model ($5 \times 9 \times 9$ points). A single non-uniform
209 measurement grid was used with the 1:20 model, consisting of $15 \times 9 \times 9$ points.

210 In order to obtain the three velocity components over the whole area, the probe of the two-
211 component LDA system was aligned in two different orientations (giving measurements either in
212 the x - y plane or the x - z plane). The three components of velocity were measured at all locations
213 over a period of 30 seconds to three minutes, depending on the measurement location. The
214 averaging time was based on the requirement that the standard error of the mean value of the x
215 component, U , fell below an arbitrary threshold of 0.006 m s^{-1} . The result was a complete three-
216 dimensional mapping of the area of interest.

217 FFID measurements in the EnFlo tunnel were carried out in a similar manner, using the same
218 averaging time criteria (applied to the standard error of the mean concentration, C , rather than U),
219 although the measurement domains were somewhat smaller in vertical extent: $0.07 < Z < 1.33$, for
220 the 1:5 model (2 grids, one with $10 \times 15 \times 8$ points up to $X = 5.67$, the other with $5 \times 9 \times 8$ points),
221 and $0.20 < Z < 2.67$, for the 1:20 model ($15 \times 9 \times 8$ points). The emitting tailpipe was placed at $Y =$
222 -0.33 and $Z = 0.19$ on the rear of each model.

223 Given the higher wind speed in the Aero tunnel, often a shorter averaging time (in the range of 20 s
224 to 3 minutes, applying the same methodology as in the EnFlo experiments with a threshold on the
225 concentration standard error) was used. The measurement grids were similar to those used in the
226 EnFlo tunnel, although the measurement domain was smaller due to the constraint enforced by the
227 dimensions of the rolling road. Experiments in the Aero tunnel were conducted both with and
228 without operation of the rolling road, to assess the significance of boundary layer effects.

229 3. Results

230 3.1 Wake characterisation

231 This section reports the results of the experimental campaign carried out using the EnFlo
232 wind tunnel. Velocities have been normalised by using the reference wind speed U_{ref} , which was
233 measured by the fixed ultrasonic anemometer (see Section 2.1). Similarly, root mean square (rms)
234 velocity components have been dimensionalised as σ_u/U_{ref} , σ_v/U_{ref} and σ_w/U_{ref} .

235 Concentrations have been normalised by using the standard expression: $C^* = (C U_{ref} h^2)/Q$, where
236 C^* is the dimensionless concentration, and Q is the source volumetric flow rate. As explained in
237 Section 2.2, distances were normalised using the vehicle height, h .

238 As explained in Section 2.1, the experiments were carried out at 2.5 m s^{-1} in the EnFlo tunnel, and
239 at 10 m s^{-1} in the Aero tunnel. The Reynolds number calculated for the 1:20 model in the EnFlo
240 tunnel was 1.25×10^5 , which is well above the critical value (Snyder, 1981) required to ensure
241 dynamic similarity for higher wind speeds and larger models. A few tests, however, were repeated at
242 5 m s^{-1} in the Aero tunnel to check for any differences in the concentration field.

243 3.2 Velocity measurements

244 This section presents mean velocity and velocity fluctuation (rms) fields measured during
245 the LDA tests in the EnFlo tunnel. Fig. 3 shows the longitudinal evolution of the measured vertical
246 profiles along the centre line, both for the 1:5 scale (Fig. 3a) and 1:20 scale (Fig. 3b) models. The
247 longitudinal velocity deficit in the wake is clearly visible in both cases. However, the surface
248 boundary condition also plays a role in reducing the flow speed near the surface, within the
249 boundary-layer that develops on the false floor. This aspect is analysed and discussed in Section 3.4.

250 Fig. 4 shows the mean velocity vectors and rms velocity contour plots for the 1:5 model in two
251 vertical planes: the $Y=0$ plane (centre line, Figs. 4a, b and c) and the $Y=-0.33$ plane (in line with
252 tailpipe, Figs. 4d, e and f). A recirculating flow region can be observed, particularly along the centre
253 line (Fig. 4a), having an approximate length of about $2h$. While an initial high speed zone exists at
254 the lowest levels, corresponding to the air flow coming from below the vehicle, the wake begins to
255 affect this region at a distance of about $1h$ because of downward spread of the wake region. As
256 observed earlier, part of this effect could be due to the interaction with the developing boundary
257 layer on the false floor (see also Section 3.4).

258 Longitudinal turbulence (shown as σ_u^2/U_{ref}^2) is particularly high within the recirculation zone, with
259 maximum levels found at heights corresponding to the upper and lower surfaces of the car (Fig. 4b).

260 This is in the shear layers that arise from flow separation at the upper and lower edges of the
261 vehicle. Similar patterns (see Figs. 5b and e) are caused by the lateral surfaces of the car. Significant
262 vertical turbulence (shown as σ_w^2/U_{ref}^2) is mainly concentrated within the recirculation wake (Figs.
263 4c and f).

264 Velocity vectors and turbulent velocity contours from the LDA measurements behind the 1:5 model
265 are plotted in horizontal planes in Fig. 5; the $Z=0.07$ plane (the lowest measured level, Figs. 5a, b
266 and c) and $Z=0.23$ plane (at tailpipe height, Figs. 5d, e and f) are shown. Regions of high
267 longitudinal variance extend in-line with the vehicle sides (Figs. 5b and e), while a zone of high
268 lateral turbulence (i.e. σ_v^2/U_{ref}^2) is observed within the recirculation region (Figs. 5c and f),
269 approximately overlapping the vertical turbulence field observed in Figs. 4c and f. These results are
270 consistent with the measurements by Kanda et al. (2006a) and Huang et al. (2009).

271 The results presented here are, of course, very geometry-dependent. In order to develop
272 mathematical models a range of different vehicle shapes and dimensions must be analysed (see,
273 e.g., the study by Al-Garni and Bernal, 2010, on a pickup truck).

274 3.3 Concentration measurements

275 Dimensionless concentrations measured during the FFID experiments in the EnFlo tunnel
276 are presented in this section, while Section 3.4 provides an overview of results from the Aero
277 Tunnel experiments with the rolling road. Fig. 6 shows results with the 1:5 scale model, presented
278 as contour plots in vertical planes (Figs. 6a, b and c) and horizontal planes (Figs. 6d and e). As in
279 the case of velocity measurements, the $Y=0$ plane (centre line, Fig. 6a) and $Y=-0.33$ plane (in line
280 with tailpipe, Fig. 6b) are shown, as well as the $Z=0.07$ (lowest section, Fig. 6c), $Z=0.23$
281 (approximately at tailpipe height, Fig. 6d) and $Z=0.60$ (approximately at the middle of the car body,
282 Fig. 6e) horizontal sections. The vertical section at $Y=0$ (Fig. 6a) highlights the effect of the
283 recirculation region, with an accumulation of tracer close to the vehicle rear driven by embedded
284 vertically aligned vortices. This is also evident in the horizontal sections at heights between the
285 vehicle base and the roof, and at $Z=0.60$ in particular (Fig. 6e). The shape of the wake and the flow
286 field reported in Section 3.2 clearly affect the development of the plume, as shown by the contour
287 plots in Figs. 6b, c and d (compare them, for instance, with Figs. 4 and 5). In general, the measured
288 plume is far from the classical Gaussian form, especially in the near wake, though that is often
289 assumed in operational mathematical models.

290 Similar contour plots for FFID measurements on the 1:20 scale model are reported in Fig. 7. Again,

291 $Y=0$ (Fig. 7a) and $Y=-0.33$ (Fig. 7b) have been chosen as the vertical sections, while horizontal
292 planes are shown at $Z=0.2$ (Fig. 7c) and $Z=0.6$ (Fig. 7d). All four figures highlight a strong
293 influence of the vehicle wake on the development of the plume, particularly near the vehicle. These
294 results with the 1:20 model, extending up to $X=47.8$, are useful for a quantitative comparison with
295 standard mathematical models, as reported in Section 4.

296 **3.4 Boundary layer effects**

297 Despite the precautions taken in designing the wind tunnel tests (see Section 2), some
298 unwanted effects due to the development of the boundary-layer on the false floor are inevitable and
299 must affect the results to some degree (Sections 3.2 and 3.3). The measurements of velocity profiles
300 above the false floor in the EnFlo tunnel, performed without the model (see Section 2.3), allowed us
301 to estimate the boundary-layer growth. The depth of the boundary-layer was approximately 15-20
302 mm at 450 mm from the floor leading edge, reaching 50-60 mm towards the downwind end of the
303 floor.

304 A preliminary experimental campaign was carried out in the ‘Aero’ wind tunnel, which features a
305 rolling road with a boundary layer suction system, in order to assess the influence of this
306 phenomenon on the data. Direct comparison of velocity data was not feasible as no velocity
307 measurements were available from the Aero tunnel and concentration measurements in the wake of
308 the vehicle models were therefore used to perform an analysis of any effects of boundary layer
309 development. Results from the experiments with a 1:5 model in the EnFlo tunnel were compared
310 with results from experiments with the 1:8 model in the Aero tunnel. Results from the 1:20 model
311 experiments from the EnFlo and Aero tunnels were compared with each other.

312 Fig. 8 shows a comparison of the vertical concentration profiles close to the model vehicle.
313 Comparison of the results in the Aero tunnel with and without the rolling road shows clear
314 differences in tracer dispersion behaviour. In particular, concentrations are generally lower close to
315 the car ($X = 0.44$, Figs. 8a and b) when the rolling road and boundary layer suction system are in
316 operation. Further from the model, the situation is reversed, at least near the ground, as seen in Figs.
317 8c and d. This may be due to increased turbulence in the latter case, which in turns increases the
318 spreading of the plume as it travels downwind. This effect is also evident in the horizontal (lateral)
319 profiles shown in Fig. 9, demonstrating that increased mixing occurs both in the vertical and lateral
320 senses. In contrast, the higher velocity of the air flow below the car when the rolling road is running
321 caused an enhanced mass exchange through the flow separation surface, decreasing the
322 concentration of tracer within the recirculation region (as explained earlier, the source was within
323 the recirculation area).

324 Differences between the EnFlo and Aero tunnel results with a stationary floor are substantial, as can
325 be seen in Figs. 8 and 9. As the experiments show, high concentration gradients can be found in the
326 vehicle wake in the vicinity of the exhaust plume. In such a situation, even a very small discrepancy
327 in probe positioning or the plume location can lead to large differences in the results obtained. The
328 different conditions in the two wind tunnels (the Aero tunnel being much narrower than the EnFlo
329 tunnel) might also contribute, in particular by affecting plume behaviour in the horizontal plane.
330 The only way to resolve this issue would be to use a very dense measurement grid that accurately
331 defined the plume structure and then compare measurements relative to their position in the plume
332 and, separately, compare plume trajectories. However, insufficient data were available to pursue this
333 approach.

334 Fig. 10 shows the evolution of the vertical profiles of concentration along the source centre line (Y
335 $= -0.33$) for the 1:20 model. The differences apparent in each set of profiles in Fig 8 are by no
336 means as pronounced in these results (e.g. compare Figs 10a and 8a). This is probably due to the
337 smaller scale, which renders the difference in turbulence levels more important as the measurement
338 points are actually closer to the ground. The enhanced mixing that results appears to annul the
339 increased exchange caused by the higher velocity beneath the car. The reduced mixing when the
340 rolling road is running (already observed in Figs. 8c, 8d and 9d) is particularly evident in Fig. 10a.

341 Vertical profiles at greater distances (Figs. 10b, c and d) actually show higher concentrations in the
342 cases with a developing boundary-layer. This counter-intuitive phenomenon is possibly caused by
343 the reduced advection speed due to the slower air flow. In the experiments with the larger models
344 (i.e. 1:5 and 1:8), this was not visible due to the limited experimental fetch covered and the fact that,
345 in absolute terms, the measurements were performed at greater distances from the ground (and so
346 the velocity differences between the cases with and without a boundary layer were less). With the
347 smaller scale of the vehicle model, this advection effect (i.e. increased concentrations due to lower
348 wind speeds) prevails on the turbulence effect (i.e. decreased concentrations due to the greater
349 mixing). The EnFlo tunnel results tend to follow the behaviour of the Aero tunnel without operation
350 of the rolling road as would be expected, at least for the vertical profiles along the plume centre line
351 shown in Fig. 10.

352 Fig. 11 shows the longitudinal evolution of dimensionless concentrations in the 1:20 model tests at
353 two different heights, both for the exhaust centre line and the car centre line. Figs. 11a and b show
354 that more material is entrained from the exhaust plume into the recirculation region in the EnFlo
355 tunnel experiments. Note that the results in Fig. 11a are at a height that is comparable with the
356 position of the shear layer in the separation from the underside of the vehicle and hence sensitive to

357 small differences in the location of the shear layer in the three simulations. Consistent behaviour in
358 this region for all three model scales is unlikely as the relative size of the underside clearance and
359 the upstream boundary layer change. In contrast to Figs. 11a and b, Figs. 11c and d show reasonably
360 consistent results for all three simulations, though again there are differences at the lower height in
361 the near field.

362 The comparisons discussed above involved measurement points taken within the first metre or so
363 from the leading edge of the floor, so that the boundary-layer depth was never more than 20-30 mm
364 (see at the beginning of this section). Despite this, the changes induced in the concentration field
365 close to the vehicle were substantial and persisted above the surface boundary-layer. The
366 explanation for this lies in the fact that the concentration field within the recirculation zone is
367 controlled by the turbulent exchange with the external flow and much of the interface is located
368 within the surface boundary-layer and affected by boundary layer turbulence. Far downstream, once
369 the wake has decayed to become merely a small perturbation to the surface boundary layer, it is the
370 latter that controls dispersion behaviour. In these circumstances, the boundary layer depth will be
371 comparable to or greater than the wake depth, especially for the 1:20 scale model. Note that the
372 extent of the rolling road did not allow us to make measurements further downstream from the
373 model than shown in Fig 11.

374 **4. Discussion**

375 The results of the wind tunnel experimental campaign represent a first step in our strategy,
376 eventually aimed at characterising and modelling nanoparticle dispersion in a vehicle wake. In this
377 respect, the study of dilution processes in close proximity to a moving car, by means of dispersion
378 of a passive tracer, is the most important phenomenon to tackle and the main reason behind this
379 experimental study. In order to plan and develop future stages in our project, it is very useful to
380 assess and compare existing mathematical models against our experimental results. This
381 preliminary comparison is reported in Sections 4.1 and 4.2. In Section 4.3 the implications of our
382 results for nanoparticle dispersion are discussed, providing other important elements for the
383 development of our future strategy to reach the proposed objectives.

384 **4.1 Building wake models**

385 A possible approach for modelling flow and dispersion in the wake of a vehicle has been
386 described by Carpentieri et al. (2011), based on methodologies used for building wake models. As a
387 preliminary evaluation of this approach, a comparison has been carried out between the wind tunnel
388 results and predictions from a simplified version of one of the most advanced parametric models for

389 building wake pollutant dispersion (i.e. BUILD, the building effects module used by ADMS, the
390 Atmospheric Dispersion Modelling System; Robins and Apsley, 2009). The model was adapted by
391 assuming that the moving car was a fixed building block, having the same dimensions (length,
392 width and height) as the modelled car. Results were non-dimensionalised using the methods
393 described in Sections 2.2 (for coordinates, dimensions and distances) and 3.1 (for velocities and
394 concentrations), so that the chosen geometrical scale of the simulated building, as well as the
395 reference wind speed and emission rate, are not relevant.

396 ADMS-BUILD simplifies the wake region by dividing the downwind space into two volumes: the
397 near-wake and the far (or main) wake. The near-wake region is adjacent to the building and includes
398 a recirculation zone where the pollutant is assumed to be well mixed. The far-wake is the region
399 where the structure of the pollutant plume is based on a perturbed Gaussian plume model. The
400 plume growth is determined by a combination of plume spread in the underlying dispersion model
401 of choice and a contribution due to the building wake. For our simplified version of the model,
402 referred to as “CAR-BUILD”, we adopted a standard Gaussian plume and the details of the model
403 formulation can be found in Appendix A.

404 Fig. 12 shows a comparison between vertical concentration profiles calculated using CAR-BUILD
405 and wind tunnel results from the 1:5 scaled experiments. The first noticeable difference between the
406 measured and calculated profiles is due to the position of the tailpipe and the fact that CAR-BUILD
407 assumes complete mixing in the near wake. The effect is that along the vehicle centre line ($Y = y/h =$
408 0 ; Figs. 12a and b) the Gaussian concentrations calculated by the model are higher than the
409 measured values, while along $Y = -0.33$ (in line with the tailpipe; Fig. 12c) measured values are
410 significantly greater than calculated concentrations, at least close to the vehicle. Further away from
411 the car, the actual mixing in the wake appears greater than that estimated by the Gaussian plume
412 formulation. This effect can be seen, for example, by looking at the similar values assumed by the
413 measured vertical profiles at $X = x/h = 10.47$ (Figs. 12b and d), while the predicted values by the
414 Gaussian model are of course higher at the centre line. The combination of these two effects (i.e.
415 complete mixing in the near wake and reduced mixing in the far wake) lead to this remarkable
416 similarity, presumably more by chance than because of the ability of the model. However, the
417 similarity in the shape of the two profiles is undeniable, meaning that the vertical mixing process is
418 reasonably well captured by the model.

419 Another effect that CAR-BUILD could not capture is the reduction in concentrations near the
420 ground, especially close to the car (e.g., $X = 2.13$, Figs. 12a and c). The lower concentrations
421 observed in the wind tunnel are mainly due to the clean air jet coming from beneath the car, while

422 the model does not take this effect into account.

423 The trend of lower mixing in far wake region continues further downwind (Fig. 13), leading to
424 significantly higher concentrations estimated by CAR-BUILD throughout the wake. It should be
425 noted, however, that a factor of 2 or 3 between model results and measurements could be expected
426 from CAR-BUILD performance.

427 **4.2 Vehicle wake models**

428 The most well known and documented vehicle wake theory is that of the E&H model. Based
429 on the perturbation analysis of the equations of motion the E&H model describes the velocity field
430 far downstream of a single vehicle moving through still air. Using the assumptions of constant
431 vehicle velocity, flat terrain and no wind, expressions were developed for the velocity deficit far
432 downwind of a vehicle (i.e. in the far-wake). A more recent study by Hider et al. (1997) saw the
433 derivation of the same expression using a different method. They also derived expressions for the
434 lateral and vertical velocity components. The E&H model is conceptually similar to ADMS/CAR-
435 BUILD. The equations for the calculation of the wake velocity perturbation are based on the same
436 assumptions, but the E&H model uses a moving wall boundary condition for the ground, simulating
437 a moving street surface below a stationary car, in place of the opposite. This effect is obviously not
438 simulated in CAR-BUILD, where both ground and obstacles are fixed.

439 A comparison between measured profiles of wind velocity in the wind tunnel and predictions from
440 the E&H approach can give further useful insight on the processes involved. For this comparison
441 we have used the formulation of the E&H model reported by Baker (2001), in which the velocity
442 deficit in the wake (U') can be calculated from the following expression:

$$443 \quad \frac{U'}{U_{ref}} = \alpha \frac{Z}{X} \exp\left(-\beta \frac{Y^2 + Z^2}{X^{0.5}}\right) \quad (1)$$

444 where α and β are constants and depend on a number of parameters within the model, such as the
445 eddy viscosity and the vehicle-drag coefficient. These are empirical parameters and could of course
446 be optimised in developing a model. Since we are mainly interested in the qualitative comparison of
447 the E&H model with the wind tunnel measurements rather than the numerical values predicted by
448 the model, we used the values given by Baker (2001), derived from the original work of Eskridge
449 and Hunt (1979); i.e. $\alpha = 2.5$, and $\beta = 4.3$.

450 The E&H model is considered valid only for $X > 10$, well into the far-wake, thus its results were
451 only compared with the 1:20 scale wind tunnel measurements. The comparison for the longitudinal

452 wind profiles at two different heights is presented in Fig. 14, along with profiles calculated by
453 CAR-BUILD, as detailed in Appendix A.

454 The direct comparison of results obtained by different models and the measurements is not
455 straightforward. This is due to the fact that wind tunnel measurements are affected by the
456 development of the boundary layer, especially in the far wake, and especially at $Z = 0.2$ which is the
457 lowest measurement level. The growing boundary layer implies a reduction in speed at a fixed
458 height as x increases. While the measured velocity profiles seem to be closer to the values estimated
459 by CAR-BUILD, the wake decay is better captured by the E&H model (see, in particular, the very
460 similar shapes in Fig. 14b). In addition, the numerical values of the E&H model could be further
461 improved by adjusting the values of α and β constants.

462 Similar conclusions were drawn by comparing vertical and lateral profiles (not shown here).
463 Overall, this comparison exercise leads us to conclude that the vehicle wake models (and even
464 building wake models) can be made adequate for describing the far-wake, provided the model
465 parameters are adjusted for the particular vehicle shape. Systematic experimental studies are
466 therefore needed on a large range of vehicle shapes and boundary conditions in order to generalise
467 this approach.

468 **4.3 Implications for nanoparticle dispersion**

469 As highlighted in Section 1, the present work is part of a greater effort to better understand
470 and characterise nanoparticle dispersion in a vehicle wake. The analysis and characterisation of the
471 vehicle wake in terms of passive tracer dispersion is a first step towards this goal. However, as
472 dilution, which in turn is related to the mean velocity and turbulence fields in the wake, plays such
473 an important role in the nanoparticle transformation processes, the results gathered during the wind
474 tunnel experimental campaign offer a key perspective in order to assess their implications for
475 nanoparticle dispersion.

476 The issues identified in the comparison exercises described in the previous Sections (4.1 and 4.2)
477 are the first that need to be tackled in order to develop suitable parameterisations for pollutant
478 dispersion in the far-wake. However, the near-wake model, designed for inert pollutants, must be
479 formulated differently in order to become suitable for nanoparticle dispersion. Small spatial and
480 temporal scales assume paramount importance in nanoparticle transformation processes, as
481 highlighted by Carpentieri et al. (2011), thus the complete mixing assumption used to describe the
482 near-wake will need to be revised.

483 The shape of the model used in the wind tunnel tests was based on the vehicle used during earlier

field measurement campaigns (Carpentieri and Kumar, 2011). A direct comparison between wind tunnel results and field measurements is not possible though, for the following reasons. Firstly, the field campaigns involved measurements of particle size distributions and number concentrations in the 5–560 nm size range in the wake of a moving diesel car. In line with earlier work (Kumar et al., 2009), emitted particles were observed to undergo a range of very fast transformation processes just after their release from the tailpipe (Carpentieri and Kumar, 2011), while the passive tracer gas used in the wind tunnel is affected by dilution only. Secondly, the particle number emission factor for the car used in the experiments could not be accurately estimated because of limitations in the setup used and instrumentation deployed during the measurement campaign. Nevertheless, a useful qualitative comparison can still be attempted.

Fig. 15 shows a comparison between one of the experimental cases of the field campaigns (in particular the case with vehicle speed $V_V = 30 \text{ km h}^{-1}$ during on-board measurements; see Carpentieri and Kumar, 2011; this case represented a typical data set) and the wind tunnel measurements with the 1:5 scale model. Results are presented as concentration ratios, these being the ratios of the observed values to the maximum of the observations. Figs. 15a and b show the concentration ratios at the 9 points defined in Fig. 15e. Note that the locations of the wind tunnel observations differ slightly from those in the field. While the relative distributions at the two upper levels ($Z > 0.3$) are somewhat similar, large differences can be observed at the lowest level. In particular, the value measured in the field at the point closest to the tailpipe ($Y = -0.30$) is much greater than that found from the wind tunnel measurements. This difference, dramatic though it is, could be due to the geometrical details of the vehicle underside of the wind tunnel model which is a great simplification of the real case. Because of this, the tailpipe in the field experiments emitted a plume at the border between the recirculation wake and the flow beneath the car, while in the wind tunnel model the tailpipe emitted within the recirculation area. For example, great differences in dilution properties were also found by Chang et al. (2009b) in their wind tunnel experiments. In similar situations, the exit momentum could also play an important role (Chang et al., 2009b). The differences in the distribution of concentrations close to the tailpipe are also apparent in the horizontal sections presented in Fig. 15c and d for the 6 points defined in Fig. 15f.

5. Summary and conclusions

Wind tunnel experiments were performed to study wind flow and pollutant dispersion in the wake of a passenger car. The experimental database built during the experiments includes velocity, turbulence and concentration measurements in the wake of three car models of scale 1:5, 1:8 and 1:20. The flow field was characterised both in the near-wake (closest to the car) and the far-wake

517 regions. While the work presented here mainly concerns the wind tunnel measurements, the
518 experiments are part of a wider integrated approach aimed at better characterising and, eventually,
519 developing mathematical parameterisations for nanoparticle dispersion in the wake of vehicles.

520 The vehicle wake has been fully characterised and analysed both in terms of the mean flow,
521 turbulence and pollutant dispersion. A comprehensive experimental data set was collected and
522 analysed to develop a better understanding of the flow and dispersion characteristics of pollutants in
523 vehicle wakes, especially in the near-wake region. Such published data are still relatively rare,
524 presumably because small scale phenomena occurring in the vehicle wake are generally neglected
525 when dealing with gaseous (usually inert) emissions. This is however not true for nanoparticles
526 (Pohjola et al., 2003). In order to provide reliable estimates of nanoparticle number concentrations
527 and size distributions, proper account must be taken of the fine scale spatial and temporal variations
528 within the flow and the near-wake, where large gradients exist, is very important in this respect.

529 From a methodological point of view, the experimental approach used in this study could be further
530 improved. In particular, the development of a boundary layer on the wind tunnel floor is a problem
531 that must be addressed before using quantitative results for model development. Preliminary results
532 obtained with a rolling floor have highlighted the differences in the measured concentrations arising
533 from this phenomenon.

534 Experimental results were also compared with flow and dispersion estimates from some of the few
535 models designed to treat the small scale structure of vehicle wakes. This comparison exercise
536 highlighted some issues that need to be addressed for the development of nanoparticle dispersion
537 model in the near- and far-wake regions:

- 538 • Existing models can adequately describe the far-wake of a vehicle in terms of velocities,
539 provided appropriate parameter optimisation is undertaken to take into account the particular
540 geometry of vehicles.
- 541 • A better characterisation of the far-wake in terms of turbulence and pollutant dispersion is
542 needed. Approaches used in urban dispersion models for building wakes do not seem able to
543 predict plume dispersion patterns from a moving vehicle to an acceptable degree.
- 544 • Operational models capable of predicting velocity and concentrations (with fine enough
545 details) at the near-wake scale do not currently exist. They must be developed in order to
546 predict nanoparticle dispersion and transformations reliably in the wake of vehicles, and
547 they must be able at least to predict short-term dilution factors.

The integrated approach, combining field experiments and wind tunnel measurements is another added value to the present study. The comparison highlighted, in particular, the importance of the correct modelling of the tailpipe position relative to the flow field beneath the car and the recirculation region behind it. This aspect is often neglected in experimental studies, but has important affects on the small scale variations in the initial stages of dispersion, when most of the transformation processes occur (Carpentieri and Kumar 2011). Even more comprehensive integration can be reached in future by adding small scale modelling tools, such as computational fluid dynamics (CFD). This integrated approach can provide mutual feedback to the methods involved (field measurements, laboratory experiments and modelling) that can help improve all aspects of the analysis and, eventually, lead to the construction of a systematic numerical and experimental database necessary for the development of nanoparticle dispersion parametric models, of which the present study represents an initial step. The present study was mainly concerned with vehicles moving in still air. Since this is not the case in many real situations, future studies may include the effects of a developed boundary layer on the dispersion mechanism. Other parameters to be included in future studies are buoyancy effects and different tailpipe exit velocities.

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7. Appendix A. Building wake derived model (CAR-BUILD)

One of the methodologies used for the calculation of velocity and concentration in the vehicle wake was adapted from the ADMS building effects module (Robins and Apsley, 2009), with some minor modifications and simplifications.

The model considers a region of perturbed flow around a building (in our case around the car), labelled as **B**, and subdivides it in several regions. In particular, a recirculating flow region, **R**, and a wake region, **W**, are defined. They correspond roughly to the near- and far-wake, though not exactly. The length of the recirculating flow region, L_R , is calculated as:

$$L_R = \frac{AW}{1 + BW/h} \quad \text{where } A = 1.8 \left(\frac{L}{h} \right)^{-0.3} \text{ and } B = 0.24$$

578 where W is the car (building) width, h is the car (building) height, L is the car (building) length.

579 The x velocity component in the main wake (thus when $x > L_R$), U , is then calculated using:

$$580 \quad U^* = \frac{U}{U_{ref}} = 1 - \hat{u} \left[\frac{W}{2\lambda_y} \right] \left[\frac{h}{2\lambda_z} \right]^2 G(\xi) H(\eta)$$

581 where:

$$582 \quad \eta = \frac{y}{\lambda_y} \quad \xi = \frac{z}{\lambda_z}$$

$$583 \quad G(\xi) = \left(\frac{\xi}{2} \right) \exp\left(-\frac{\xi^2}{4} \right) \quad H(\eta) = \left(\frac{1}{2\sqrt{\pi}} \right) \exp\left(-\frac{\eta^2}{4} \right)$$

$$584 \quad \lambda_y(x) = \left[\frac{D_y(x - x_0)}{U_{ref}} \right]^{1/2} \quad \lambda_z(x) = \left[\frac{D_z(x - x_0)}{U_{ref}} \right]^{1/2}$$

$$585 \quad D_y = \kappa u_* h \quad D_z = 2\kappa u_* h$$

586 κ is the Von Karman constant (0.4), and the friction velocity u_* was taken as $0.01 U_{ref}$. The virtual
587 origin, x_0 , is set so that the longitudinal velocity remains positive through the main wake region,
588 while:

$$589 \quad \hat{u} = \frac{C_G}{\sqrt{\pi}} \quad C_G = 0.8$$

590 The concentrations are calculated by assuming a standard Gaussian plume dispersing from the
591 recirculating flow region (with ground reflection). The dispersion parameters, σ_y and σ_z , are taken to
592 be proportional (proportionality factor = 0.5) to the wake dimensions, L_y and L_z , calculated as:

$$593 \quad L_y = \mu \lambda_y \quad L_z = \mu \lambda_z \quad \mu = 2\sqrt{2}$$

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Figure captions

Fig. 1. Three-dimensional rendering of the wind tunnel models; (a) isometric view, (b) top view, (c) front view, and (d) side view.

Fig. 2. Schematic representation (not in scale) of the experimental set up in the wind tunnel.

Fig. 3. Selected vertical profiles of longitudinal dimensionless mean speed (U/U_{ref}) from the EnFlo tunnel along the vehicle centre line ($y = 0$) for (a) the 1:5 model, and (b) the 1:20 model.

Fig. 4. LDA measurements in the wake of the 1:5 model, vertical planes from the EnFlo tunnel: (a) U/U_{ref} - W/U_{ref} vector plot at $Y=0$, (b) σ_u^2/U_{ref}^2 velocity variance contour plot at $Y=0$, (c) σ_w^2/U_{ref}^2 velocity variance contour plot at $Y=0$, (d) U/U_{ref} - W/U_{ref} vector plot at $Y=-0.33$, (e) σ_u^2/U_{ref}^2 velocity variance contour plot at $Y=-0.33$, (f) σ_w^2/U_{ref}^2 velocity variance contour plot at $Y=-0.33$. $Y=-0.33$ is approximately in line with the tailpipe; the car is drawn to scale.

Fig. 5. LDA measurements in the wake of the 1:5 model, horizontal planes from the EnFlo tunnel: (a) U/U_{ref} - V/U_{ref} vector plot at $Z=0.07$, (b) σ_u^2/U_{ref}^2 velocity variance contour plot at $Z=0.07$, (c) σ_v^2/U_{ref}^2 velocity variance contour plot at $Z=0.07$, (d) U/U_{ref} - V/U_{ref} vector plot at $Z=0.23$, (e) σ_u^2/U_{ref}^2 velocity variance contour plot at $Z=0.23$, (f) σ_v^2/U_{ref}^2 velocity variance contour plot at $Z=0.23$. $Z=0.07$ is the lowest height for the measurements, while $Z=0.23$ is approximately at the same height as the tailpipe; the car is drawn to scale.

Fig. 6. FFID measurements in the wake of the 1:5 model from the EnFlo tunnel; C^* contour plots at: (a) $Y=0$ vertical plane, (b) $Y=-0.33$ vertical plane, (c) $Z=0.07$ horizontal plane, (d) $Z=0.23$ vertical plane, (e) $Z=0.60$ vertical plane. $Z=0.07$ is the lowest height for the measurements, $Z=0.23$ and $Y=-0.33$ are approximately in line with the tailpipe, $Y=0$ is the centre line and $Z=0.60$ is approximately at the middle of the car body; the car is drawn to scale.

Fig. 7. FFID measurements in the wake of the 1:20 model from the EnFlo tunnel showing C^* contour plots at: (a) $Y=0$ vertical plane, (b) $Y=-0.33$ vertical plane, (c) $Z=0.20$ horizontal plane, (d) $Z=0.60$ horizontal plane. $Z=0.20$ and $Y=-0.33$ are approximately in line with the tailpipe, $Y=0$ is the centre line and $Z=0.60$ is approximately at the middle of the car body; the car is drawn to scale.

Fig. 8. Selected vertical profiles of dimensionless concentration from the wind tunnel tests in the ‘EnFlo’ (1:5 model) and ‘Aero’ (1:8 model, with and without rolling road operation) tunnels.

Fig. 9. Selected lateral profiles of dimensionless concentration from the wind tunnel tests in the ‘EnFlo’ (1:5 model) and ‘Aero’ (1:8 model, with and without the rolling road operation) tunnels.

Fig. 10. Selected vertical profiles of dimensionless concentration from the wind tunnel tests in the ‘EnFlo’ and ‘Aero’ (both with and without the rolling road) tunnels for 1:20 model.

Fig. 11. Selected dimensionless concentration longitudinal profiles during the wind tunnel tests in the ‘EnFlo’ and ‘Aero’ (both with and without the rolling road) tunnels for 1:20 model.

741 **Fig. 12.** Comparison between selected vertical profiles of dimensionless concentration in the
742 ‘EnFlo’ (1:5 model) tests and those calculated by CAR-BUILD.

743 **Fig. 13.** Comparison between selected vertical profiles of dimensionless concentration in the
744 ‘EnFlo’ (1:20 model) tests and those calculated by CAR-BUILD.

745 **Fig. 14.** Comparison between selected longitudinal profiles of dimensionless velocity in the ‘EnFlo’
746 (1:20 model) tests and those calculated by the E&H model and CAR-BUILD.

747 **Fig. 15.** Comparison of normalised concentrations in the wake of the test vehicle. (a) Field
748 measurements at $X=0.3$; (b) wind tunnel measurements at $X=0.4$, 1:5 model; (c) field measurements
749 at $Z=0.33$; (d) wind tunnel measurements at $Z=0.37$, 1:5 model; (e) field measurement points at
750 $X=0.3$; (f) field measurement points at $Z=0.33$. Area of bubbles corresponds to the magnitude of
751 concentration at each point, normalised by the maximum value among the full set of 12
752 observations.

Research highlights

- ▶ A car wake was characterised through wind tunnel measurements
- ▶ Large gradients of velocities and tracer concentrations were found in the near-wake
- ▶ Current wake models adequately describe the velocities in the far-wake
- ▶ A better characterisation of turbulence and pollutant dispersion is needed
- ▶ Near-wake models do not exist, yet they are necessary for some applications

Figure 1

Figure 2

Figure 3

Figure 4 (Colour)

Figure 4 (Black & White)

Figure 5 (Colour)

Figure 5 (Black & White)

Figure 6 (Colour)

Figure 6 (Black & White)

Figure 7 (Colour)

Figure 7 (Black & White)

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

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