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Underbody flow control for base drag reduction of a real car model

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Abstract

A 1:5 scale realistic car model of the original Twingo GT but presenting a flat underbody and no exhaust line is tested in a wind tunnel at Reynolds numbers $Re = 2.15 \times 10^5$ to 4.3×10^5 . A range of underbody flow characteristic velocities $U_b = [0.5 - 0.72] U_\infty$ (U_∞ the free-stream velocity) is obtained by two techniques: flow obstruction and low momentum injection. Force balance, pressure measurements and Particle Image Velocimetry are used to characterize the aerodynamics of the model while changing the underbody flow velocity. A very sharp transition in the wake is found at a critical underbody velocity $U_b = 0.65U_\infty$. It corresponds to a sudden wake reversal with a bistable behavior between 2 equilibrium states, N or P depending on the vertical base pressure gradient or the wake orientation. The drag of the N state is larger than that of the P state. The control of the wake state by reducing the underbody flow velocity leads to beneficial increase of the base suction of approximately 20% when selecting the P state compared to the N state. The low momentum injection technique reduces drag by 10% but is ineffective at yaws 5° and 10° , while the obstruction technique consistently increases base suction but induces additional drag.

1. Introduction

The passenger car industry has shown increasing interest in underbody flow to improve the aerodynamic performance of cars. The underbody structure that mainly consists of wheels arches, exhausts lines and cooling system is a source of drag (see for instance Yuan and Wang (2017)) due to the multiple flow separation it generates compared to a smooth plate. An important geometrical effect for drag reduction is the angle at rear separation (called the diffuser angle) that is able to increase the pressure at the base of the vehicle as shown in Cooper et al. (1998) of which applications can be found in Huminic and Huminic (2020); Buscariolo et al. (2021) for simplified geometries and in Guerrero et al. (2022) for a more realistic car model. For ground clearances (vertical distance between the underbody and the road) typically larger than 8% the body height (Cooper et al., 1998), the drag coefficient obtained with moving ground (the real on-road boundary condition) remains sensibly close to that with static ground. This general trend is consistent with the pressure distribu-

tions obtained around real cars by Carr (1975) in on-road condition and wind tunnels with static ground. Similarly, the CFD of Wang et al. (2019) on a generic commercial car model, with static or moving ground showed almost no difference in the wake. Hence it seems that the boundary layer that develops on the static ground below the underbody flow and behind the car has sufficiently small effect on passenger-car aerodynamics that wind tunnel testing with static ground is a relevant approach.

The sensitivity of the rear wake orientation of industrial minivans to the underbody flow has been evidenced with variations of axle clearances (vertical gaps between the road and the underbody at the front and rear axles) and closure of the front air intake by Bonnavion et al. (2019). The front air intake system impacts the underbody flow because the incoming air flowing through the engine parts to be cooled is evacuated with very low momentum in the car underbody. The closure of the front air intake increases the underbody flow velocity as would an increase of the clearance. Bonnavion et al. (2019) investigated 4 real different models with rotating wheels and road effect in a full scale wind tunnel; namely the Peugeot 5008, Peugeot Partner, Citroën Berlingo and Renault Kangoo. They found

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49 that large clearances or closed air intake are as- 103
50 sociated with a negative vertical (perpendicular to 104
51 the ground) component of the base pressure gradi- 105
52 ent (called N state of the wake) while small clear- 106
53 ance or open air intake are associated with a posi- 107
54 tive vertical component of the base pressure gradi- 108
55 ent (called P state of the wake). The rear wake orien- 109
56 tation correspond to a flow deviation towards the 110
57 same direction of the base pressure gradient. The 111
58 transition between the P and N state is not contin- 112
59 uous but discrete where the mean gradient jumps 113
60 between the two distinct values of the P and N state 114
61 involving random bistable dynamics. These wake 115
62 states can be recovered with simplified geometries 116
63 having a taller than wide rectangular base and a 117
64 static ground. Grandemange et al. (2013) was 118
65 the first to evidence vertical states on a Ahmed- 119
66 type model (Ahmed, 1983), referred to as the z - 120
67 instability because of the z -direction perpendicular 121
68 to the ground of the vertical base pressure gradients. 122
69 Later, Schmidt et al. (2018) confirmed the presence 123
70 of vertical P and N states in the rear wake of a Gen- 124
71 eral European Transport System, a simplified geom- 125
72 etry to mimic a heavy-duty vehicle. The first and 126
73 so far the only numerical simulation to report wake 127
74 states in the vertical direction is due to Dalla Longa 128
75 et al. (2019). Recently, Fan et al. (2022) found, for 129
76 a taller than wide Ahmed-type model, discrete tran- 130
77 sitions between the vertical P and N states either 131
78 induced by the pitch, the ground proximity and the 132
79 yaw. Fan et al. (2024) investigated the states ob- 133
80 servation modifying the cross flow of the wake by 134
81 means of body pitch and flow orientation using top 135
82 and bottom tappers. Whatever the means used, an 136
83 upwash increase is likely to reverse an N state into a 137
84 P state, and conversely a downwash increase is likely 138
85 to reverse a P state into an N state. 139

86 There are now strong evidences that the wake states 140
87 observed for the industrial minivans and simplified 141
88 ground vehicle models relate to a fundamental prop- 142
89 erty of three-dimensional bluff-bodies presenting a 143
90 wide recirculating region at their base. In the ab- 144
91 sence of a ground proximity, the recent theoretical 145
92 work of Zampogna and Boujo (2023) shows that 146
93 for a Reynolds number of few hundreds (the critical 147
94 Reynolds number actually depends on the forebody 148
95 geometry and body length), the recirculating flow 149
96 at the base of a prism loses the symmetry of the 150
97 geometry and encompasses a pitchfork bifurcation 151
98 towards a deviated wake defining the steady global 152
99 instability. The deviation occurs in the direction of 153
100 the major axis of the rectangular base resulting in a 154
101 permanent base pressure gradient in that same direc- 155
102 tion. There are two possible orientations having base

103 pressure gradient of opposite signs, the so-called P 104
105 and N states. Hence, the observation of the different 106
107 wake states for industrial minivans and simplified ge- 108
109 ometries having a rectangular base presenting a ver- 110
111 tical major axis (i.e.; taller than wide base) is very 112
113 likely to be a persistence at large Reynolds number 114
115 and with a ground proximity of the steady global 116
117 instability revealed by Zampogna and Boujo (2023).

118 As a possible universal property of recirculating 119
120 flow at the rear of three-dimensional bluff-bodies, 121
122 the steady global instability should be shared by a 123
124 large variety of industrial vehicles. Although it is 125
126 rarely explicitly mentioned as an instability in the 127
128 literature, global wake asymmetries in the vertical 129
130 direction have been reported for realistic models by 131
132 other authors. The full scale real SUV studied by 133
134 Khalighi et al. (2012) displays a clear vertical asym- 135
136 metry in agreement with a P state observable in the 137
138 symmetry plane of the wake flow field and also in 139
140 the base pressure distribution. Avadiar et al. (2018) 141
142 conducted wind tunnel testing to characterize a Dri- 143
144 vAer estate vehicle having a flat underbody surface. 145
146 A wake vertical asymmetry consistent with a P state 147
148 is also observable in their pressure distribution. The 149
150 same DrivAer estate vehicle has been investigated 151
152 with a CFD in Wang et al. (2019) to characterize 153
154 the difference between a moving and static ground. 155
156 Their conclusion confirms that the static ground con- 157
158 figuration only locally alters the flow field in close 159
160 proximity to the ground, and therefore its impact on 161
162 the flow near the automobile surfaces and in the wake 163
164 is limited. The P state of the wake remains observed 165
166 in all cases. No bistability phenomena was reported 167
168 in Khalighi et al. (2012); Avadiar et al. (2018); Wang 169
170 et al. (2019) who considered only one flow configura- 171
172 tion. It then seems that parametric studies involving 173
174 variable body attitude and air intake such as those 175
176 investigated in Bonnavion et al. (2019) are necessary 177
178 to evidence bi-stable dynamics.

179 Due to the absence of symmetry in the vertical 180
181 direction (related to the ground proximity and model 182
183 shape), there is no reason for the drag of both P and 184
185 N wake states to be identical. The relative difference 186
187 during the bi-stable dynamics has been reported to 188
189 be about 3% for the industrial minivans (Bonnnavion 190
191 et al., 2019) and the simplified geometry (Fan et al., 192
193 2022), although the state which minimizes the drag 194
195 is not the same. Bonnavion et al. (2019) found that 196
197 the wake P state has the lowest drag for minivans, 198
199 while Fan et al. (2022) reported the wake N state 200
201 to have the lowest drag for the simplified geometry. 202
203 This apparent contradiction might be explained by 204
205 the difference in lift coefficients, that is positive for 206
207 minivans and negative for the simplified body. It is

then likely that the low drag wake having a vertical base pressure gradient of the same sign as the lift coefficient always contributes to the lift in such a way to reduce its magnitude. The part of the drag induced by the mean lift (Howell, 2015) might thus be reduced (resp. increased) by the low (resp. large) drag wake state for both the real minivans and the simplified geometry.

The ideas of the present work is (i) to show that in addition to the car models cited above, the rear wake of a popular car geometry (a Renault Twingo model) presents the global steady instability, thus highlighting the importance of this fundamental property for industrial aerodynamics and (ii) to use the known sensitivity of the states orientation to the underbody velocity to control wake and drag. This control technique of the recirculating region, likely independent to the geometrical detail of the body might have a potential of a wide range of application. Technically the first manipulation technique, related to the air cooling system of real cars, is to inject low momentum in the underbody with steady jets of adjustable flow rate. The second technique is to create a flow obstruction in the underbody. Eventually, the base pressure gradient dynamics obtained during the wind tunnel testing manipulating the underbody flow is compared to real environment data. The article is organized as follows. The experimental setup is detailed in Sect.2. Next, Sect.3 is devoted to the presentation and discussion of the results that are concluded in Sect.4.

2. Experimental configuration

This section describes the experimental setup including the real car model arrangement in the wind tunnel and the different measurement techniques used. In addition, we expose details on the underbody devices used to perturb the vertical wake equilibrium.

2.1. Wind-tunnel facility and instrumented car model

The present experiment is performed in a closed-loop subsonic wind-tunnel with a 6.25:1 contraction ratio. The 10m-long working section has a $2 \times 2\text{m}^2$ cross-sectional area and the free-stream turbulent intensity is less than 0.6%. The real car model shown in FIG.1a is a Renault Twingo GT. The model is centred between the side walls, the ceiling, and the floor within the test section and placed in wall proximity with a plate up raised above the floor within the test section. The coordinate system is defined as $(\mathbf{x}, \mathbf{y}, \mathbf{z})$

in the streamwise, spanwise, wall-normal directions, respectively, as shown in FIG.1a and FIG.1b. The real car model has a width, w of 297mm and a height, h of 215mm, leading to an aspect ratio, w/h of 1.38, and a length, L of 653mm, the four square supports connected to the wheels have a side length of 15mm. The ground clearance, is set to $c = 44\text{mm}$ and the body have a frontal area of 0.0765 m^2 . The model corresponds to the original real Twingo GT configuration with a scale of 1:5 without exhaust line and underbody real geometry. In the present case, the underbody has a flat surface. The blockage ratio, defined as the ratio of the projected area of the model (including the model support) in the direction of incoming flow to the cross-sectional area of the wind tunnel test section is of 4.3%.

2.2. Force, pressure and velocity measurements

The total drag and side force coefficients C_D and C_y , respectively, are defined by $C_D = F_x/(S.q_\infty)$, and $C_y = F_y/(S.q_\infty)$, where F_x and F_y are the measured drag and side forces, $q_\infty = \frac{1}{2}\rho U_\infty^2$, with ρ the air density, and S the projected frontal body area. In order to quantify the total aerodynamic drag and side forces, a 6-components DELTA ATI balance (MC-3A model 100) with a sensitivity of $5.4\mu\text{V}/\text{VN}$ and a capacity of 220N is used. A Dewesoft signal conditioner processes the raw sensor measurements with a resulting resolution estimated to $\pm 0.01\text{N}$. Force measurements are low-pass filtered using a zero-phase digital filter in order to reduce noise and preserve the temporality of the signals.

The pressure is measured at 63 locations on a 9×9 grid at the back of the body as shown in FIG.1c. The pressure taps are equally spaced with distances $\delta y^* = 0.102$ in the \mathbf{y} -direction and $\delta z^* = 0.093$ in the \mathbf{z} -direction. The instantaneous pressure coefficient is computed by:

$$c_p(t) = \frac{p(t) - p_\infty}{q_\infty}$$

with $q_\infty = \frac{1}{2}\rho U_\infty^2$ and where ρ denotes the air density, and p_∞ the reference static pressure, measured at the side-wall of the test section, aligned with the front of the body. The base suction coefficient c_b is computed from the spatial average of the 63 pressure taps at the base:

$$c_b(t) = -\frac{1}{63} \sum_{i=1}^9 \sum_{j=1}^7 c_p(y_i, z_j, t)$$

The base suction coefficient represents the contribution of the body base to the total drag coefficient.

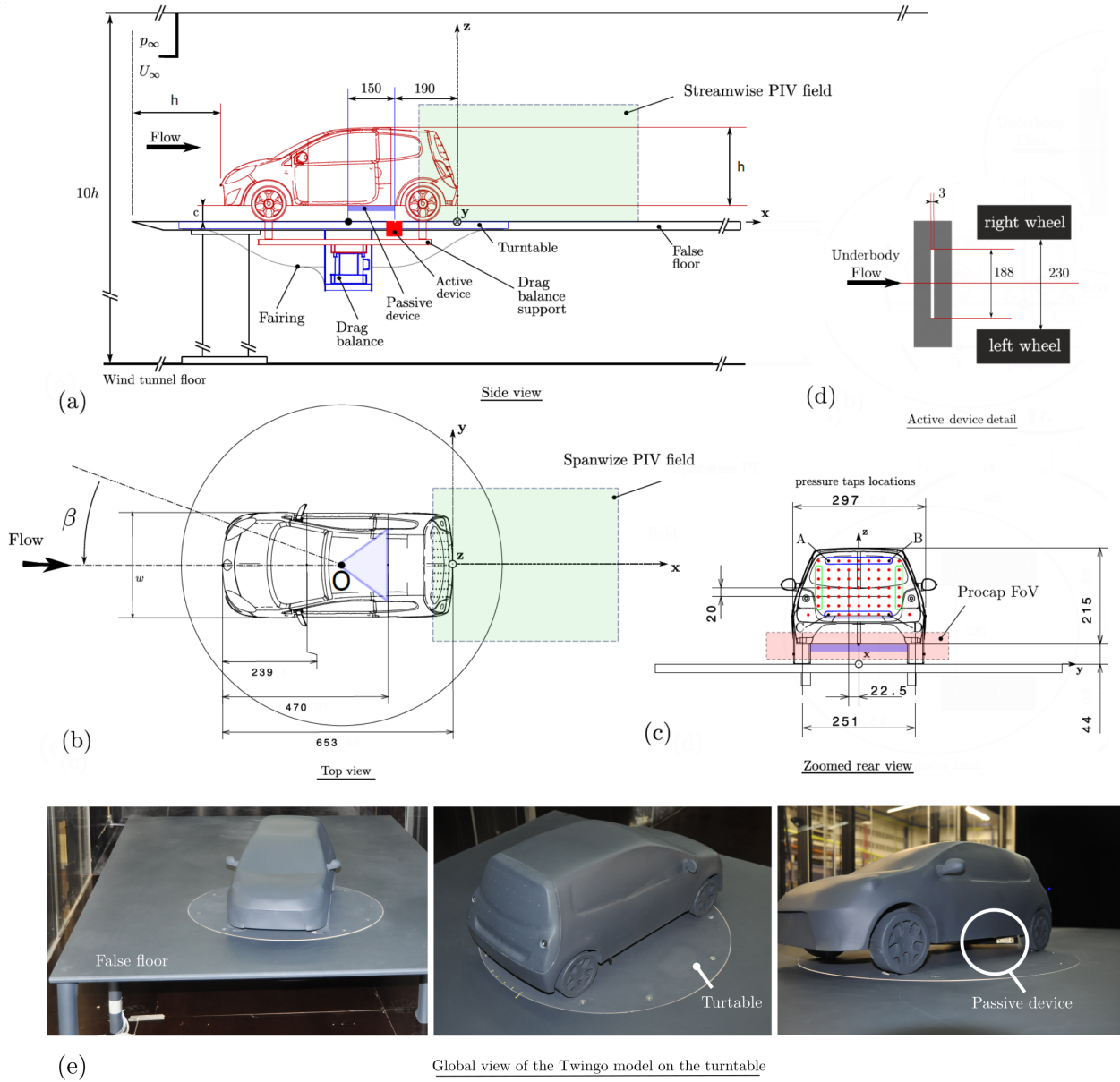


Figure 1: Experimental set-up. (a) Arrangement of the car model inside the test section including the control devices location and the PIV field of view (FoV), (b) Top view of the yawed arrangement with the fixed spanwise PIV FoV, (c) Time-resolved pressure location on the base, (d) Detail of the active control device. (e) Illustrations (several views) of the Twingo model placed on the turntable with the passive control system. All dimensions are in mm

As reported in Roshko (1993), it is a fundamental characteristic for bluff body flows that is sensitive to the rear wake dynamics. The temporal mean and standard deviation are denoted C_p and C'_p , C_b and C'_b for the pressure and base suction coefficients respectively. The pressure scanner is located inside the model so that it is linked to each tap with less than 150mm of vinyl tube to limit the filtering effect of the tubing, leading to a natural low pass filtering of cutoff frequency approximately equal to 150Hz ($f_c^* = 1.41$). The accuracy of the pressure scanner (effective measurement range of 2000 Pa) is given by the manufacturer to be $\pm 0.15\%$ of the measurement range corresponding to ± 3 Pa. However, converged time averaged values have a better accuracy that falls below ± 0.5 Pa. So the accuracy in terms of mean base suction coefficients is ± 0.001 . The 63 pressure channels are recorded during 30s for each jet cases and during 300s for the cases with the passive triangle device (TR) at a sampling frequency of 850Hz per channel. The wake asymmetry is assessed by using the dimensionless horizontal and vertical base pressure gradients, g_y and g_z . The four pressure taps group (**L**, **R**, **T**, **B**) indicated in blue and green in FIG.1c are used to compute the base pressure gradient components:

$$g_y = \frac{\langle c_p \rangle_{\mathbf{R}} - \langle c_p \rangle_{\mathbf{L}}}{8\delta y^*}, \quad g_z = \frac{\langle c_p \rangle_{\mathbf{T}} - \langle c_p \rangle_{\mathbf{B}}}{6\delta z^*}$$

with $\langle \cdot \rangle_n$ denotes the spatial average of the taps group n . For the comparison with on-road real car testing (appendix), only points **A**, **B**, **C** and **D** locations (see FIG.1c) are used for the calculation of the gradients components to have same pressure taps location in both cases (model and full scale). The temporal mean and standard deviation of both gradient components $i = y, z$ are denoted G_i and G'_i respectively.

In the paper, we adopt the following notation : the superscript * denotes the non-dimensional value by using h , U_∞ . Instantaneous quantities are denoted with lower case letters, their temporal mean with upper-case letters, and their standard deviation with primed upper-case letters. Also, P and N stand for the positive and negative states of the vertical pressure gradient g_z .

The Particle Image Velocimetry (PIV) measurements are carried out with a standard two-component TSI system, composed of a double-pulse 200mJ dual-head Nd-Yag (Quantel BSLT220) laser system and two high-resolution CCD Powerview cameras with a full resolution of 2048×2048 pixels and micro NIKKOR 50mm optical lens. The seeder is

a TSI oil droplet atomizer 9307 whose droplets diameter's main mode is about $d_p = 1\mu\text{m}$. The seeding is released in the settling chamber of the wind tunnel. The vector fields are obtained by processing the PIV images using a recursive cross-correlation algorithm with a final interrogation window size of 16×16 pixels with 50% overlap. The resulting PIV fields of view passing through the streamwise and the spanwise middle planes of the car model as mentioned in FIG.1 are about $310\text{mm} \times 280\text{mm}$ (i.e. $1.44h \times 1.30h$) and $250\text{mm} \times 360\text{mm}$ ($1.16h \times 1.67h$) respectively. For every test case, 2000 time-uncorrelated PIV snapshots are recorded with a repetition rate of 7Hz. The maximum uncertainty on the instantaneous velocity fields considering an absolute displacement error of 0.1 pixels is estimated to be less than $0.01U_\infty$.

The complex three-dimensional active control jet and underbody flows behind the car model (pink areas on FIG.1 named Procap FoV) are measured with the probe Capture anemometry (ProCap system) consisting of a hand-guided 5-hole pressure probe, whose instantaneous position is tracked in real time by a motion capture camera system. The location of the probe is obtained by the infrared cameras through reflective passive markers on the probe. The tracking rate of 200 Hz ensures that each measurement point can be attributed to a position in the volume of interest. All three velocity components, static and dynamic pressure are measured with a five-hole probe and interpolated onto a regular grid and presented on a screen in real time. For the presented measurement a spatial resolution of 5mm was chosen with a total measurement time for a full area of interest scan at this resolution is at the order of 10 minutes. The data are post-processed using both ParaView and Matlab. Based on the height of the model, the Reynolds number of this flow is defined as $Re = U_\infty h / \nu$, where ν is the kinematic viscosity of the air at ambient temperature and U_∞ the free-stream velocity. Experiments are conducted at three different free-stream velocities, U_∞ of 15m/s, 20m/s and 30m/s leading to Reynolds numbers varying from $Re = 2.15 \times 10^5$ to 4.30×10^5 .

2.3. Control devices

The car clearance can be independently equipped with two kind of actuators; a passive device having the shape of an isosceles triangle obstructing one third of the ground clearance height (see FIG.1a,b). This passive control device is named TR in the following; an active device based on a flush mounted air knife blowers controlled by a proportional flow rate solenoid valve (FLOW CONTROL-VEF212 model), as

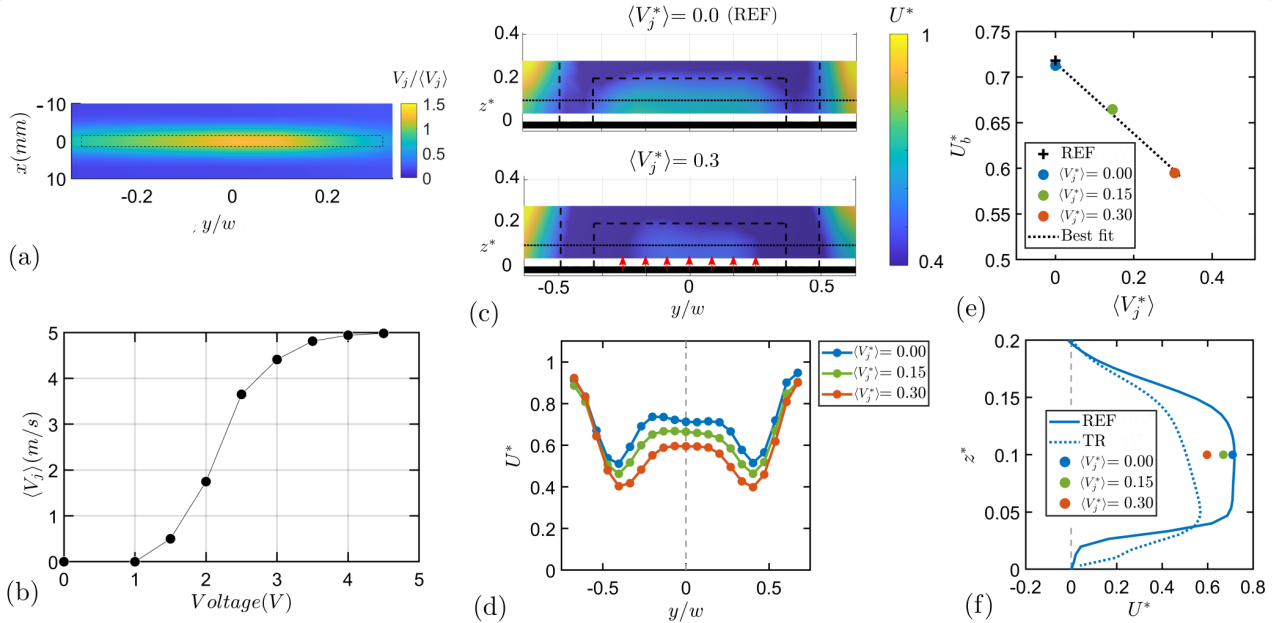


Figure 2: Underbody flow characterisation with and without controls. (a) Mean wall normal velocity field at the plan $z = 5\text{mm}$ above the blowing slit for a valve power supply voltage of 2.5V . (b) Calibration of the power supply voltage with the jet velocity coefficient. (c) Mean streamwise velocity field at $x^* = 0$ (underbody exit) for the baseline (top) and for $\langle V_j^* \rangle = 0.3$ (bottom). (d) Mean streamwise velocity profiles at $z/c = 0.5$ for jet velocity coefficients $\langle V_j^* \rangle = 0, 0.15, 0.3$. (e) Characteristic underbody flow bulk velocity, U_b^* vs. the jet velocity, $\langle V_j^* \rangle$. (f) Streamwise velocity profile along the wall normal direction in the mid-plane of the model for the baseline (REF) and for the passive device TR superimposed to the characteristic underbody velocity U_b^* obtained from (d).

354 illustrated in FIG.1d and wall blowing actuator, here- 379
 355 after named WBA. The slit width is $w_s = 3\text{mm}$ and 380
 356 the actuation length is $l_s = 188\text{mm}$. The active de- 381
 357 vice can generate different flow rate Q related to the 382
 358 mean jet velocity $\langle V_j \rangle = Q/(w_s l_s)$. Technically, the 383
 359 ProCap is used to calibrate the valve power supply 384
 360 voltage on $\langle V_j \rangle$ when the wind tunnel is switched- 385
 361 off and the car model removed. FIG.2a shows the 386
 362 mean wall normal velocity distribution at the plan 387
 363 $z = 5\text{mm}$ given by the ProCap, of which its integra- 388
 364 tion provides the value $\langle V_j \rangle$. The velocity distribu- 389
 365 tion is almost centred to the middle plan of the set- 390
 366 up with a velocity attenuation observed as one ap- 391
 367 proaches the lateral extremities of the injection slot. 392
 368 The similar trend is observed for all the different 393
 369 supply voltages. The evolution of the mean jet ve- 394
 370 locity, $\langle V_j \rangle$ is plotted against the solenoid valve volt- 395
 371 age supply in FIG.2b and reaches a maximum value 396
 372 of 5 m/s . The nonlinear behaviour is attributed to 397
 373 the electronic control system itself, but perfectly re- 398
 374 producible and repeatable.

375 The WBA control parameter is defined as the ve- 398
 376 locity coefficient $\langle V_j^* \rangle$, it ranges from 0 to 0.3 for the 399
 377 overall Reynolds number studied. The velocity co- 400
 378 efficient can be converted into a flow rate coefficient 401

$C_Q = \frac{\langle V_j \rangle w_s l_s}{U_\infty w c} = 0.043 \langle V_j^* \rangle$, where the injected flow 402
 403 rate is compared to a reference underbody flow rate. 404
 Accordingly to the velocity coefficient range, we have 405
 $0 < C_Q < 0.013$ in this study.

3. Results

Results are organized as follows. First, the under- 406
 407 body flow is characterized in §3.1 for both passive 408
 409 device (TR) and active wall blowing actuator sys- 410
 411 tem (WBA). The effects of the wall blowing actuator 412
 and the passive device contributing to the suction 413
 and drag coefficients are evidenced in §3.2. Wake 414
 reversals between the P and N state and their bi- 415
 stable dynamics are then investigated varying the 416
 underbody bulk velocity in §3.3. A detailed analy- 417
 sis of the demonstrative passive manipulations of the 418
 wake state selection is investigated to prove its sig- 419
 nificance. Their aerodynamic impact is compared 420
 in terms of robustness with the blowing actuator 421
 wake flow response in §3.4 varying yaw angle. Fi- 422
 nally, wake dynamics obtained from on-road testing 423
 described in the appendix are compared to the wind 424
 tunnel testing in §3.5 to open perspectives for real 425
 application.

3.1. Underbody flow characterization

The velocity field at the underbody exit is investigated to determine the influence of the two control devices and to provide a characteristic underbody flow velocity U_b .

For the active device WBA, it is achieved by extracting the mean streamwise velocity field at the plane $x^* = 0$ from the ProCap 3D-measurements (see ProCap FoV in FIG.1c). FIG.2c(top) shows the streamwise velocity for the baseline (REF) where a typical velocity of $U^* \approx 0.7$ can be observed at the central part. The blowing case at a velocity $\langle V_j^* \rangle = 0.3$ (lower than the typical underbody flow) in FIG.2c(bottom) clearly lowers the underbody flow to $U^* \approx 0.6$. We define the characteristic velocity U_b^* as the velocity at mid clearance ($z/c = 0.5$ or equivalently $z^* = 0.1$) and on the symmetry plane $y^* = 0$. FIG.2d illustrates the definition of U_b^* from the horizontal velocity profile at $z/c = 0.5$ obtained for 3 blowing cases. It can be seen that U_b^* is representative of the largest velocity at the underbody exit corresponding to a plateau value in between the wheels. The relation between the jet velocity coefficient $\langle V_j^* \rangle$ and the characteristic underbody velocity U_b^* is shown in FIG.2f. This relationship is used together with that of FIG.2b to convert the voltage of the valve power supply into the characteristic velocity U_b^* of all experiments using the active device WBA in the following.

The PIV system has been used to characterize the underbody flow with the passive device TR. The streamwise velocity profile at mid-plane of the underbody exit ($x^* = 0, y^* = 0$) is shown in FIG.2f without and with the device. Compared to the values U_b^* obtained during the WBA experiments, there is a good match between the two cases with no control (REF and $\langle V_j^* \rangle = 0$), while the case with the TR device achieves the smallest underbody flow of all controlled cases.

3.2. Wake states identification

The global contribution of the active and the passive devices to the suction coefficient C_b as a function of the characteristic velocity U_b^* is evidenced in FIG.3(top) for the three studied Reynolds numbers. There is a strong variation around a critical underbody velocity of $U_{bc}^* \approx 0.635$, where the suction coefficient drops from 0.26 to 0.22 as the underbody flow decreases. It corresponds to a base suction reduction of about 15%. The 3 TR cases having the smallest underbody flow velocity also drop by similar amplitudes from the REF values. This transition seems to occur whatever is the Reynolds number and control

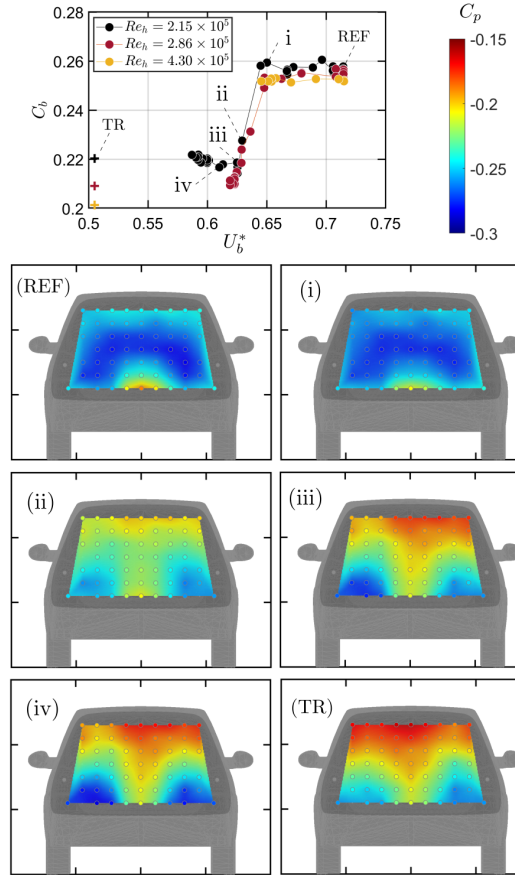


Figure 3: C_b against U_b^* for the three studied Re_h and some associated map for $Re_h = 2.15 \times 10^5$ corresponding to different states from the baseline (REF), around the transition (from (i) to (iv)) and with the passive device (TR). Colored + symbols refer to the TR cases.

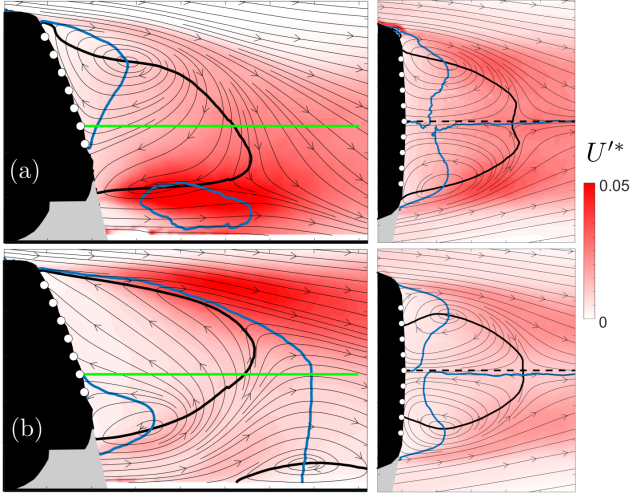


Figure 4: Characteristic wake reversal based on particle image velocimetry (PIV) field of view (FoV) in the vertical mid-plane (left side) and horizontal plane (right side and following the green line), (a) baseline (REF), (b) passive control device (TR). Black lines denote the iso-contour with a mean stream-wise velocity equal to zero, blue lines the same for the normal velocity. Colormap refers to the stream-wise component of the Reynolds stress at $Re_h = 2.15 \times 10^5$.

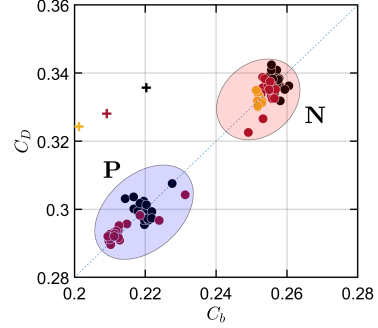


Figure 5: C_D against C_b for the three studied Re_h , with the TR passive device (+), and with the active wall blowing actuator (o).

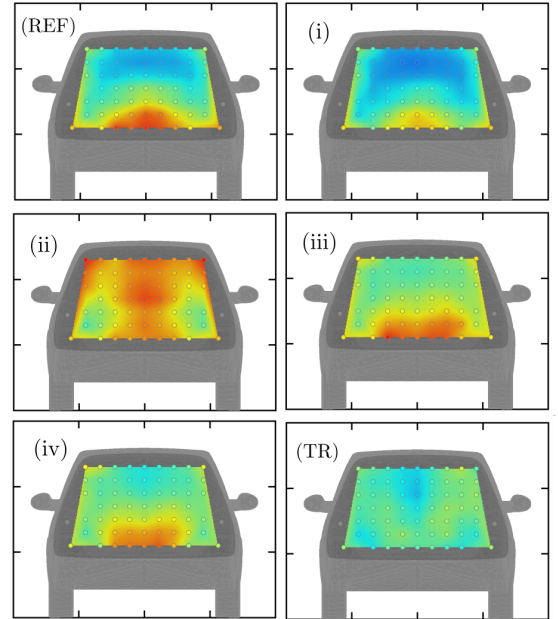
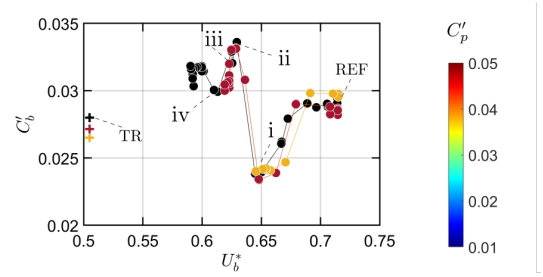


Figure 6: C'_p against U_b^* for the three studied Re_h and for the various states of the FIG.3.

454 device type. To investigate the causes of this transition
 455 some points corresponding to different states
 456 from the baseline (REF), around the transition (from
 457 (i) to (iv)) and with the passive device (TR) are de-
 458 tailed in the second part of the FIG.3(bottom).

459 For the baseline (REF) and the case with $U_b^* > U_{b_c}^*$
 460 (i.e.: case (i)), the mean pressure distribution at the
 461 base of the car shows a vertical negative gradient
 462 indicative of a vertical asymmetric state N of the
 463 wake. For these cases before the transition, the pres-
 464 sure distribution shows very small sensitivity to the
 465 underbody flow.

466 At the transition $U_b^* \approx U_{b_c}^*$ (i.e.: case (ii)), the
 467 pressure distribution changes drastically, noticeably
 468 with the appearance of a positive vertical gradient.
 469 After the transition, $U_b^* < U_{b_c}^*$ (i.e.: cases (iii), (iv)
 470 and (TR)) there is almost no sensitivity of the pres-
 471 sure distribution to the underbody flow that exhibits
 472 now a clear positive vertical gradient indicative of a
 473 vertical asymmetric state P of the wake. The transi-
 474 tion is thus associated with a vertical base pressure
 475 gradient reversal that is indeed induced by the wake
 476 reversal evidenced in FIG.4.

477 The wake flow topology associated with the state
 478 change is highlighted through the velocity fields on
 479 both sides of the transition, between the baseline
 480 shown in FIG.4(a) and the TR case in FIG.4(b).
 481 In both cases the mean wake has a planar sym-
 482 metry with respect to the plane $y^* = 0$. The

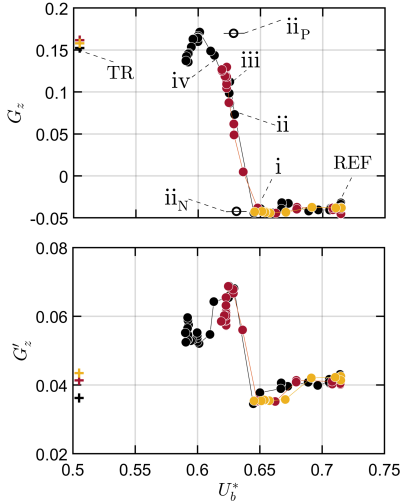


Figure 7: G_z and G'_z for various U_b^* and for the three studied Re_h . Conditional states are given for the case (ii) on G_z in order to capture the two states.

mean velocity field in the plane of symmetry displayed in FIG.4(b)(left)) shows a region with a closed streamlines on the side of lowest fluctuations U^{I*} and a region of the impinging back flow on the side of the largest fluctuations U^{I*} . The vertical base pressure gradient evidenced in the distributions of FIG.3(REF) and FIG.3(TR) is orientated from the closed streamline region (low pressure) towards the impinging back-flow (high pressure). Thus FIG.4(a) indicates an N state and FIG.4(b) a P state. The mean recirculating flow structure of the 2 wake states is similar to that reported for real minivans in Bonnavion et al. (2019) and also for simplified bodies with taller than wide rectangular base (Grandemange et al., 2013; Schmidt et al., 2018; Dalla Longa et al., 2019). The observed transition from the N state to the P state obtained by decreasing the underbody velocity in FIG.3 is equivalent to the states transition reported by Bonnavion et al. (2019) from closed to opened air intake of the Peugeot Partner with a moving ground and rotating wheels at a given attitude as shown in their Figure 16 (a & d).

As can be seen in FIG.4(b), the P state is associated with a flow separation on the floor marked with the zero iso-contour of the mean streamwise velocity. This separation is due to the dynamics of the boundary layer developing on the static ground and facing the adverse pressure gradient produced by the large car base suction (or the low base pressure coefficient). In the light of this observation, it is judicious to discuss the use of the static ground instead of a moving ground to address ground vehicle aerodynamics. In the work of Wang et al. (2019), the

effect of the adverse pressure gradient produced by the DrivAer-Estate base suction is observable on the static ground. Although it does not produce a separation on the ground as in FIG.4(b), it thickens significantly the boundary layer creating an upwash effect on the rear part of the recirculating region. The recent work of Fan et al. (2024) demonstrated for a simplified geometry that a wake in the N state requires additional upwash effect (or a positive vertical velocity) to produce a reversal towards the P state. It is then possible that the static ground indirectly contribute to the selection of the P state when U_b^* is decreased in FIG.3 by the upwash effect produced by the boundary layer development due the low pressure at the base of the vehicle. However, since the N to P transition is triggered by the only closing/opening of the air intake of the Peugeot Partner in Bonnavion et al. (2019) with a moving ground (where flow separation on the ground is impossible because of the absence of a boundary layer), we are confident that the separation on the static ground is not the only mechanism to reverse an N state to a P state. The other mechanism would be simply the decrease of the underbody velocity as it is the case for the Peugeot Partner in Bonnavion et al. (2019). As we can't rule out a possible contribution of the static ground to the wake transition in our work, we believe that the critical underbody velocity $U_{b_c}^* \approx 0.635$ may be reduced with a moving ground.

The consequence on the drag can be seen in FIG.5 where the drag coefficient is plotted as a function of the base suction. For the WBA control, two clusters can be distinguished, the first is composed of states N and the second of states P, all of them seems to follow a trend $C_D = C_b + 0.08$ indicating that any gain on C_b is equal to a gain on C_D . In other words, the drag reduction is uniquely due to the base suction change. The constant $C_0 = 0.08$ is likely to be the drag contribution of all parts of the car that is not the base. For the TR control, the drag coefficients are shifted towards larger values due to the drag contribution of the passive device such that now $C_0 = 0.12$.

The transition involves large pressure fluctuation as can be seen in the fluctuation C'_b of the base suction as a function of the underbody velocity in FIG.6(top). Actually the highest fluctuations are obtained for the (ii) case where the base in FIG.6(ii) is covered at the top and bottom by large constant pressure fluctuations. For the case (i), fluctuations seem to decrease however the area of measurements does not cover the full base, and a high fluctuation region can be missed, thus biasing the result. The origin of the fluctuation at the transition is further

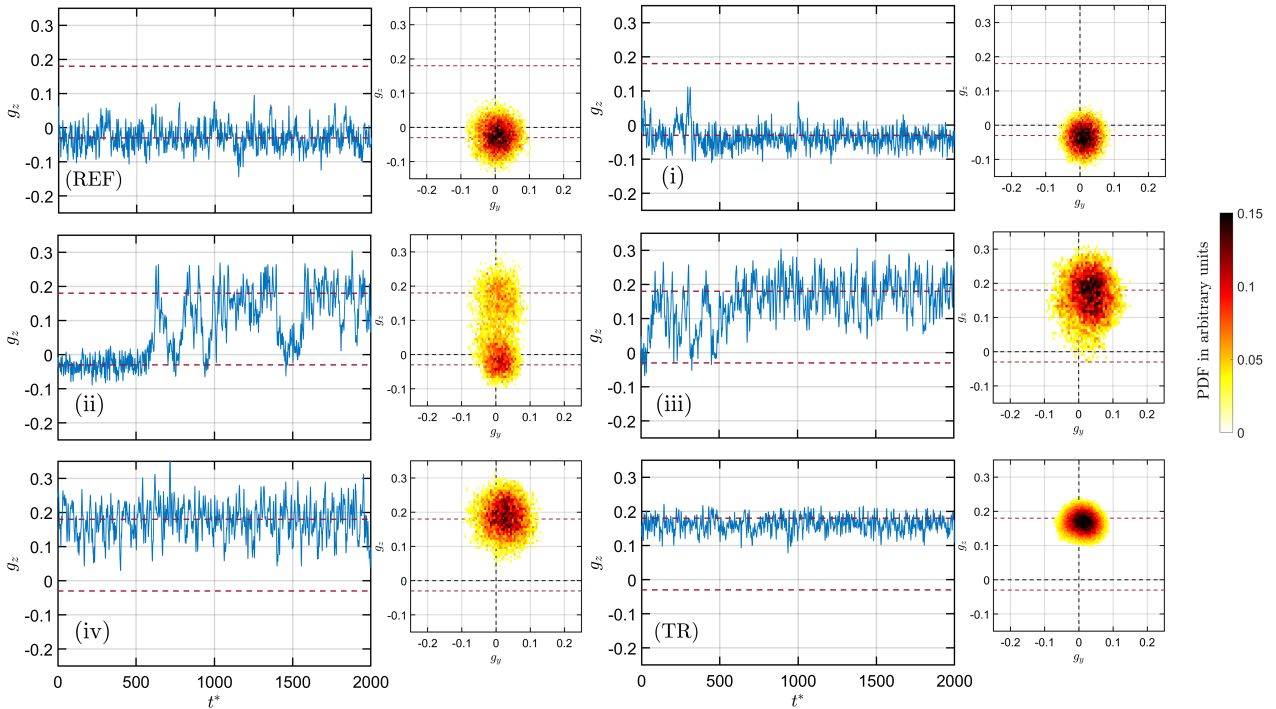


Figure 8: Time history of g_z corresponding to the states of the Fig.7 with the associated PDFs of g_y and g_z at $Re_h = 2.15 \times 10^5$.

570 studied in the next section.

571 3.3. Bistable transition

572 A focus on the wake dynamics and statistics is
 573 now addressed through the measurement of the base
 574 pressure gradients. FIG.7 shows the mean compo-
 575 nent of the vertical base pressure gradient G_z and
 576 its fluctuation G'_z as a function of U_b^* . Unsurpris-
 577 ingly, the mean vertical component switches from a
 578 negative value of approximately -0.05 to a positive
 579 value of approximately 0.15 with a crisis of fluctua-
 580 tion during the transition.

581 The global wake dynamics during the transition is
 582 illustrated in FIG.8 showing both the temporal evo-
 583 lution of the instantaneous vertical gradient g_z and
 584 its joint PDF with g_y . For clarity, gradients are low
 585 pass filtered in the time history plots with a moving
 586 50 ms window. This figure essentially shows that
 587 at the transition, the crisis of fluctuations in case
 588 (ii) is produced by bistable dynamics between the
 589 two wake states P and N. The value of the mean
 590 vertical gradient for each state, obtained by a sim-
 591 ple conditionnal averaging, is reported in FIG.8 with
 592 labels ii_P and ii_N . There is no doubt that this dis-
 593 crete transition is of same nature as in Bonnavion
 594 et al. (2019), thus revealing that the wake of the Re-
 595 nault Twingo GT is subjected to a steady instability

596 responsible for the wake asymmetry in the vertical
 597 direction. An identical transition has been observed
 598 by Szmigiel (2017) in the wake of simplified boat-
 599 tailed truck model varying the underbody velocity by
 600 means of grids of different porosity. They observed a
 601 transition from the P to N state when the characteris-
 602 tic underbody velocity U_b^* is increased from 0.4 to
 603 0.85 with a sharp transition at 0.7 (see their Figure
 604 5.6b). It is worth mentioning that the same model
 605 studied in Castelain et al. (2018) but with no boat-
 606 tailing (i.e.: square-back rear) only shows a clear P
 607 state until 0.85. It can be speculated that the transi-
 608 tion to the N state for this rear geometry would have
 609 been observed with larger underbody velocity, pro-
 610 duced for instance by a larger clearance as in Grande-
 611 mance et al. (2013). In the present study, the critical
 612 underbody velocity for the transition ($U_{bc}^* \approx 0.635$)
 613 being significantly lower than 0.85 likely results from
 614 the velocity decrease induced by the top boat tail.

The transition between the two wake states gener-
 615 ates notable changes in the dynamic activity of the
 616 unsteady global wake modes. FIG.9 shows the spec-
 617 tral content of the two pressure gradients g_y and
 618 g_z as well as the base suction coefficient for differ-
 619 ent cases: the reference case, TR and WBA with
 620 $U_b^* = 0.62$ (iv). The reference is in the N state while
 621 both TR and (iv) are in the P state.

623 The P state of the wake displays a similar spec-
624 trum whether it is achieved with the passive device
625 or blowing as can be seen by comparing FIG.9(a)
626 and FIG.9(b). In both cases, only a concentration of
627 energy around $f^* = 0.2$ could be associated with a
628 mode in the g_y component corresponding to an anti-
629 symmetric horizontal mode likely to involve the lat-
630 eral shears of the base separation. There is no clear
631 concentration for the vertical component g_z where
632 instead, the energy spreads over a large domain ex-
633 panding towards low frequencies. On the other hand,
634 a clear concentration of energy is observed for g_z
635 around $f^* = 0.16$ for the N state of the reference
636 wake in FIG.9(c) likely to be associated with a ver-
637 tical antisymmetric mode involving the top and bot-
638 tom shears of the base separation. For this N state,
639 the horizontal mode at $f^* = 0.2$ is also identifiable
640 in g_y , but with another concentration at $f^* = 0.035$.
641 It is clear from these spectra that the P state and
642 the N state are not a mirrored symmetry to each
643 other (as suggested by the velocity fields in FIG.4),
644 otherwise we would have expected identical spectra.
645 Differences are thus related to all top/down asym-
646 metries such as the trapezoidal shape of the base,
647 the floor, wheels etc...

648 3.4. Yaw angle condition

649 For the baseline case, yawing the body leads to
650 an expected clear left/right asymmetry in the wake
651 (FIG.10(a,b),) as well as in the base pressure distri-
652 bution (FIG.10(e,f)) where the base pressure gradi-
653 ent becomes horizontal. The same trend at yaw is
654 reported by Fan et al. (2022) for the simplified ge-
655 ometry where the horizontal component at the base
656 has the same sign of the yaw angle. For the (TR)
657 case that selects the P state of the wake at no yaw,
658 it appears that the wake remains left/right symmet-
659 ric until at least a yaw of 5° (FIG.10(c)) with still a
660 dominant positive vertical base pressure gradient, in-
661 dicating that the wake is still in a P state at 5° yaw,
662 as can be seen in the corresponding pressure distri-
663 bution in FIG.10(g). The left/right asymmetry be-
664 comes more obvious for a yaw of 10° in FIG.10(d,h).
665 The values of the base pressure and the mean pres-
666 sure gradient components are reported in FIG.11 at
667 $\langle V_j^* \rangle = 0$ with black filled symbols for the baseline
668 and empty symbols for the TR case. The larger base
669 drag reduction is observed at 5° , and this is possi-
670 bly a consequence to the wake that is kept in the P
671 state (the low drag state as evidenced in the previous
672 section) as seen in FIG.10(g).

673 The underbody blowing WBA case at yaw has al-
674 most no effect on the base drag in FIG.11(a). It

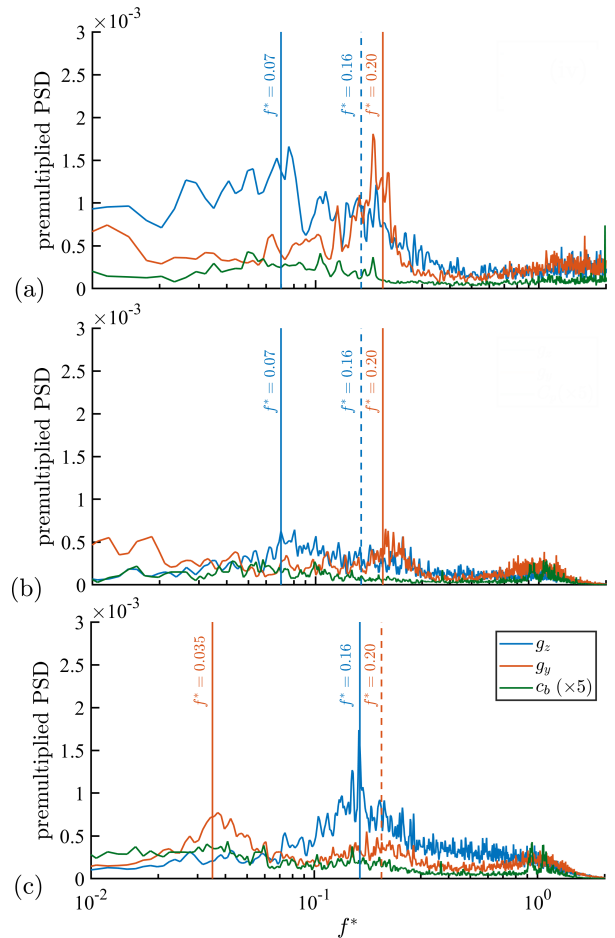


Figure 9: Premultiplied power spectrum densities of g_z , g_y and c_b for the WBA (iv) case in (a), the TR case in (b) and the baseline (REF) in (c) at $Re = 2.15 \times 10^5$.

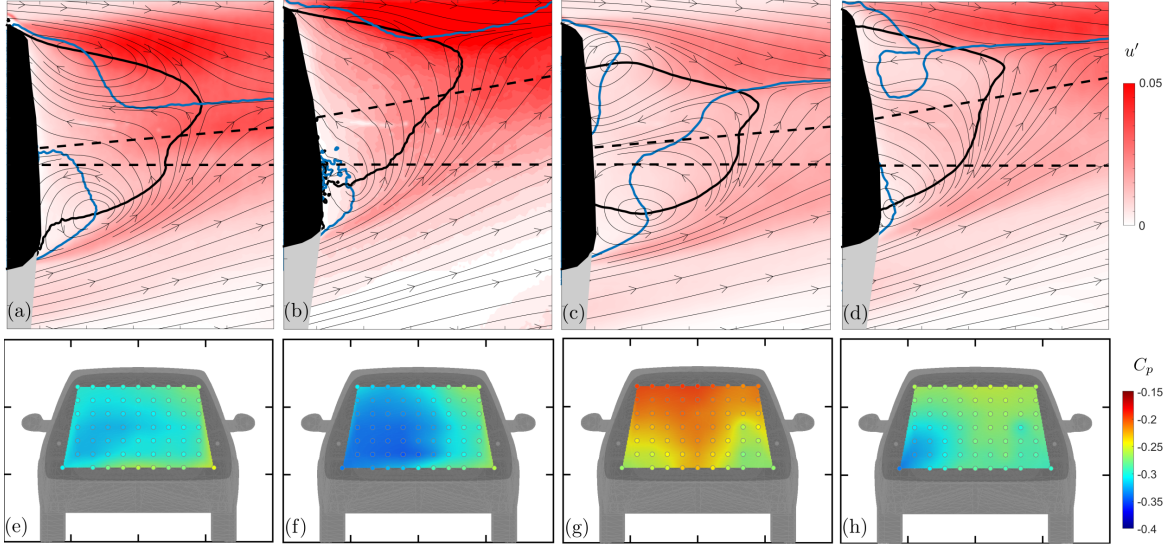


Figure 10: Yaw effect at 5° (a,e,c,g) and 10° (b,f,d,h) on the wake for the baseline (two first columns) and the TR cases (two last columns), (a) to (d) streamlines with the streamwise component of the Reynolds stress and (e) to (h), mean pressure coefficient distribution at $Re = 2.15 \times 10^5$.

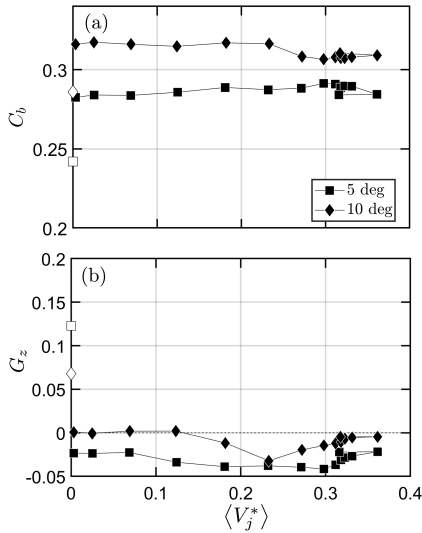


Figure 11: (a) Base suction coefficient C_b , (b) component G_z of the mean base pressure gradient versus $\langle V_j^* \rangle$ for 5° and 10° yaw angles at $Re = 2.15 \times 10^5$ for the WBA (filled symbols). Open symbols denote the TR configuration.

675 seems that even for the lowest yaw 5° , the benefi-
 676 cial P state can't be triggered by the blowing. As
 677 a conclusion, drag reduction by underbody blowing
 678 is possible only if it is capable to produce a global
 679 effect of wake reversal, that is not achieved here for
 680 yaws at 5° and larger values.

681 To summarize, the wake of the real car model in
 682 the wind tunnel configuration is subjected to a global
 683 instability implying the possibility of 2 equilibrium
 684 states. The drag of the N state is found to be larger
 685 than that of the P state (as also found with real
 686 minivans wake in [Bonnaïon et al. \(2019\)](#)). The control
 687 of the wake state by reducing the underbody
 688 flow with an active device leads to important drag
 689 reduction of approximately 10% when selecting the
 690 P state compared to the N state. The presence of
 691 the wake instability thus offers perspective for flow
 692 control and should be taken into account into industrial
 693 aerodynamics optimization. A first question is
 694 : what about the wake state in real driving situa-
 695 tion ? We address the question with real environ-
 696 ment testing on a gasoline Renault Twingo during
 697 a motorway trip (see appendix "On-road testing").
 698 Equivalences with the wind tunnel experiment are
 699 actually not straightforward. With the difference in
 700 Reynolds numbers and the unsteady conditions related
 701 to the real environment, the additional complexity
 702 of rotating wheels, road effect, and the air intake
 703 system affect in a non-trivial way the underbody
 704 flow, making impossible to predict the wake state
 705 of the gasoline Renault Twingo from results

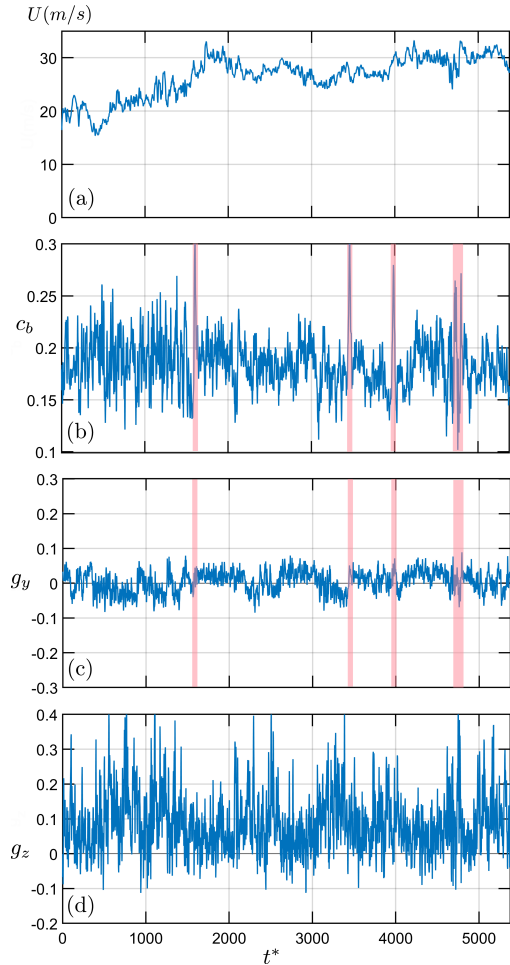


Figure 12: On-road time series, (a) vehicle velocity, (b) base suction coefficient, (c) horizontal g_y and (d) vertical g_z base pressure gradient. Pink bars denote overtaking events on the motorway.

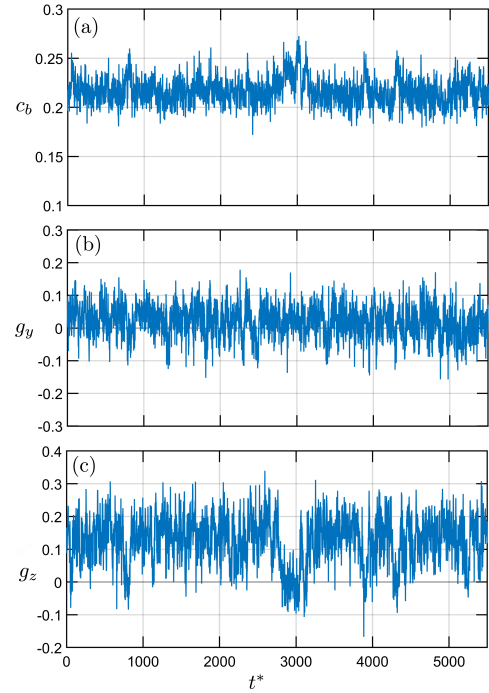


Figure 13: Active control time series (WBA) at $U_b^* = 0.62$, (a) base suction coefficient, (b) horizontal g_y and (c) vertical g_z base pressure gradient. For comparison with FIG.12, gradient components are recalculated from positions A,B,C and D (see appendix).

706 obtained in the wind tunnel in FIG.7.

707 3.5. Comparison with a real environment wake dy- 708 namics of the gasoline Renault Twingo

709 The test has been carried out in real conditions as
710 described in the appendix “On-road testing” and the
711 main measurements are presented in FIG.12 with re-
712 spect to the dimensionless time t^* . While FIG.12(a)
713 gives the relative speed of the vehicle during the test,
714 FIG.12(b) depicts the base pressure coefficient high-
715 lighting the vehicle overtaking with pink areas. It
716 can be seen that after the entry phase on the motor-
717 way at lower speed the pressure coefficient is fluctu-
718 ating less and evolves around an average value of 0.19
719 with variations ranging from 0.22 to 0.1 and even 0.3
720 when overtaking occurred. Concerning the horizon-
721 tal pressure gradient, represented in FIG.12(c), an
722 evolution centered around zero with a relatively low

723 amplitude around ± 0.05 is systematically observed
724 with sign changes that may correspond to environ-
725 ment modifications. For the vertical pressure gradi-
726 ent component, plotted in FIG.12(d), strong fluctu-
727 ations are observed with a globally positive average
728 value along the entire journey, highlighting a wake
729 more likely to be associated with a P state.

730 In order to avoid any misleading interpretation,
731 the gradient components obtained from the wind
732 tunnel study above, are recalculated from pressure
733 probes restricted to **A**, **B**, **C** and **D** positions as for
734 the gasoline Twingo, and for the case (WBA) having
735 the underbody flow characteristics $U_b^* = 0.62$ that
736 also selects a state P of the wake (see FIG.13). Com-
737 paring the vertical gradient components of FIG.13(c)
738 and FIG.12(d), clear differences remain between on-
739 road and wind tunnel testing. While clear state
740 switches are identifiable in FIG.12(d) (such as around
741 $t^* = 3000$), the gradient fluctuates more homoge-
742 neously on a low frequency basis between 2 extreme
743 values that could be ascribed to the P and N states.
744 The correlation in the frequency domain between the
745 base suction and the base pressure gradient compo-
746 nents is obtained from the complex coherence func-
747 tion shown in FIG.14. Although the (WBA) case

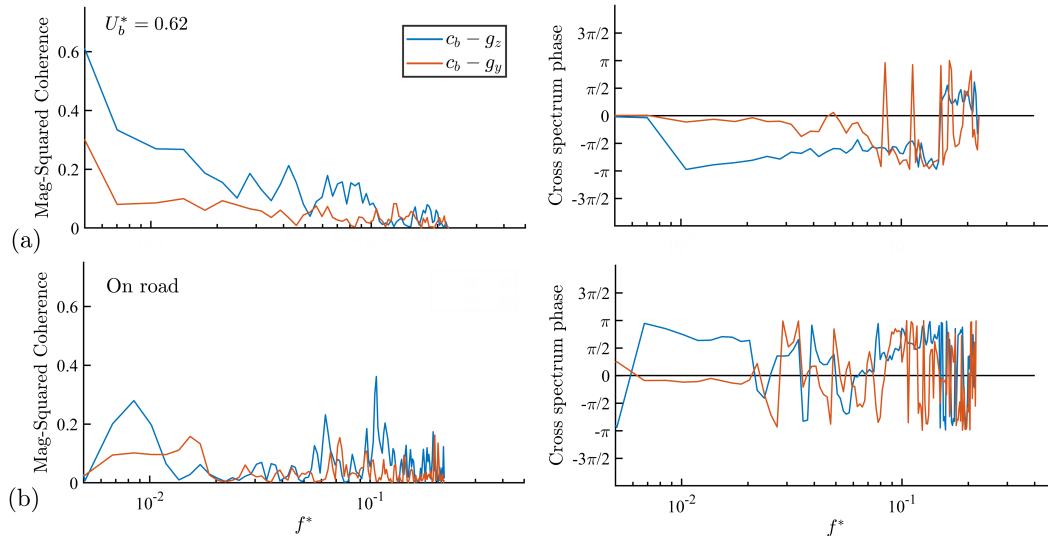


Figure 14: Magnitude squared coherence and cross spectrum phase between c_b and the two gradient components, g_y and g_z for the (a) active control (WBA) at $U_b^* = 0.62$, (b) on road test. All are computed from the time series of FIG.12 and FIG.13.

748 presents a dominant P state of the wake, the few
 749 switches towards the N state are responsible for the
 750 evident correlation at low frequency between the
 751 vertical component g_z and the base suction c_b in
 752 FIG.14(a, left) with a π shift in FIG.14(a, right). For
 753 the on-road testing, FIG.14(b) also indicates a simi-
 754 lar correlation at low frequency, but much weaker
 755 than for the wind tunnel testing.

756 4. Conclusion

757 A car model corresponding to the original real
 758 Twingo GT configuration with a scale of 1:5 with
 759 an underbody flat surface and without exhaust line
 760 tested in a wind tunnel is subjected to a global
 761 instability implying the possibility of 2 equilibrium
 762 states, N or P depending on the value of the base
 763 pressure gradient. The drag of the N state is
 764 found to be larger than that of the P state (as
 765 also found with real minivans wake in Bonnavion
 766 et al. (2019)). The major contribution of the work
 767 is to show that the control of the wake state by
 768 reducing the underbody flow with an active device
 769 leads to important drag reduction of approximately
 770 10% when selecting the P state compared to the
 771 N state. The transition occurs at a critical under-
 772 body velocity of $U_{b_c} \approx 0.635U_\infty$. Based on the
 773 observation of a similar transition with moving
 774 ground (the correct ground boundary condition for
 775 vehicles), it is speculated that the static ground in
 776 the present experiment overestimates the critical
 777 velocity compared to moving ground. The very clear

778 result is encouraging and may provide interesting
 779 perspective for flow control in real application. For
 780 this purpose, the base pressure gradient has been
 781 measured on a gasoline Twingo GT during an on-
 782 road testing. There are clear difficulties to compare
 783 both wind tunnel and on-road testing due to the
 784 large difference in underbody flows both vehicle
 785 may have. As the underbody flow characterisation
 786 is not accessible during the on-road testing, we have
 787 chosen to compare with the wind tunnel case having
 788 a similar state selection. A correlation between
 789 the vertical base pressure gradient and the base
 790 suction of same nature as that identified in the wind
 791 tunnel testing is still observable but much weaker.
 792 This latter result needs further development of
 793 on-road testing with on-board active control as
 794 real-life intermittent inflow conditions induce more
 795 complex dynamics, which are not captured in basic
 796 wind tunnel testing with uniform and low turbulent
 797 intensity flow.

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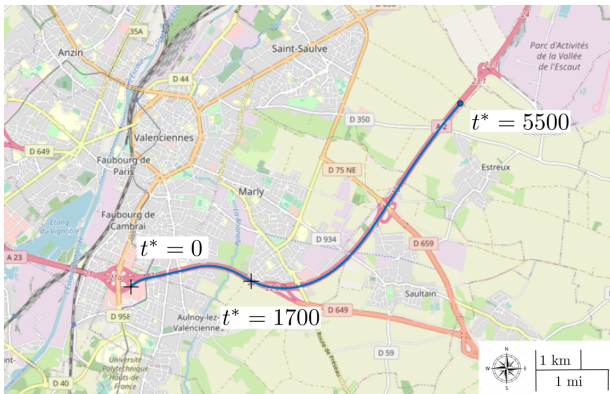


Figure 15: Motorway journey associated with the test sequence obtained using the on-board global positioning system.



Figure 16: Instrumented test vehicle

Appendix. On-road testing

The sequence considered is a motorway journey (see FIG.15) with a departure with an acceleration phase corresponding to an entry on the motorway between $t^* = 0$ to 1700 followed by a phase at relatively constant speed with variations in environmental topology (line of trees, bridges, overtaking vehicles,...). A driver and an operator passenger are boarded in the front seats of the vehicle. The test vehicle used was a real Renault Twingo (as shown on FIG.16), with full scale dimensions including the exhaust line and the various underbody equipment leading to an overall lower ground clearance with non-constant upstream-downstream air flow depending on the underbody geometry. A set of pressure taps are installed at the vehicle rear surface only on specific location (A, B, C and D see FIG.1d) since it was not possible to drill directly all the part of the rear window. Nevertheless, the installed pressure taps are located to have the vertical and hor-

izontal gradient at quite the same location of the four common positions (A, B, C and D) as it is the case for the wind tunnel model. As a consequence we do not have access to the full pressure map on the rear surface, so only an estimation of the pressure coefficient and the pressure gradient components are obtained base on these pressure taps. The tapping were connected to a pressure scanner (Scanivalve MPS4264) with 1 m of vinyl tube at a sampling frequency of 10 pressure samples per second. The power supplies are decoupled from that of the vehicle to avoid any interference problem or impedance matching. The dynamic pressure, q_∞ and the reference pressure, p_∞ were capture using a car front cover mounted standard Pitot-static probe as shown in FIG.16. The probe remained in position throughout the entire test run. This probe is not able to provide the instantaneous yaw angle data, and just measure the relative speed of the car. The pressure measurement were gathered in a synchronized way in order to be compute the pressure coefficient and the two pressure gradient components. The vehicle was driven at an indicated velocity between 20 to 30 m/s during the on-road test.

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