On the applicability of trapped vortices to ground vehicles

Abdessalem Bouferrouk
Department of Engineering Design and Mathematics, University of West of England, Bristol, UK.

Abstract
The aim of this paper is twofold: first to review an important area of research in fluid dynamics: that of trapped vortices, and secondly, to highlight the opportunities/challenges of the trapped vortex concept when applied to ground vehicles. It is shown that trapped vortices are an effective technology for the reduction of drag on aerodynamic vehicles. There is, however, a formidable challenge of the control of such vortices for the concept to be successfully used on ground vehicles. The paper provides some suggestions on how trapped vortices may be implemented and controlled to enhance the performance of some ground vehicles.

***Keywords**:* trapped vortices, ground vehicles, flow control, drag reduction, downforce, vortex stabilisation.

1 INTRODUCTION AND MOTIVATION

Large-scale vortices that form naturally in high Reynolds number flows past bluff bodies are shed downstream creating chains of vortices in their trail (Figure 1(a)). This leads to an increase in drag, unsteady loads, and an unsteady wake with large energy losses. In such cases, instabilities develop leading to high levels of noise and large stresses on components. However, if large scale vortices are prevented from shedding and are kept near the body surface, they become *trapped*. When this occurs, drag and unsteadiness are reduced while for a lifting wing, the lift increases. One way of trapping such vortices is using vortex cavities as shown in Figure 1(b). The boundary of the trapped vortex is defined by an enclosing streamline and the whole fluid structure forms a steady vortex bubble. A trapped vortex is a mechanism for separation control, and a means to delay stall at high angles of incidence. Vortex flows have long existed on flapping wing insects that utilise spiraling strong vortices to generate high lift at very low speeds (1). Despite being an old concept, vortex trapping is not well known within the academic community, and particularly within ground vehicles. Because ground vehicles have bluff body shapes, large scale separations similar to Figure 1 (a) exist. Therefore, there is potential of exploiting trapped vortices on ground vehicles for improving their aerodynamic performance. Unlike the case with aircraft, application of trapped vortices to ground vehicles may be quicker and cheaper. One chief purpose of this paper is to revisit the trapped vortex concept and stimulate interest in its implementation on ground vehicles.

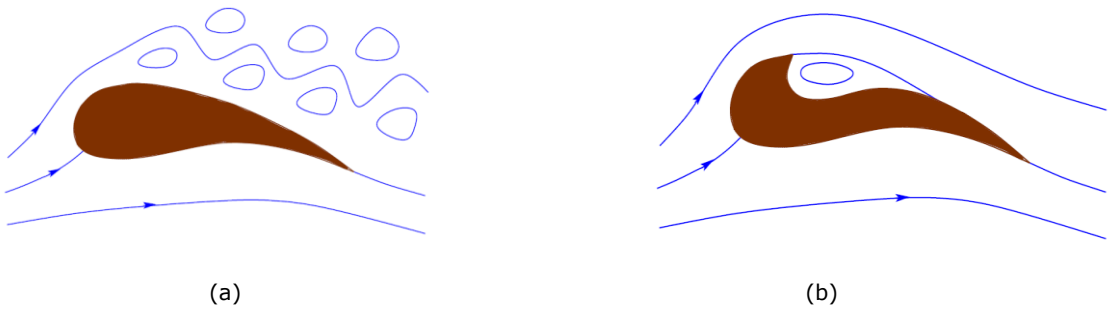


Figure 1: (a) Shed vortices around a bluff body, (b) a trapped vortex inside a vortex cavity.

2 BRIEF HISTORICAL REVIEW

The origins of the trapped vortex go back to the works of W. A. Kasper (2) who claimed that his glider was able to achieve a significant lift-to-drag ratio at low speeds which was attributed to a large separation eddy above the wing (Figure 2 (a)). The EKIP aircraft, which had several vortex cavities with central bodies, see Figure 2 (b), was supposedly able to trap vortices inside, and improve the aerodynamic performance as a result (3). Only few studies have been dedicated to exploiting trapped vortices e.g. for lift enhancement (4), reduction of drag and flow unsteadiness (5), control of flow separation (6), and for vehicle control (5).

(a) (b)

Figure 2: Trapped vortices: (a) on a Kasper wing (2), (b) EKIP wing with vortex cells and central bodies (6).

In recent years, with interest in large transport aircraft, actively controlled trapped vortices were studied within the VortexCell2050 project (6), with positive outcomes. Tutty et al. (7) were able to stabilise a vortex trapped in a cavity using suction. Bouferrouk (8) showed that stabilisation of a vortex trapped in a nearly circular cavity required minimum mass flow rate with unsteady suction, but only in a limited range of flow conditions. Lasagna et al. (9) found that distributed suction required less energy input compared with localised suction, similar to the findings of Bouferrouk (8). It was also established that the drag curve exhibited a hysteresis loop. Other studies had looked into using fences for trapping vortices on wings, e.g. (5). It is worth noting that all studies agree that a trapped vortex can only improve the aerodynamic performance if the flow remains stable at all times, otherwise perturbations cause the vortex to shed downstream, leading to the situation in Figure 1 (a). Therefore, there is a need for effective flow control strategies, advanced aerodynamic design, and intelligent use of sensors and actuators that achieve vortex stabilisation with minimum energy expenditure.

3 APPLICATION OF TRAPPED VORTICES TO GROUND VEHICLES

Flow separations take place along the body surface of a ground vehicle, from the front to the back and in the wake (10). Reduction of vortex shedding by trapping vortices would reduce pressure drag and, consequently, fuel costs for these vehicles. Regardless of the type of motive power, reductions in drag are necessary if aerodynamic efficiencies are to be achieved. Certainly, the focus of commercial vehicles of today is not only on speed but also on energy consumption while maximising the payload. However, ground vehicles have the added complexity of a moving ground, and must negotiate the flow in the clearance between the lower surface and the ground. Applications of trapped vortices to ground vehicles have been scarce. Notably, two studies are found: the first involves using trapped vortices on a race car (11) and the other uses the concept on commercial tractor–trailer trucks (12). In what follows, some suggestions are provided on how vortices may be trapped and stabilised on the following ground vehicles: road cars, racing cars, commercial truck trailers and high speed trains.

3.1 Application of trapped vortices to road cars

Here, the most striking flow features are the longitudinal vortices along the car body and the large recirculation region in the wake (Figure 3). The back low pressure region is the main reason for increased pressure drag. The rear base flow can be responsible for over 70% of the total drag. From Figure 3, a rear angle of 30° induces the smallest wake size with minimum drag. Table 1 summarises typical contributions to total drag for a road car (13).

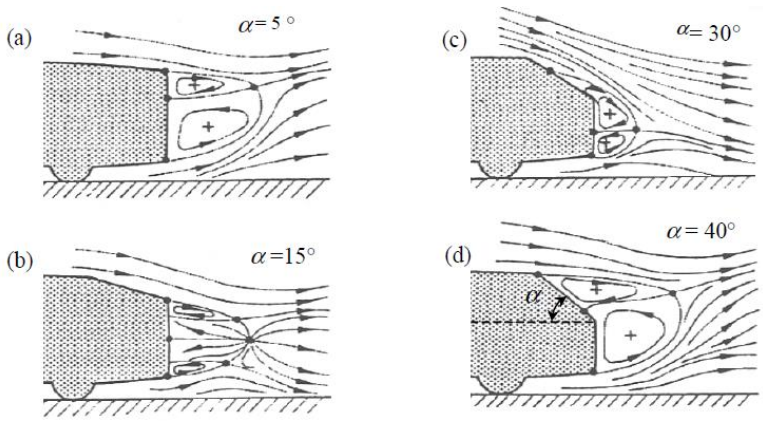


Figure 3: General flow structure in the near wake of a road car (14).

Table 1: Components of drag on a road car (13).

Position	**Percent of C_D**
A-pillar	5%
Side-view mirror and other accessory	7%
Front part	3%
Cooling circuit (motor, interior, brakes)	8%
Rear end	30%
Wheels	15%
Vehicle sides	2%
Underbody	30%

The role of trapped vortices would be either to increase the base pressure, reduce the front stagnation pressure, or both. One way of reducing drag from the flow on the roof is to employ vortex generators (VGs) to keep the boundary layer attached. Combining vortex generators with suction and blowing at the rear of the car may reduce the size of the wake flow, decreasing the drag further. If the separated flow from the car's upper surface becomes trapped, the resulting low pressure region creates a net lifting effect similar to that on an aircraft wing; this is clearly undesirable. However, if the flow underneath the car could be actively trapped with suction, the induced low pressure zone produces a net downforce that would allow the car to have better road adhesion. Further, trapping the flow below the car stops it from being entrained into the wake, potentially increasing the back pressure and reducing flow unsteadiness. Generation of downforce with trapped vortices may, however, create some induced drag. Double fence concepts (15) could be used for vortex trapping underneath the car with wall suction for enhanced stabilisation. The effects of the size and distance between the fences, suction distribution, and the clearance from the ground must be investigated to create stable vortices with minimum energy requirements. The sucked fluid could be used to break up the separated back flow, further shrinking the wake size. The energy to drive the suction pump could come from a small Stirling engine that operates on recovered waste heat. An alternative method is to mount a surface boundary with corrugations to trap multiple vortices; a similar concept was investigated by Yeung (16) on a wing with encouraging results. This latter solution may prove easier and cheaper to implement on a road car compared with a vortex cavity or fences that may be constrained for aesthetic reasons. However, underbody fences and discrete corrugations for vortex trapping are less intrusive.

3.2 Application of trapped vortices to racing cars

Since the weight, centre of mass, tire condition, and propulsive power are strictly controlled for racing cars, aerodynamics has the highest potential in offering a competitive advantage in performance for such vehicles (17). In particular, downforce has a direct impact on road adhesion and cornering speeds necessary for winning races. But drag reduction and associated fuel savings can also be used by midfield teams to exploit the characteristics of some circuits.

Underbody diffusers are particularly efficient since they can contribute up to 50% of downforce without a significant penalty due to lift induced drag (18). The remaining downforce is mostly generated by the inverted front and rear wings. The inverted front wings with guide vanes act to suck air into the car's underbelly, creating a low pressure region and a downforce is generated. Just like on a lifting wing, the flow on the lower surface may become separated, leading to a reduction in downforce. To increase the ability of the inverted wing to generate greater downforce a leading edge flap to create a large vortex on the lower surface with wall suction for stabilisation can be used (Figure 4). Alternatively, vortex cavities can be used for flow trapping. Using central bodies inside the cavities could stabilise the vortex without active suction; such systems were reportedly successful on the EKIP aircraft (19).

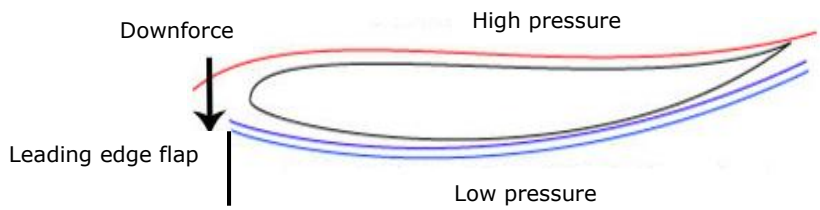


Figure 4: Using a leading edge flap on an inverted wing (with wall suction) for vortex generation and trapping.

One particular study that looked into the impact of trapped vortices in race car ground effects was that of Garcia and Katz (11). They used a flat plate with vortex generators and a moving ground. The VGs generated vortices which were then trapped between the plate and the ground. The result was an increase in the downforce especially at low clearance heights from the ground and at various orientations of the VGs, even when the plate was mounted parallel to the ground. The results were later supported by Katz and Morey (20)

who demonstrated that vortices generated by VGs create a suction force between the vehicle and the ground that improved the tire adhesion as well as the vehicle's cornering and traction performance.

The underbody diffuser is most effective in creating more downforce when there is clear air entrained underneath. However, this is not always the case because of devices upstream and due to flow entrainments from the sides. Consequently, the underbody flow may be separated and highly unsteady (Figure 5). If a large scale vortex can be trapped underneath the car, this would result in a low pressure region that induces an increased level of downforce, similar to the inverted wing case. The shape of the diffuser can naturally achieve the same function as a surface cavity, but the addition of small flaps in front of the curved section can help create stronger vortices. Wall suction can then be used to obtain a stabilised vortex. Furthermore, if the exhaust engine flow can be directed underneath the car it would energise the existing trapped vortex whilst allowing it to extend over a larger, low pressure region. Apart from downforce, trapped vortices can be exploited for mitigating the effects of hysteresis loops that may exist in sustained flow separations.

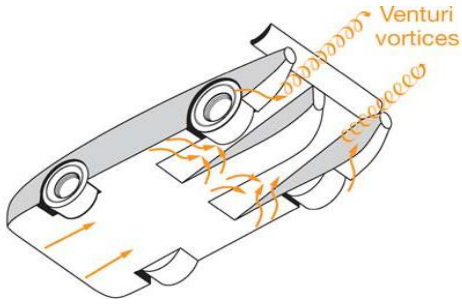


Figure 5: Race car diffuser with separated vortices (17).

A large share of the drag on a NASCAR race car is due to the highly separated underbody flow (see Figure 6). Since underbody streamlining is not allowed with these cars, flow adjustments using trapped vortices to control underbody flow separation could result in saving large travelling distances when traveling at 200 mph.

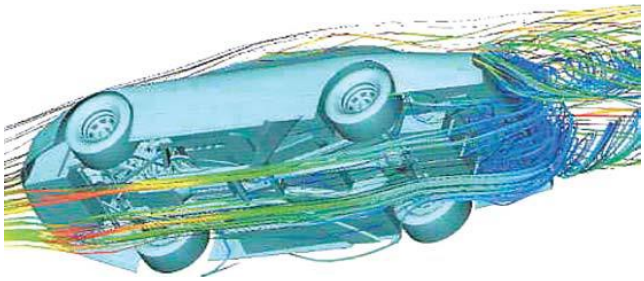


Figure 6: Flow around a NASCAR race car (17).

3.3 Application of trapped vortices to truck trailers

Approximately 40% of the fuel consumption of trucks is used to overcome aerodynamic drag (21), making it a significant factor in the financial and environmental impact of this transport sector. In Figure 7, front end shape optimisation of the tractor and reduction of the gap between the front end and the trailer results in reduced drag due to a reduction in the number of separated regions.

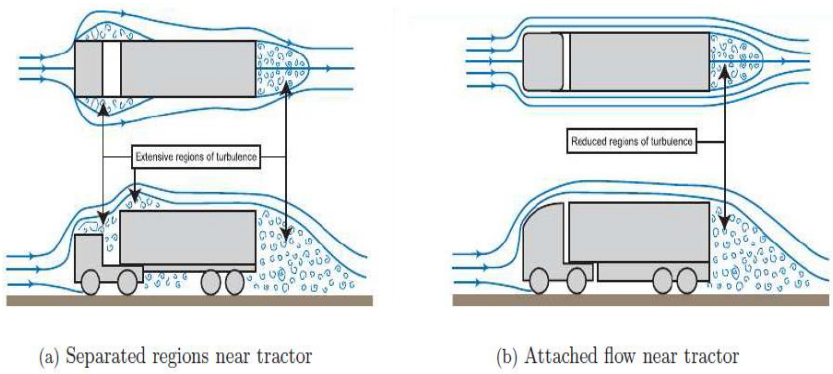


Figure 7: Tractor front end streamlining to reduce pressure drag around a tractor trailer (22).

Between 50% and 60% of drag may be due to the trailer of a tractor (23). It is thus important to focus on the trailer for drag reduction, but also on the flow along the underside of the body (30%), see Figure 8.

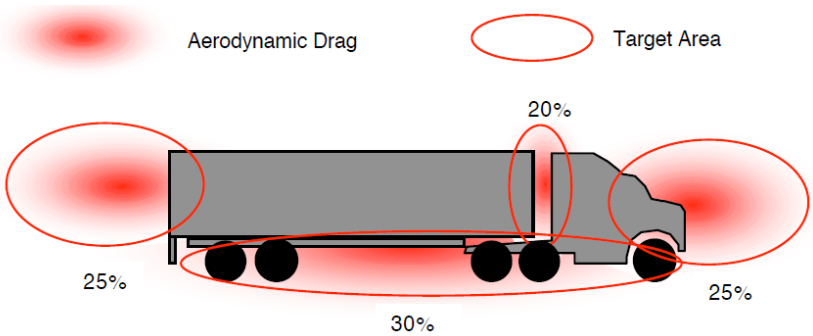
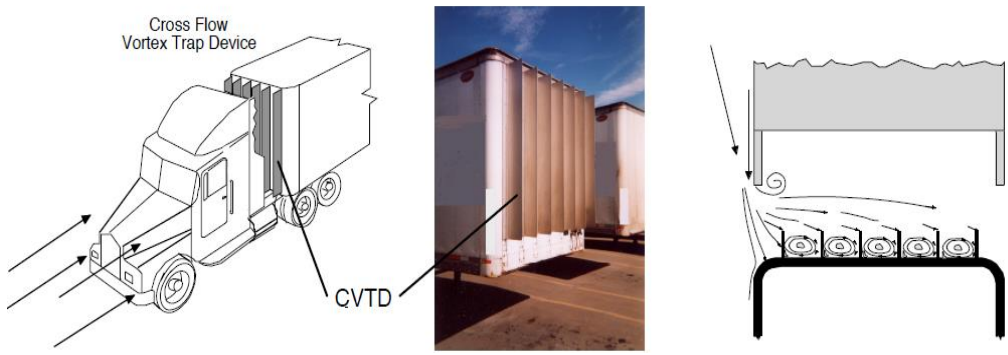


Figure 8: Areas of high drag around a trailer-tractor truck (12).

The Cross-flow Vortex Trap Device (CVTD) was placed on the forward facing front of the trailer of a trailer-tractor truck (12), see Figure 9. The use of the CVTD ensures that the gap cross flow separates at the leading edges of the CVTD surface, generating vortices that are trapped between the adjacent CVTD surfaces. The resulting lower pressure on the front face of the trailer leads to drag reductions.



(a) (b)

Figure 9: The CVTD installed on the trailer front face (a), trapped vortices along the trailer (b) (12).

It was shown that factors such as vehicle interference, atmospheric effects and road conditions may act to further increase the impact of aerodynamics on heavy truck fuel consumption (24). Although aerodynamic solutions can improve the fuel economy by 20 % (12), the adaptation of aerodynamic innovations on heavy trucks has been slow due to concerns related to operations and maintenance which is driven by device complexity, weight and cost (12).

Another concept that utilises trapped vortices is a Vortex Strake Device (VSD) to reduce the aerodynamic drag due to a large wake behind a trailer (12). The role of the VSD is to limit the number of separated vortices shedding at the rear end of the trailer, see Figure 11. The consequence is a reduction of pressure drag as well as unsteadiness. A combined fuel saving of 8% was achieved at an average speed of 47.5 miles/hour for the two vortex concepts above, corresponding to 20% drag reduction (12). These simple, low cost aerodynamic solutions occurred without any noticeable effects on the operational utility of the trailer, maintenance costs, procedures, or the handling qualities of the trucks (12).

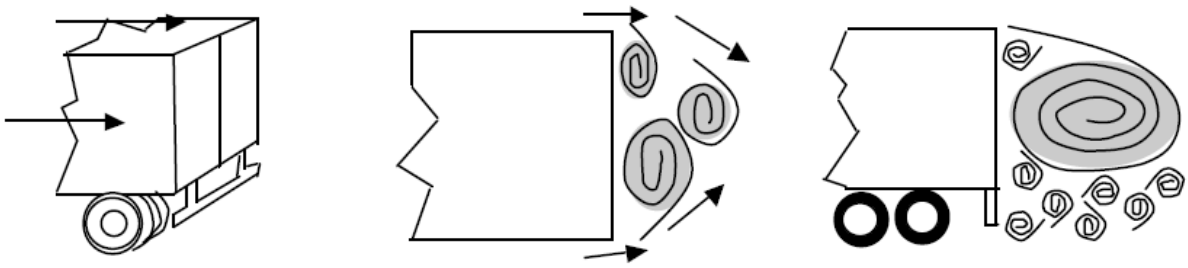


Figure 10: General flow characteristic around a trailer of a heavy truck (12).

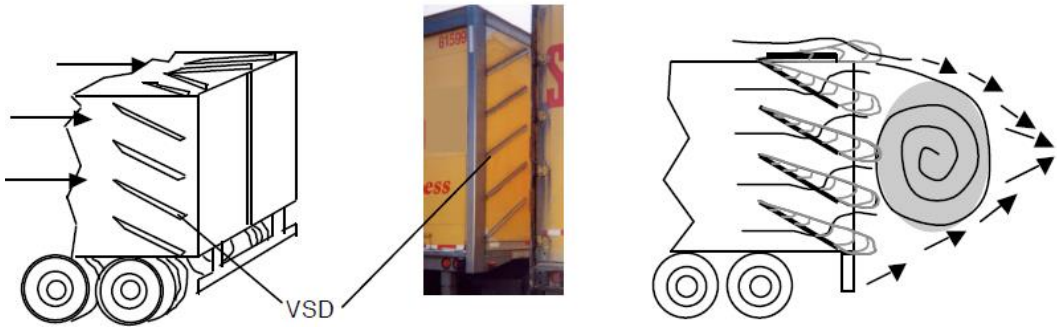


Figure 11: The VSD installed on the aft portion of a trailer (12).

As a continuation to the study of Wood (12), vortex trapping devices in the form of flaps/fences and vortex cavities could be used along the underbody of the trailer to create multiple vortex flows whose net effect is a lower pressure region for increased downforce. For these vehicles, the procedures for field tests of vortex trapping must not disrupt their operation.

3.4 Application of trapped vortices to high speed trains

3.4.1 Crosswind safety

In the presence of strong crosswinds, high speed trains become vulnerable to derailment off the track. A number of train derailments due to crosswinds have occurred recently (25). The most dangerous situations include running over embankments, sudden gusts and trains coming out of tunnels. A typical picture of the flow around a high speed train in a crosswind is shown in Figure 12. The main aspects are the stagnation region on the streamwise face and the low pressure region on the lee side face. The net pressure difference generates a side force that acts to push the train off the track. The wind also flows over the train roof and along the underside. The recirculation zone is equivalent to a wake flow in crosswinds. There is also a lifting force and a turning moment on the train.

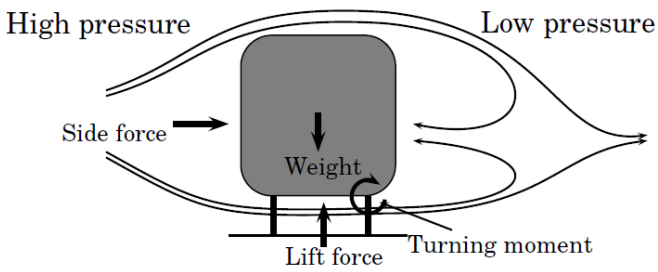


Figure 12: Crosswind flow around a high speed train (26).

The flow structure around a high speed train may depend on the Reynolds number as described by Copley (27) and shown in Figure 13 for three regimes: (a) sub-critical, (b) critical, and (c) super-critical.

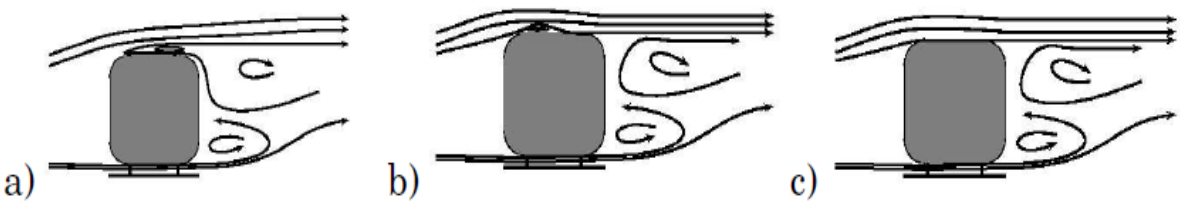


Figure 13: Reynolds number effects on the crosswind flow around high speed trains (26).

Existing methods to reduce crosswind effects are not cost effective, e.g. trains in the UK have to stop on track if the crosswinds reach 80mph. Active flow control on high speed trains remains in its infancy, and trapped vortices have never been applied to such vehicles. One possible application is to trap the underside flow using flaps or wall cavities for two purposes: 1) to increase the downforce, and 2) to control the flow such that the resulting flow in the lee side has a smaller wake and thus a reduced side force. Also, surface corrugations or vortex generators combined with wall suction can trap vortices to create a low pressure region on the wind facing side to reduce the magnitude of the side force. Consequently, the turning moment will be lower, leading to greater crosswind stability.

3.4.2 Slipstreams

Train slipstreams induce high velocities that can be a serious danger to the safety of track workers, equipment, people on platforms, and could also affect trackside and platform structures due to pressure and velocity pulses (28). The strength of slipstreams is intensified in the presence of crosswinds, at high speeds, and if the train surface is rough or discontinuous. The slipstream flow around a train is illustrated in Figure 14, showing a turbulent flow which contains a number of interacting small and large scale vortices. If the flow can be trapped close to the surface of the train the effects of slipstreams will be reduced as the flow can remain attached over longer sections of the train. However, this might result in a stronger wake as well increasing skin friction drag, so active flow control with suction would be needed at the back of the train and to reduce the effects of turbulent wall streaks along the train surface.

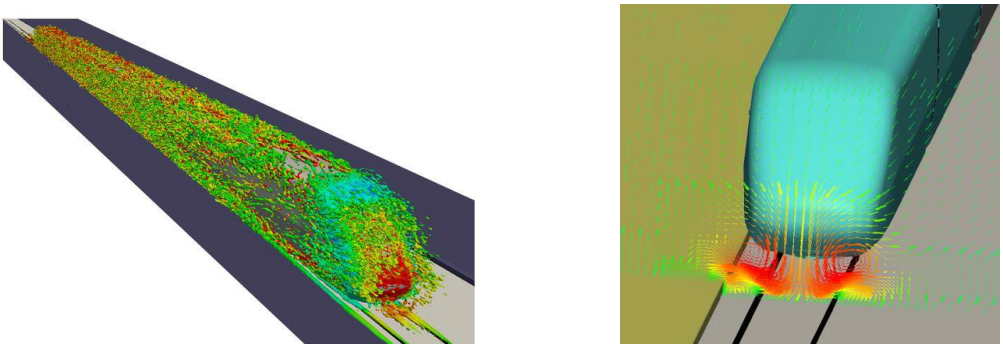


Figure 16: Slipstream flow: (a) flow along the main train body, (b) wake vortices (28).

4. CONCLUSIONS AND FUTURE WORK

This paper has presented a brief account of the development of the trapped vortex concept through which the major benefits are demonstrated. By considering road cars, racing cars, tractor trailer trucks and high speed trains, it is shown that ground vehicles present favourable platforms for the application of trapped vortices to improve their performance, in terms of reduction of pressure drag and flow unsteadiness, increased downforce, control of hysteresis, crosswind stability, reduction of unsteady loads, and alleviating slipstream effects. Whenever large scale flow separation occurs from the surfaces of ground vehicles, actively controlled trapped vortices can improve aerodynamic performance. However, given the variety of flow scenarios with ground vehicles and their different purposes, trapped vortices alone cannot solve all aerodynamic problems. The technique can be used in conjunction with other methods such as back face suction and blowing, shape optimisation, and vortex generators. There will be a need to compare, at least qualitatively, the effectiveness of trapped vortices with existing means of aerodynamic flow control on ground vehicles. In order to energise and sustain trapped vortices, the opportunity to use exhaust engine flows should be explored. Only specific areas around a ground vehicle, e.g. excluding upper body surfaces, can be targeted for implementation of trapped vortices. One advantage of actively controlled trapped vortices is their minimum effect on the design of the vehicle, especially when implemented underneath the body.

Because active flow control (e.g. unsteady suction) and flows around ground vehicles are both unsteady, there is a need to use unsteady techniques (e.g. URANS, LES, PANS, or DES) with trapped vortex flows. Since trapped vortices reduce vortex shedding and unsteadiness, this presents opportunities for researching the aero acoustics of high lift aerofoils with vortex trapping capabilities. For high speed trains, implementing the concept to reduce the effects of strong pressure pulses at tunnel exits could be explored. The role of quick and robust shape optimisation methods, such as the adjoint methods, would be vital in exploring optimum cavity profiles that achieve stabilisation with minimum energy. There remain open questions on the type of flow conditions under which the trapped vortex is beneficial depending on the geometry, vortex size, vortex strength, and stability with respect to large scale vortex shedding. A serious consideration for system identification techniques based on trapped vortices should be investigated. Limited work on this front was presented in (8). Implementation of trapped vortices should begin with simplified geometries to allow quick assessment of the concept. It would be important to accurately simulate a moving ground with an atmospheric boundary layer (ABL) as this latter is known to become skewed in crosswinds (29). The ability to visualise the flow for control of trapped vortices e.g. using the elevated ground method, would be important. Whatever the application of trapped vortices is, the issue of vortex stabilisation remains central to the successful implementation of the concept on ground vehicles.

REFERENCE LIST

[1] Brookes, M. (1997). On a wing and a vortex. New Scientist Magazine, 24-27, October 11.

[2] Kasper, W.A. (1975). Some ideas of vortex lift. Society of Automative Engineers, paper 750547, 12pp.

[3] Chernyshenko, S. I. (2009). VortexCell 2050: Fundamentals of actively controlled flows with trapped vortices. Summary Report for the 6th EU Framework programme for research and technological development.

[4] Buchholz, M. D., Tso, J. (2000). Lift augmentation on Delta wing with leading-edge fences and Gurney

flap. Journal of Aircraft Technology, Vol. 37, No. 6, pp-1050-1057.
[5] Riddle, T. W., Rogers, S. E., Ross, J. C., Cummings, R. M. (1999). An experimental analysis of vortex trapping techniques. Journal of Fluids Engineering, Vol. 121, pp-555-559.
[6] Baranov, P., Guvernyuk, S., Zubin, M., Isaev, S. A. (2000). Numerical and physical modelling of the circulation flow in a vortex cell in the wall of a rectilinear channel. Fluid Dynamics, Vol. 35, No. 5, pp-663-673.
[7] Tutty, O., Buffoni, M., Kerminbekov, R., Donelli, R., De Gregorio, F., Rogers, E. (2013). Control of flow with trapped vortices: theory and experiments. International Journal of Flow Control, 5, (2), 89-109.
[8] Bouferrouk, A. (2007). A discrete vortex method analysis tools for control of flows with trapped vortices. PhD Thesis. University of Southampton.
[9] Lasagna, D., Donelli, R., De Gregorio, F., Iuso, G. (2011). Effects of a trapped vortex cell on a thick wing airfoil. Experiments in Fluids, Vol. 51 (5), pp-1360-1384.
[10] Bruneau, C. H., Creusé, E., Depeyras, D., Gilliéron, P., Mortazavi, I. (2012). Active and Passive Flow Control around Simplified Ground Vehicles, Journal of Applied Fluid Mechanics, Vol. 5, No. 1, pp. 89-93.
[11] Garcia, D. L., Katz, J. (2003). Trapped vortex in ground effect. AIAA Journal, Vol. 41, No. 4, pp-674-678.
[12] Wood, R. M., Bauer, X. S. (2003). Simple and low-cost aerodynamic drag reduction devices for tractor-trailor trucks. SAE International.
[13] Gohlke, M. (2008). Drag reduction by flow control at PSA Peugeot-Citroën. KATnet II Separation Control Workshop, Toulouse.
[14] Ahmed, S.R. (1983). Influence of base slant on the wake structure and drag of road vehicles. Transactions of the ASME, Journal of Fluids Engineering V105, P429-434.
[15] Rossow, V. J. (1992). Two-fence concept for efficient trapping of vortices on airfoils. Journal of Aircraft, Vol. 29, No.5 (1992), pp. 847-855.
[16] Yeung, W. W. H. (2009). Vortex trapping on a surface with an indentation and corrugations. Mathematics and Computers in Simulation 79 (11):3243-3257.
[17] Puglisevich, L. S. (2013). Large Eddy Simulation for Automotive Vortical Flows in Ground Effect, PhD Thesis, University of Loughborough.
[18] Katz, J. (2006). Aerodynamics of race cars. Annual Review of Fluid Mechanics, Vol. 38, pp.27-63.
[19] http://www.ekip-aviation-concern.com/
[20] Katz, J., Morey, F. (2008). Aerodynamic of large scale vortex generator in ground effect. J. Fluids Eng., 130, 6 pages.
[21] Hucho, W. H. (1988). Aerodynamics of Road Vehicles. Fourth Ed., pp. 415-488.
[22] Van Leeuwen, P. M. (2009). Computational Analysis of Base Drag Reduction Using Active Flow Control, Master of Science Thesis, Delft University of Technology.
[23] Van Raemdonck, G. M. R. (2006). Design of an aerodynamic aid for a tractor trailer combination, Master's thesis, Delft University of Technology.
[24] Tyrrell, C. L. (1987). Aerodynamics and Fuel Economy On Highway Experience. SAE 872278.
[25] Baker, C. J. (2010). Train aerodynamics problems & solutions, Railway Strategies, Issue April-May.
[26] Hemida, H. (2006). Large-Eddy Simulation of the Flow around Simplified High-Speed Trains under Side Wind Conditions, Thesis for Licentiate of Engineering, Chalmers Institute of Technology, Sweden.
[27] Copley, J. M. (1987). The three-dimensional flow around railway trains. Journal of Wind Engineering and Industrial Aerodynamics, 26:21.52.
[28] Hemida, H., Baker, C. J. (2011). The calculation of train slipstreams using Large-Eddy Simulation techniques, WCRR, Lille, France.
[29] Bouferrouk, A., Hargreaves, D., Morvan, H. (2012). CFD Simulations of Crosswind Impinging on a High Speed Train Model. 18th Australasian Fluid Mechanics Conference, Launceston, Australia, 3-7 December.