

# **Thermal management concept of a taxi vehicle with rear engine application**

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## **ABSTRACT**

In this paper, powertrain cooling studies on a new design rear engine rear wheel drive vehicle within the scope of the New York City "Taxi of Tomorrow" tender are explained. First of all, vehicle properties and cooling requirements of the powertrain are determined. Before performing thermal management tests of the vehicle, detailed CFD analysis have been done in order to predict cooling performance. After completing the analysis, engine cooling tests have been performed on a modified vehicle that was a front engine front wheel drive previously. In this study, both front engine/front wheel drive (before modification) and rear engine/rear wheel drive vehicles have been subjected to heat management tests for comparison. Finally, possible modifications in order to improve cooling performance of rear engine implementation and additional engine compartment ventilation techniques are mentioned.

## **1 INTRODUCTION**

Nowadays, rear- or mid-engine applications are mostly used in sport cars. There are only a few passenger cars that are manufactured as rear engine vehicles. But in history there are a lot of iconic rear engine vehicles that have been manufactured, such as Tatra 77 [1], Tucker'48, VW Beetle, Chevrolet Corvair, Porsche [2] and some of them have innovative rear engine cooling solutions awarded by patent. In the cooling systems of these vehicles, cooling air is taken from the side or top of the vehicle. Currently, there are two rear engine cooling system design configurations documented in automotive literature. In the first configuration, the radiator is mounted in the same position as a front engine vehicle (e.g. Smart FourTwo). In the second configuration, there are two small radiators and they are mounted on the left and right sides of the engine. In this option cooling air is taken from the sides of the vehicle [3].

But these are not applicable in this project because of the space and manufacturing limitations. First of all, the radiator cannot be mounted in front of the vehicle because of the requirements of the luggage volume and restrictions of the routing and length of the cooling hoses. The second alternative, side cooling air intake, is rejected because of the styling of the vehicle. Because of the low cost requirement and possible different powertrain applications in the future - such as CNG, hybrid and electric - the radiator and other powertrain cooling parts should be carry-over. Therefore, defined radiators cannot be mounted on the side of the vehicle because of the sizes. In consequence, the radiator has to be mounted in the rear of the vehicle and also at the rear of the engine.

Before deciding the exact position of the radiator, possible engine heat dissipation rates and powertrain packaging tolerances have been studied. According to the engine heat dissipation rate, required air mass flow rate to the radiator has been determined. In order to analyze the air flow route around the vehicle and to decide the place of the cooling air inlet, aerodynamic analysis has also been performed.

Finally, a front engine/front wheel drive vehicle was selected as a donor vehicle and modified to a rear engine/rear wheel drive vehicle. The donor vehicle was subjected to heat management tests before and after modification.

## 2 DESIGN PROPERTIES

Properties of the new design vehicle are listed below:

**Table 1 Powertrain vehicle properties**

Engine Fuel:	Gasoline
Engine Displacement:	2360 cc
Engine Power:	129 kW (@6000rpm)
Engine Torque:	225 Nm (@4400rpm)
Vehicle Weight:	2700 kg
Ground Clearance:	200 mm
Frontal Area:	3,085 m <sup>2</sup>
Wheelbase:	3260 mm
Trackwidth:	1580 mm
Vehicle Length:	4830 mm
Vehicle Height:	1920 mm
Vehicle Width:	1922 mm
Design Intend:	Urban usage, taxi
Average Speed:	25 km/h
(Average speed of a taxi when looking for a fare is about 11km/h)	
Required maximum speed:	110 km/h
Stationary waiting time:	40%

**Table 2 Predicted maximum powertrain cooling requirements**

Component	Heat Dissipation Rate
Engine	40 kW
Radiator	100 kW

### 3 ANALYSIS

#### 3.1 Aerodynamic analysis

The main reason of the aerodynamic analysis is to determine drag coefficient of the vehicle which affects fuel consumption, predict low and high pressure areas, separation points and down force which affects vehicle dynamics. All these parameters are also investigated deeply in this project. But, in this paper, separation points and negative pressure areas are examined to determine induction and exiting sections of the cooling air.

External model was designed in the Catia V5 R20 [4]. Flow analysis was performed in the Ansys Fluent V12.1 [5].

Analysis properties:

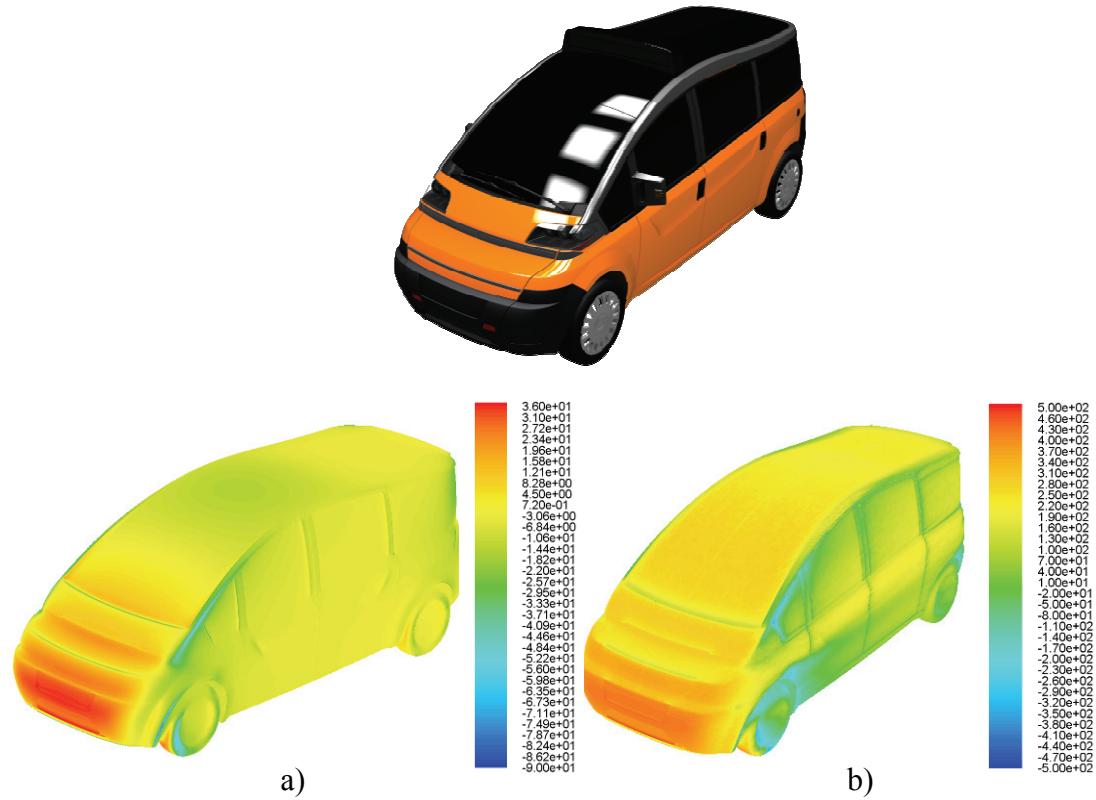
Model: Pressure based, steady

Turbulence model: k- $\epsilon$ , realizable, enhanced wall treatment

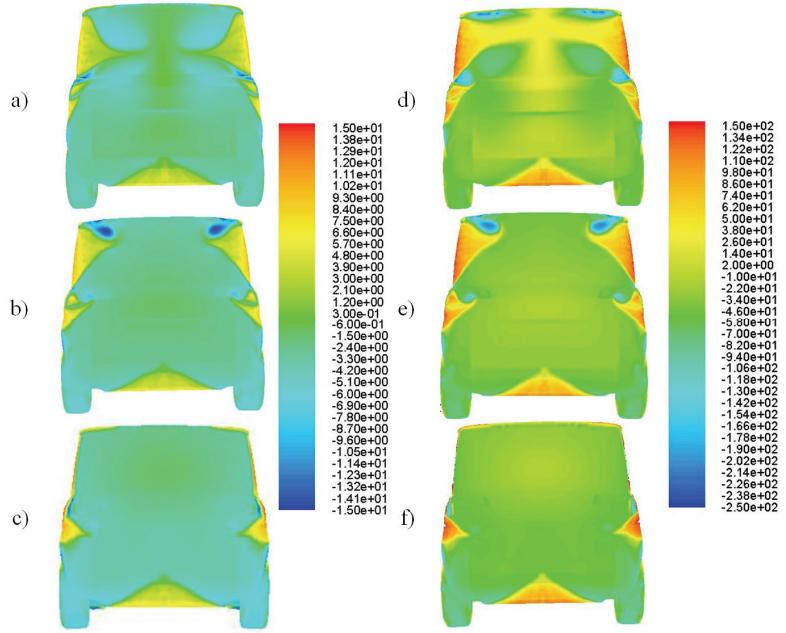
Mesh count: 4.000.000 cells

Ambient temperature: 25 °C

All aerodynamic analysis was performed at three vehicle speeds: 11km/h (average speed of a taxi when looking for a fare [6]), 25 km/h (NY Taxi average speed of whole shift [6]) and 90 km/h. In the Figure 1, pressure contours of the Karsan V1 vehicle can be seen at the 90 km/h freestream velocity.



**Figure 1 Pressure contours (Pa) of Karsan V1**  
**a) @ 25 km/h, b) @ 90 km/h**



**Figure 2 Pressure contours (Pa) of Karsan V1**  
**@ 25km/h a) original, b) with spoiler, c) with d-pillar spoiler**  
**and @ 90km/h d) original, e) with spoiler, f) with d-pillar spoiler**

According to the pressure contours, the upper side of the rear tires and underbody of the vehicle are available to open cooling air intakes. The rear of the vehicle is in a low pressure region. If the cooling air can be routed to the rear of the vehicle, then air can be easily discharged. Therefore, radiator was decided to be mounted at the rear of the vehicle and engine.

After the first coarse aerodynamic analysis, several finer analyses were also performed to examine rear spoiler, d-pillar spoiler and cooling air discharging effects on the rear pressure region of the vehicle. Effects of the rear spoiler, d-pillar spoiler and cooling air discharge on the drag coefficient are listed below.

**Table 3 Drag coefficient of Karsan V1**

Version	Cd
Original	0.412
With spoiler	0.404
With D-pillar spoiler	0.397
Cooling air discharge	0.390

In the aerodynamic analysis, all parameters were examined separately. Upper air flow separates from the surface easier by the help of rear spoiler, side air flow separates from the D-pillar by the help of a D-pillar spoiler and Cd decreases about 2% and 4% respectively. Cooling air discharge to the wake region of the vehicle increases the back pressure of the vehicle which decreases pressure difference between the front and the back of the vehicle and causes a decrease in Cd of more than 5%. In the following stages of the project, besides the pedestrian and motorcycle drivers safety, air flowrate and direction will be also examined during optimization of the cooling system and rear grill.

### 3.2 Engine cooling analysis

First of all, air flow analysis of radiator and motor compartment section were performed separately. Engine and radiator compartment inlet air speeds are taken from the aerodynamic analysis and requirements of the radiator. In both compartments, all analyses were performed at 25 km/h vehicle velocities. Engine heat dissipation rate was taken as 40 kW and radiator heat dissipation rate taken as 100 kW. Gambit was used as a mesher and Ansys Fluent was used as a CFD analysis tool.

Analysis parameters (for both engine and radiator compartments)

Model: 3D, pressure based, steady

Turbulence model: k- $\epsilon$

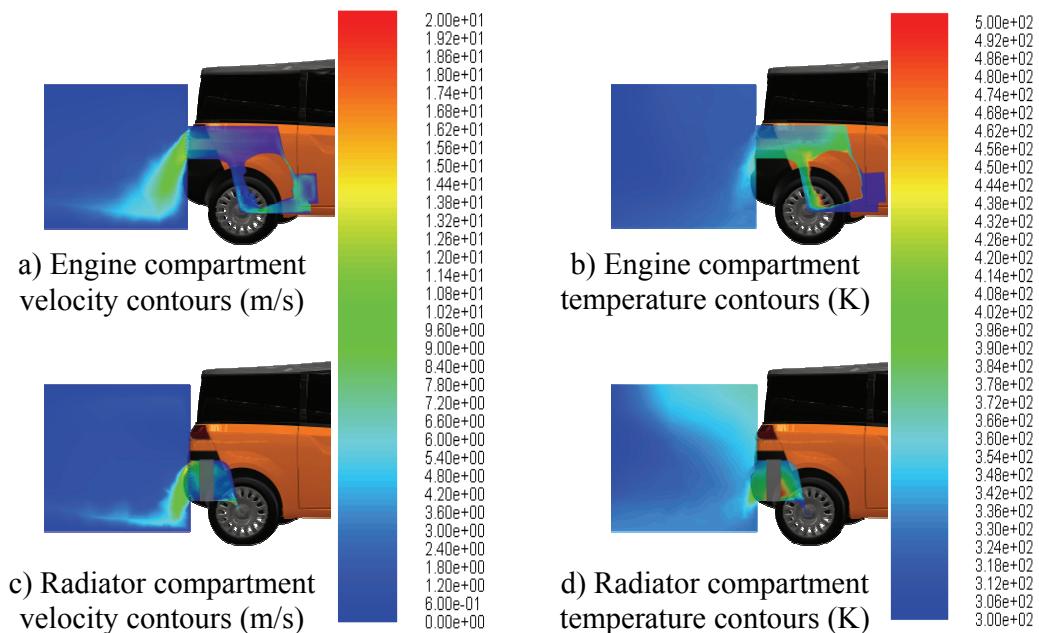
Mesh count: 2.5 million cells

Ambient temperature: 25°C

Below, concept design of the engine cooling system can be seen. For the engine compartment, cooling air is taken from the bottom side of the vehicle and routed by the help of the deflection plate made of composite and discharged to the rear of the vehicle. For the radiator compartment, cooling air is also taken from the bottom side of the vehicle. Air is directed to the radiator by the help of the radiator fans. Exhaust muffler is also separated from the engine and radiator compartments to avoid additional heat gain.



**Figure 3 Preliminary cooling system design concept**



**Figure 4 Cooling analysis results of engine and radiator compartments (@ 25 km/h)**

After completing engine and radiator compartments separately, combined powertrain cooling analyses were performed.

#### Analysis parameters

Model: 3D, pressure based, steady

Turbulence model: k- $\epsilon$

Mesh count: 5.5 million cells



**Figure 5 Temperature contours (K) of cooling analysis results of combined engine and radiator compartments**

**Table 4 Cooling air temperatures and velocities at the back of the vehicle (@ 25°C ambient temperature)**

Parameter	Separated		Combined powertrain compartment
	Engine compartment	Radiator compartment	
Maximum Air Velocity	10 m/s	11 m/s	7 m/s
Maximum Air Temperature	75 °C	50 °C	95 °C

Because of the ground clearance restrictions, the air deflection plate has been modified and the height difference between the bottom of the vehicle and the bottom line of the deflector has been decreased to zero. Then external aerodynamic analysis has been repeated in order to check cooling air inlet mass flow rate. These modifications could not be introduced to the prototype vehicle due to the ongoing test. Therefore the new modifications could not be tested in the first attribute prototype.

In Figure 5, velocity contours of the Karsan V1 can be seen. The main aim of these analyses is to determine the supplied air mass flow rate to the combined engine and radiator compartment. According to this analysis, required air mass flow rate can be inducted to the engine and radiator compartment but air discharging velocity is lower than the previous analysis.



**Figure 6 Velocity contours (km/h) (no level difference between base level of the vehicle and engine compartment intake) (Velocity: 25km/h)**

#### 4 TESTS

Donor vehicle was chosen according to the wheelbase, trackwidth and loading capacity. In the first attribute prototype, called as AP0, the engine is not the same engine that will be used in the real vehicle. Therefore engine of the donor vehicle is different from the proposed vehicle. The main aim of the AP0 is comparing front engine front wheel drive vehicle ride handling, thermal management and packaging characteristics with the rear engine rear wheel drive vehicle. Donor vehicle contains a 2.0 liter diesel engine with turbocharger and intercooler. Power of the engine is 88 kW.

Donor vehicle properties:

Radiator size of the engine: 700mm x 400mm

There were two fans on the radiator. Properties of the fans:

1st fan: 9 blades with 360mm diameter, 7 m/s air velocity

2nd fan: 6 blades with 325mm diameter, 7 m/s air velocity

All thermal management tests were performed on the same road over the same distance.

Test track: 8km out and return

Test count: Two subsequent tests were performed in order to complete required data set and to check oil and engine coolant temperatures.

Test conditions: 1st gear 25km/h vehicle velocity (~2750 rpm engine speed), 2nd gear 40km/h vehicle velocity (~2500rpm engine speed)

Temperature measuring points:

- Oil dipstick,
- Coolant temperature @ engine out
- Coolant temperature @ engine in
- Air temperature before radiator (4 thermocouples)
- Air temperature after radiator (4 thermocouples)
- Air temperature before intercooler (2 thermocouples)
- Air temperature after intercooler (2 thermocouples)
- Temperature above ECU
- Under bonnet temperature (above the engine)
- Temperature above the heat shield of the catalytic converter

#### 4.1 Tests with front engine

Before performing the heat management tests, engine was run until the engine oil temperature exceeded 90°C and the fan operated a minimum of one time. Fans are located at the front of the radiator and also at the front of the vehicle.

Ambient temperature: 12 °C

Test weight: 2700kg

Test duration: 142 minutes (two simultaneous tests were performed = 71 min x 2)

First test section : 22.0 min. (1st gear 25 km/h)

Second test section : 13.3 min. (2nd gear 40 km/h)

Third test section : 13.5 min. (2st gear 40 km/h return)

Fourth test section : 22.2 min. (1st gear 25 km/h return)

**Table 5**

Condition	Thermocouple Location	Maximum Temperature (°C)	Condition	Thermocouple Location	Maximum Temperature (°C)
1st Gear 25km/h	Oil Dipstick	113.7	2nd Gear 40km/h	Oil Dipstick	111.1
	Coolant Inlet	91.0		Coolant Inlet	84.0
	Coolant Outlet	111.0		Coolant Outlet	102.4
	Radiator Inlet 1	13.8		Radiator Inlet 1	10.7
	Radiator Inlet 2	15.5		Radiator Inlet 2	9.9
	Radiator Inlet 3	14.0		Radiator Inlet 3	10.1
	Radiator Inlet 4	14.5		Radiator Inlet 4	10.6
	Intercooler Inlet 1	16.0		Intercooler Inlet 1	10.4
	Intercooler Inlet 2	16.1		Intercooler Inlet 2	10.0
	Radiator Outlet 1	42.8		Radiator Outlet 1	44.6
	Radiator Outlet 2	87.9		Radiator Outlet 2	78.9
	Radiator Outlet 3	89.1		Radiator Outlet 3	83.2
	Radiator Outlet 4	86.2		Radiator Outlet 4	78.1
	Intercooler Outlet 1	45.8		Intercooler Outlet 1	40.1
	Intercooler Outlet 2	51.1		Intercooler Outlet 2	44.0
	ECU	32.2		ECU	32.4
	Underhood	55.2		Underhood	44.4
	Catalytic Converter	78.8		Catalytic Converter	65.9

#### 4.2 Tests with rear engine

During modification, because of the exhaust packaging problems, and since the vehicle had been designed as a front engine vehicle, the combined powertrain compartment was selected as a the first test setup. All following engine cooling tests were performed with the combined powertrain compartment.

Before performing the heat management tests, the engine was run until the engine oil temperature exceeded 90°C and the fan performed a minimum of one time. Fans are located at the back of the radiator, and take the air from the engine compartment and discharge to the back of the vehicle.

Test duration: 142 minutes (two simultaneous tests were performed = 71min x 2)

Ambient temperature: 8°C

Test weight: 2700kg

First test section : 22.6 min. (1st gear 25 km/h)

Second test section : 13.5 min. (2nd gear 40 km/h)

Third test section : 14.0 min. (2st gear 40 km/h return)

Fourth test section : 21.1 min. (1st gear 25 km/h return)

**Table 6**

Condition	Thermocouple Location	Maximum Temperature (°C)	Condition	Thermocouple Location	Maximum Temperature (°C)
1st Gear 25km/h	Oil Dipstick	107.9	2nd Gear 40km/h	Oil Dipstick	108.2
	Coolant Inlet	96.7		Coolant Inlet	96.8
	Coolant Outlet	97.8		Coolant Outlet	98.7
	Radiator Inlet 1	54.6		Radiator Inlet 1	57.4
	Radiator Inlet 2	50.7		Radiator Inlet 2	52.4
	Radiator Inlet 3	50.7		Radiator Inlet 3	39.2
	Radiator Inlet 4	36.5		Radiator Inlet 4	35.0
	Intercooler Inlet 1	40.9		Intercooler Inlet 1	43.1
	Intercooler Inlet 2	34.3		Intercooler Inlet 2	38.1
	Radiator Outlet 1	74.3		Radiator Outlet 1	70.5
	Radiator Outlet 2	72.4		Radiator Outlet 2	72.7
	Radiator Outlet 3	76.1		Radiator Outlet 3	74.1
	Radiator Outlet 4	46.6		Radiator Outlet 4	75.3
	Intercooler Outlet 1	48.0		Intercooler Outlet 1	46.2
	Intercooler Outlet 2	45.1		Intercooler Outlet 2	45.2
	ECU	35.5		ECU	29.4
	Underhood	56.6		Underhood	51.8
	Catalytic Converter	65.2		Catalytic Converter	44.1

#### 4.3 Comparison

According to the road tests, maximum engine coolant outlet and oil temperature differences between front engine and rear engine vehicles came out to be about 4°C (ambient temperature difference is about 4°C). But the maximum engine coolant inlet temperature differences were about 6°C and 13°C for 1<sup>st</sup> and 2<sup>nd</sup> gear tests, respectively. The temperature difference of the coolant through the radiator was lower for the rear engine vehicle than the front engine vehicle, which means heat transfer from the radiator is lower for the rear engine vehicle than the front engine vehicle. Air temperature increase through the radiator is lower for the rear engine vehicle, which supports the previous explanation. Radiator inlet air temperatures were higher and oil temperatures were lower for the rear engine vehicle since cooling air is taken from the bottom side of the vehicle after passing through the engine compartment. Underhood and ECU temperatures are very close to each other for 1<sup>st</sup> gear tests. For second gear tests, underhood temperature is higher for the rear engine vehicle since the air cannot flow through the small gap between the engine and firewall. As a result, rear engine vehicle cooling performance is very close to the front engine vehicle at 1<sup>st</sup> gear 25 km/h. When the vehicle velocity increases, cooling performance gets better for the front engine vehicle but remains the same for the rear engine vehicle. For the front engine vehicle, cooling air comes directly from the front of the vehicle and air velocity is equal to the vehicle velocity. But for the rear engine vehicle, air is supplied from the bottom air flow and directed to the radiator by the help of deflector plate. Since the engine compartment is not a sealed volume, air taken from the bottom of the vehicle escapes from undesired openings, especially halfshaft openings. Air flows between the tires and engine compartment faster than in the engine compartment. Therefore, air in the engine compartment escapes from the engine compartment to the outside through the halfshaft openings, which increases with increasing speed. This can also be eliminated with a small deflector design in front of the halfshaft openings.

## **5 FUTURE WORKS**

After completing heat management analysis and tests on the AP0 vehicle, styling and aerodynamic properties of the vehicle will be reviewed. Cooling analysis will be also modified according to the test results and a more detailed analysis model will be prepared.

Discharging air velocity and direction will be examined closely during the following analysis and prototypes. Air deflector design will be changed according to the external flow analyses, heat management analyses and tests. Besides the pedestrian and motorcycle drivers safety, air flowrate and direction effects on  $C_d$  will be also considered. Combined effects of the spoilers and discharging air on the drag coefficient will also be examined. Possible engine compartment and radiator compartment separation options will be studied. Air to boil tests will be simulated by using CFD tools and performed on the following prototypes by using a real engine.

## **6 CONCLUSION**

In this study, cooling system development studies of a new design rear engine vehicle were explained. First of all, powertrain cooling requirements and vehicle properties were presented. Afterwards, external and powertrain compartment airflow analyses were performed by using CFD tools. In the external analysis, drag coefficients were examined closely. Discharging air effects on the  $C_d$  were also investigated. According to the CFD analysis, cooling strategy was determined and applied to the first prototype. A front engine/front wheel drive vehicle was chosen as a donor vehicle and modified to rear engine/rear wheel drive vehicle. All heat management tests were performed for both configurations and both configurations show similar cooling performances at low velocities. But, at higher velocities, cooling performance of the rear engine vehicle remains the same because of the air deflector geometry and air leakage through the halfshaft openings, whereas the cooling performance with front engine gets better due to the direct relationship between vehicle speed and air flowrate through the radiator. This results show that, by means of special air routing and prevention of the air leakage with the help of small deflectors, a similar relationship between vehicle velocity and air flowrate should be realized.

## **7 REFERENCES**

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- 2 Prevost, C.P (2003), Radiator system for use on automobiles having rear engines, US6505696 B1
- 3 Brezek, R. (1948), Rear fender accommodation of radiator for rear engine vehicles, US2581072.
- 4 CATIA V5 R20, <http://3ds.com>
- 5 Ansys Fluent 12.1, <http://www.ansys.com>
- 6 Ricardo, 2008, New York City taxi of tomorrow RFI Appendix 1 Vehicle technical specification