MANIPAL INSTITUTE OF TECHNOLOGY
MANIPAL
(A constituent unit of MAHE, Manipal)

VI SEMESTER B.TECH. (PROGRAM ELECTIVE-II)

END SEMESTER EXAMINATIONS, MARCH 2024

VEHICLE AERODYNAMICS [AAE4038]

REVISED CREDIT SYSTEM

Time: 3 Hours	**Date: 08 May 2024**	**Max. Marks: 50**

Instructions to Candidates:
- Answer **ALL** the questions.
- Missing data may be suitably assumed.

QN.	Questions	*Marks/ Scheme*	*CO*	*BL*
Q1.	Analyse the influence of aerodynamics on fuel consumption of light road vehicles like car, for various parameters. May show the consumptions maps.	*4*	*2*	*4*
Q2.	Explain the boundary layer development theory for a viscous flow over flat plate.	*3*	*1*	*2*
Q3.	Illustrate the aerodynamic stability under sidewind across the vehicle.	*3*	*3*	*3*
Q4.	Analyse the impact of natural and artificial side-wind gust on stability of a vehicle.	*4*	*3*	*4*
Q5.	Compare the different components resistance on fuel consumption of a tractor semitruck.	*3*	*4*	*4*
Q6.	Discover the requirement of a wind tunnel for aerodynamic testing of a road vehicles, and the steps to follow the final design through it.	*3*	*5*	*3*
Q7.	Analyse the limitation of wind tunnels.	*4*	*5*	*4*
Q8.	Illustrate the Vehicle dynamics under side wind, and control system.	*3*	*3*	*3*
Q9.	Analyse the impact of yaw angle on drag of a semitruck.	*3*	*4*	*4*
Q10.	Analyse the construction of a Large full-scale wind tunnel by Daimler-Benz AG with approx. line diagram.	*5*	*5*	*4*
Q11.	Explore the influence of the Reynolds number on wind tunnel testing.	*3*	*4*	*3*

Q12.	Analyse how the air density impacts the aerodynamic drag over the vehicle.	***2***	***1***	***3***
Q13.	Analyse the methodology of wind tunnel simulation of a road vehicle with scaled models.	***4***	***5***	***4***
Q14.	Suggest the drag reduction of a commercial vehicle by add-ons.	***4***	***4***	***5***
Q15.	Discuss side wind sensitivity for a road vehicle.	***2***	***3***	***2***

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VEHICLE AERODYNAMICS [AAE4038]

ANSWER SCHEME

REVISED CREDIT SYSTEM

Time: 3 Hours **Date: 08 MaY 2024** **Max. Marks: 50**

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QN.	Questions	*Marks/ Scheme*	*CO*	*BL*
Q1.	Analyse the influence of aerodynamics on fuel consumption of light road vehicles like car, for various parameters. May show the consumptions maps.	*4*	*2*	*4*

Ans. The aerodynamic load has larger impact on the total resistance of the vehicle, with varying geometry and speed it varies a lot. Leading to a larger force to overcome the negative aero-force, leading higher fuel consummation.

4 marks for explanation (if diagram, 2 marks directly)

Often the specific fuel consumption diagram is not available at the time of calculation, particularly if theoretical variations of engine output are required. In this case hypothetical performance maps can be constructed by normalizing that for an existing engine. In effect, the mean effective pressure (MEP) and the engine revolutions n of this known diagram can be adjusted according to the ratio of the stated outputs of the engines. The hypothetical diagrams are therefore derived as follows:

Specific fuel consumption, $b_s = b_{so}$ Equation 1.68

Mean effective pressure, $MEP = MEP_o \, {}^{P_{stated}}/_{P_{stted\ o}}$ Equation 1.69

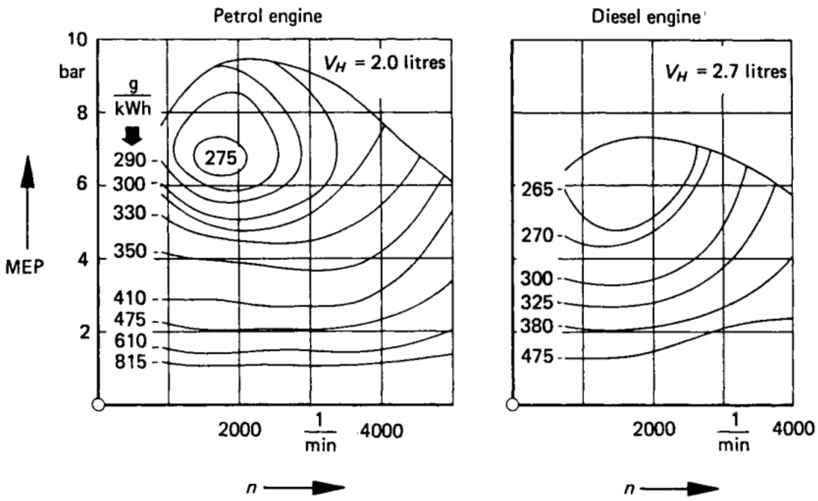
Engine speed, $n = n_o \, {}^{n_{stated}}/_{n_{stted\ o}}$ Equation 1.70

where the suffix 'O' refers to the values from the diagram of the existing representative engine. The fuel consumption on idle and the amount of fuel injected by the accelerator pump are adapted to suit the various engines using the following formulae.

Idle consumption, $B_I = B_o {}^{V_H}/_{V_{Ho}}$ Equation 1.71

Accelerators pump out, $B_A = B_{Ao} {}^{V_H}/_{V_{Ho}}$ Equation 1.72

where V_H is the displacement volume of the engine.



Q2. Explain the boundary layer development theory for a viscous flow over flat plate. ***3*** ***1*** ***2***

Ans

1 for explanation 2 for diagram or 2 for explanation and 1 for equation

- When a fluid flows over a solid, the intermolecular force or adhesion (between dissimilar molecules or molecules from different surfaces) act, which is mostly responsible for friction.
- It resists the fluid flow, in fact the fluid layer adjacent to the solid surface observes no motion. This condition is called no slip condition.
- The effect of friction decreases with thickness of fluid referring to Figure 1.13, and after a certain distance, it is equal to the streamline velocity V_∞.
- This minimum thickness δ is known as *boundary layer thickness*, within which flow is viscous and afterwards it is inviscid flow.
- The corresponding external flow has parallel streamlines and constant velocity V_∞, and pressure p_∞.
- The viscous flow within the boundary layer fulfils the 'no-slip' condition along the wall. In the front part of the plate the

boundary layer flow is steady and (almost) parallel to the wall.

- This state of the flow is called laminar. The thickness of the boundary layer increases downstream according to;

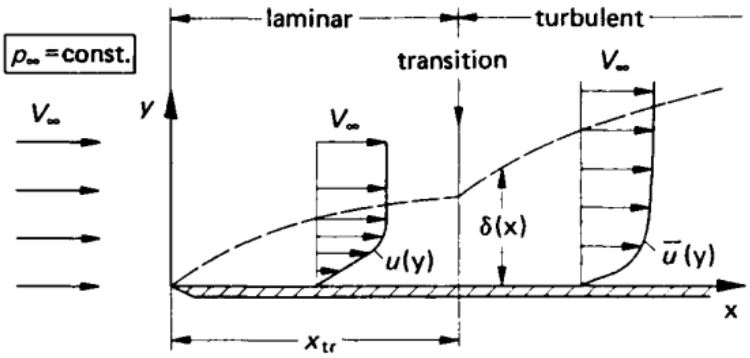
$$\delta = \sqrt{\left(\nu / V_\infty\right)} \times \sqrt{x}$$

Equation 1.28

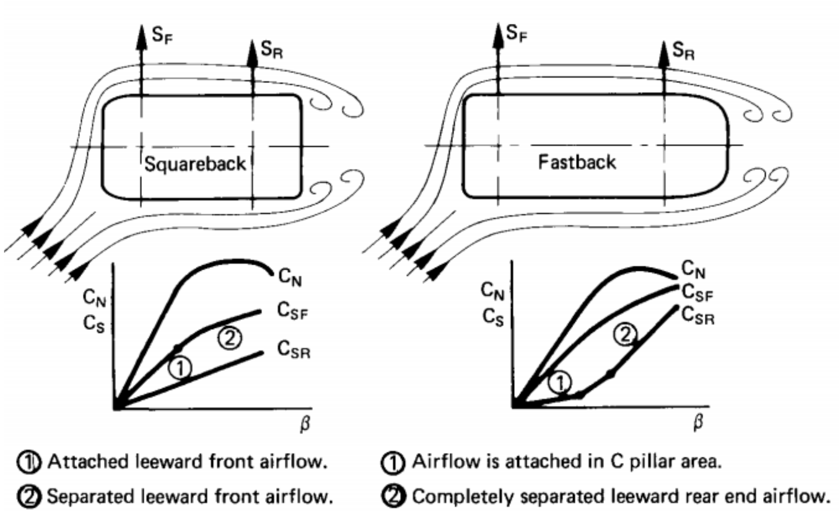
With increasing distance x and kinematic viscosity ν and with decreasing free stream velocity V_∞, the boundary layer thickness increases. The laminar state of the boundary layer flow is stable against disturbances for certain conditions only. At a distance $x = x_{tr}$ from the leading edge of the plate a transition to the so-called turbulent state of the boundary layer takes place. The transition between the two states of the boundary layer flow is largely governed by the value of the Reynolds number. For the flat plate, transition occurs around;

$$Re_{x_{tr}} = {V_\infty x_{tr}}/{\nu} = 5 \times 10^5$$

but this value applies only for a negligible pressure gradient in the external flow.



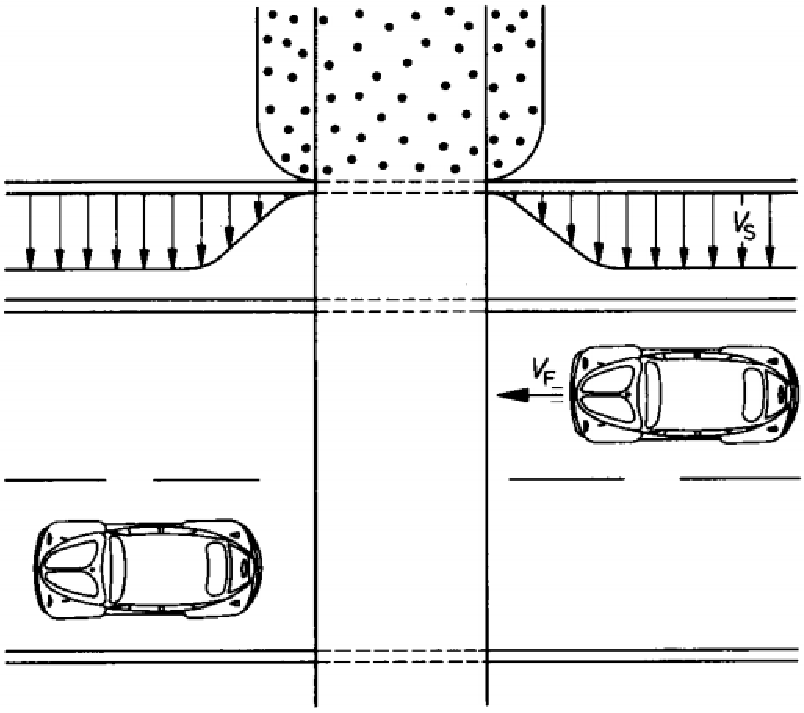
Q3.	Explain the aerodynamic stability under sidewind across the vehicle.	***3 3 3***
Ans.	The concentration of the negative pressures on the leeward side, at the front of the vehicle, is largely responsible for the aerodynamic yawing moment. This is the characteristic that causes instability. In other words, when side winds on a vehicle cause an angular deviation β (yaw angle), the effect of this aerodynamic yawing moment tends to increase the angle β further. From Figure 5.4 for small yaw angles, very high negative (suction) pressures occur at the leeward side of the vehicle's front end and the leeward A-pillar, whereas further downstream the leeward side exhibits low negative pressures only. For larger angles of yaw, the air flow separates at the leeward front fender corner and at the A-pillar, which results in smaller negative pressure peaks in these areas.	***3 for explanation without diagram, if diagram 2 for it***



Q4.	Analyse the impact of natural and artificial side-wind gust on stability of a vehicle.	***4***	***3***	***4***

Ans. It was stated above that the turbulence level of natural wind is of the order of unity: Tu ≈ 1. Thus, when the side wind has the velocity V, the speed can suddenly increase to 2V or drop to zero. The effect of natural wind squalling seems to be the same regardless of whether the cause is building development or vegetation (bushes, etc.). Whereas the constant side-wind conditions can be compensated for by a constant steering angle, the side-wind case cannot be anticipated and calls for sudden correction. It is therefore more dangerous.

2 for diagram 2 for explanation/ 3 for explanation without diagram

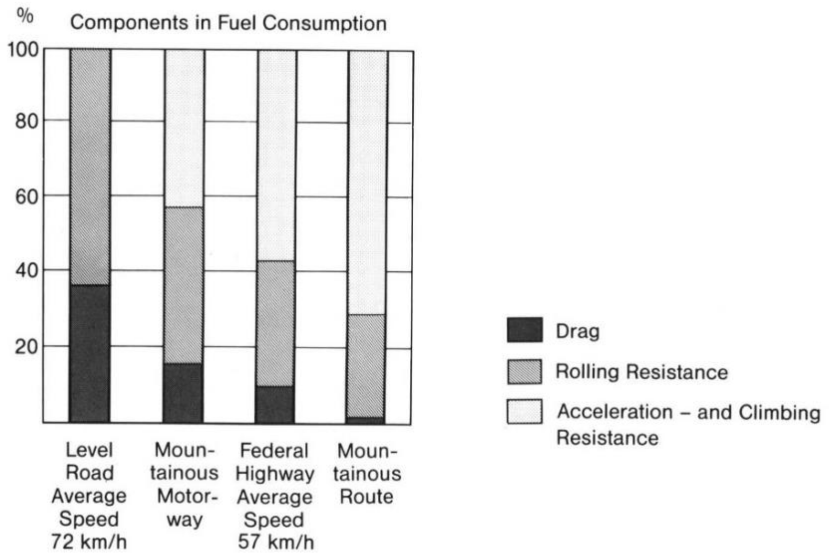


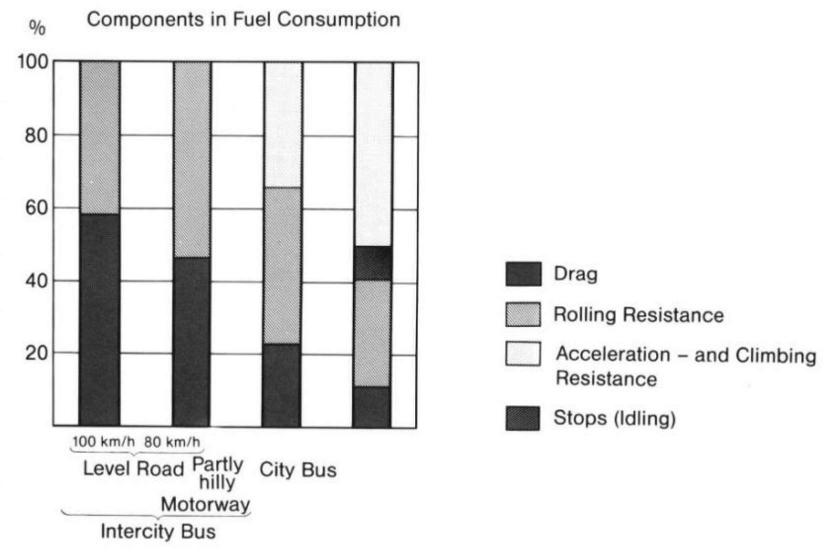
The same applies to driving between bridge abutments under side-wind conditions. Initially the vehicle moves in a constant side-wind area with an appropriate constant steering angle towards the wind. It then comes into the sheltered area adjacent to the bridge abutment, and the driver must then steer to the left in order to avoid driving off the right-hand side of the road. With this new steering angle, the vehicle is then again exposed to side wind from the right, which leads to a violent reaction by the driver.

Q5. Compare the different components resistance on fuel consumption of a tractor semitruck. *3* *4* *4*

Ans.

If diagram 3 for it or 3 for explanation with 1 diagram else 2





Q6. Explore the requirement of a wind tunnel for aerodynamic testing of a road vehicles, and the steps to follow the final design through it. *3* *5* *3*

Ans. **Requirements for a vehicle wind tunnel**

2 for the requirement, 1 for benefit

- Much development work is required to achieve the aerodynamic qualities and thermal characteristics of vehicles, as described in the previous chapters.
- In this work, the road is an important test instrument and in the

final analysis this is where the results must prove themselves.

- The wind tunnel is however an essential development tool, with which reality is simulated—but not duplicated.
- Before attempting simulation of this type, it is necessary to analyse the original phenomenon.

Advantages of a wind tunnel

- Accurate results to minimize assumptions.
- Opportunity for architectural expression.
- Construction savings for the owner.
- Improve earning potential with maximum floor space.
- Assurance – often recommended by code.
- Increased litigation protection.

Q7. Analyse the limitation of wind tunnels. ***4 5 4***

Ans. **Limitations of simulation** ***2 marks to any two points***

a) Air flow quality

- A uniform velocity distribution over the cross-section of the air stream is not only important for simulation but also to facilitate comparison between tunnels.
- With a contraction ratio of K = 4 and correct nozzle design, a velocity distribution can be achieved in which the local velocity does not deviate more than ±1 per cent from the mean velocity except at the edge of the jet.
- This is sufficient for automobile aerodynamics purposes. It is important that the wind tunnel air stream be aligned precisely relative to the test vehicle. In automobile wind tunnels, the boundary layer which forms on the ground plane increases the effective angle of attack.
- The angle of attack has a considerable influence upon the drag, particularly when edge radii are optimized.
- Asymmetries in the chamber surrounding the test section of an open-jet wind tunnel can produce an angle of yaw in the wind tunnel stream.
- As long as this remains small it has only a slight influence upon the drag. However, a precisely directed jet is required for exact determination of the lateral forces and moment.
- Despite the extra cost it is best to make the wind tunnel nozzle adjustable so that the air stream can be set to the exact

direction.

b) Ground plane boundary layer.

- The relative motion between the road and vehicle is simulated only in exceptional cases.
- As a rule, the level floor of the test section is used as the road.
- As a matter of principle, the boundary layer that forms on the floor of the test section results in a different flow field than during driving on the road.
- A series of suggestions have been made to improve the simulation of the road in wind tunnels.
- One solution to this simulation task is the use of a running belt.
- However, the support of the model over the moving belt presents difficulties, particularly with large and heavy models.

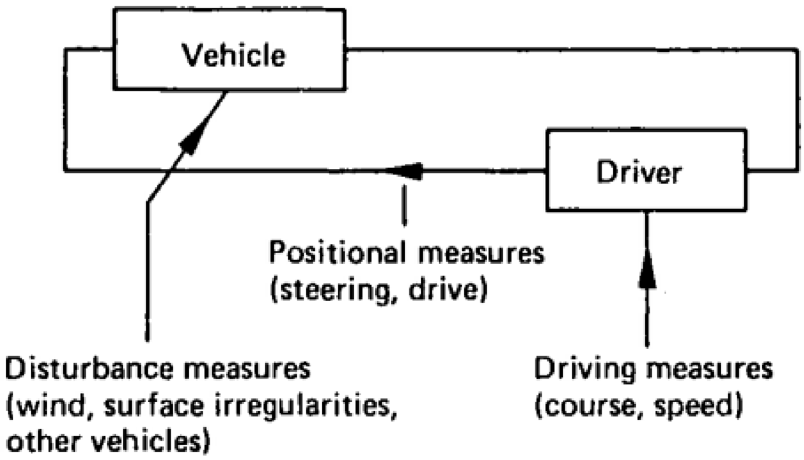
c) Air flow blockage, streamline deformation, pressure gradient

- The flow of air around a vehicle in the wind tunnel is influenced by the flow conditions existing at the boundaries of the jet.
- The closer these boundaries are to the model the more the flow around the model is changed, compared to an infinitely large jet cross-section.
- In a closed test section, the streamlines around the vehicle are forced closer together, in an open test section they widen out. In the first case, the effective approach velocity is greater, in the second less than that at the nozzle.
- Without correction, this leads to drag coefficients which are too large in a closed test section and too small in an open test section.
- The same applies for all of the other force and moment coefficients.

Q8. Explain the Vehicle dynamics under side wind, and control system. ***3 3 3***

Ans. No general definition exists for the side-wind sensitivity of vehicles. In most of the many studies into this problem the effect of side winds on vehicles has been established either from test results or with the help of computer models. To represent the side-wind sensitivity phenomenon completely, the driver must also be taken into consideration. The relationship between the driver and the vehicle, ***3 for explanation***

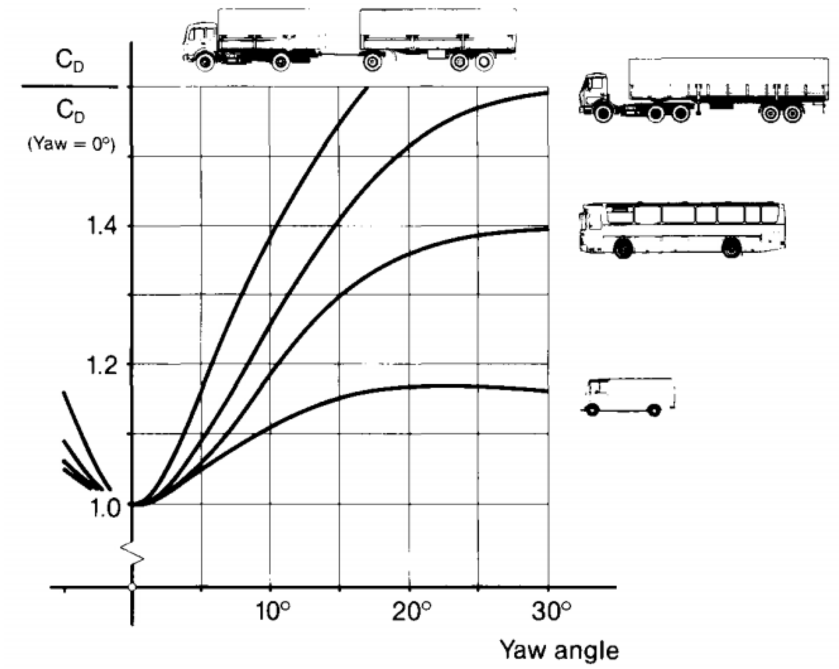
must be fully understood. The necessary investigation is however complicated by the fact that the driver is an adaptive controller; that is to say, he or she adapts to the characteristics of the vehicle being driven. There are so many unknowns about driver adaptability that the driver/vehicle system cannot yet be fully explained theoretically.



Q9. Analyse the impact of yaw angle on drag of a semitruck. *3 4 4*

Ans. The drag coefficient at zero yaw angle, equivalent to driving in still air, gives insufficient indication of aerodynamic characteristics in real operation, where the tangential force coefficient cT (due to yaw) must be taken into account (Figure 0.11). All vehicle types—with the exception of the light van—show a marked increase in cT with increasing yaw angle.

No diagram needed, 3 for explanation

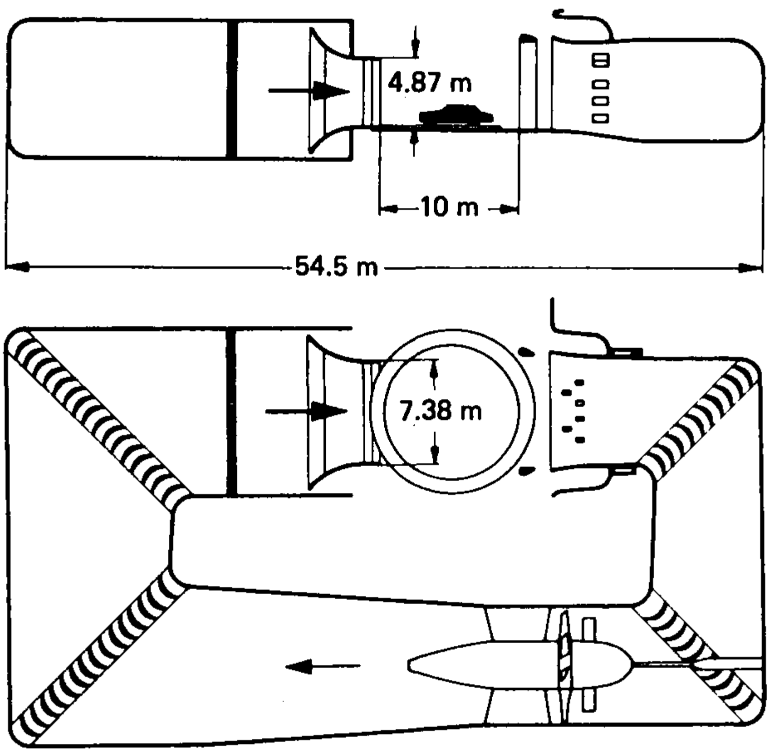


Q10. Analyse the construction of a Large full-scale wind tunnel by Daimler-Benz AG with approx. line diagram. *5 5 4*

Ans. **Daimler-Benz AG wind tunnels**

3 marks for diagram if present & 2 for explanation/ without diagram max 3 for explanation

- This wind tunnel was designed under the direction of W. Kamm, opened in 1939 as part of the Forschungsinstitut für Kraftfahrwesen und Fahrzeugmotoren (FKFS), Stuttgart, Germany, and was completely overhauled in 1977, when it was taken over by Daimler-Benz AG.
- This wind tunnel is distinguished by an exceptionally high blowing velocity of V_{max} = 270 km/h. Such a high velocity is an advantage for the development of fast vehicles; it is then possible to directly examine the position of the vehicle resulting from the air forces and moments, and the effect of such changes upon the aerodynamics even at top speed.
- For comparison, Fig. 0.18 shows the large climatic wind tunnel at Volkswagen AG in Wolfsburg, Germany. This tunnel can be fully air conditioned; it is exceptionally well suited for all motor vehicle aerodynamic purposes.
- The limitation of the wind speed to V_{max} = 180 km/h is reasonable for a manufacturer of passenger cars and small vans, particularly as Reynolds number influences are unlikely and have never been observed for such high velocities.



Nozzle cross-section: 32.6 m^2
Maximum wind speed: 270 km/h
Fan power: 4000 kW

Q11. Explore the influence of the Reynolds number on wind tunnel testing. ***3*** ***4*** ***3***

Ans. In addition to the requirement for geometric similarity, the flow around the model and the full-scale version must be mechanically similar. For incompressible flow this condition is fulfilled when the Reynolds numbers for the scale model and full-scale version are equal. The Reynolds number is defined as

3 for explanation

$$Re = {V_\infty l}/{\nu}$$

V_∞, is the velocity of the undisturbed oncoming flow, *l* the length of the vehicle and ν the kinematic viscosity of the working fluid. Mechanical similarity is therefore present when the following equation is true:

$$ {V_1 l_1}/{\nu_1} = {V_2 l_2}/{\nu_2}$$

Since, as a rule, model testing is accomplished in air (tests in water tunnels are seldom performed on vehicle models) the requirement for mechanical similarity is satisfied when the products of the velocities and lengths are equal.

This condition is generally not maintained in tests on models with a scale of 1:4; the Reynolds numbers amount to one-quarter to one-half of the value of the full-scale version.

Since the drag resulting from friction is small in comparison to the drag resulting from pressure for motor vehicles it could be assumed that the influence of the Reynolds number is small within the stated Reynolds number range. In fact, drag measurements on vehicles exist that show hardly any Reynolds number influence. However, the following two examples show that serious errors can result through violation of the Reynolds law of similarity.

There are two ways to achieve the Reynolds number of the large version with scale models. Frequently the suggestion is made to increase the model scale but this would require a larger model wind tunnel. The advantage of the easy-to-handle model and the ease of quickly modifying the shape are rapidly lost with increasing dimensions. Limits therefore exist in this direction. In practice the largest model scale used for passenger vehicles is the 3/8 scale. On the other hand, a frequent suggestion is to increase the air stream velocity in the model wind tunnels. Figure 0.16 shows that there is little scope for this either. Due to the bluntness of the vehicle body, greatly increased velocities are reached at individual points of the vehicle contour. As calculations and measurements on elliptical bodies of revolution and cylinders show, the critical Mach number, i.e. the Mach number for undisturbed oncoming flow, at which the speed of sound is first reached locally at the contour of the body, is reduced to very low values with increasing bluntness. Even below the critical Mach number the drag begins to increase due to compressibility effects. For vehicle shapes, this is probably much more difficult to calculate than the influence of the Reynolds number upon the local separation.

Q12. Analyse how the air density impacts the aerodynamic drag over the vehicle. ***2*** ***1*** ***3***

Ans. The increased density increases mass concentration or viscous loading over the vehicle surface, leading to higher drag, and hence larger fuel consumption. Use Reynolds explanation. ***2 marks***

Q13. Analyse the methodology of wind tunnel simulation of a road vehicle with scaled models. ***4*** ***5*** ***4***

Ans. Even today, many tests are still performed on scale models. These tests are comparatively inexpensive; a further advantage is the handiness of smaller models for transport and for shape modifications. The most common scale in Europe for passenger cars is 1:4, though in small model tunnels 1:5 is also used. In the USA the '3/8 scale' is most common. For commercial vehicles a scale of 1:10 is popular. If a large wind tunnel is available, 1:2.5 is selected. However, in the development of passenger cars the use of reduced scale models is decreasing because the transferability of model tests to full-scale is uncertain; this is discussed in greater detail in the next section. Also, designers prefer working on full-size models; judging the shape of scale models is very difficult. Details in the shape such as indentations, curvatures, window recesses, tyre beads and welts are overemphasized as a rule on scale models. On full-scale models, which represent the basis for model selection and later design, these exaggerations are reduced. Therefore, one of the basic prerequisites for performing tests on scale models, the geometrical similarity to the full-scale version, is not fulfilled. However, if the wind tunnel model is produced by reducing the size of an existing full-scale model this problem is eliminated. A scale of 1:4 is then just large enough to reproduce all of the primary details to scale. ***4 marks for explanation, 1 per step***

Since the underside of the vehicle has a great influence upon the flow of air around the vehicle all of its significant parts must also be represented. Full-size models are generally built on an existing (reinforced) chassis; in this manner the flow of cooling air through the vehicle can also be simulated, an absolutely necessary prerequisite for optimization of the front of the vehicle. Since the vehicle position has an influence upon the flow of air around the vehicle, it must be fixed precisely and adjusted for reproducibility. There are two possibilities for testing a vehicle in the ready-to-drive state: either the suspension is fixed in a given position, or the suspension remains free. In the latter case the vehicle is loaded with one half of the maximum permissible load so that it is in the design position. According to the aerodynamic forces and moments, the vehicle will adopt a similar attitude in the tunnel as when driving on the road. However, as a rule the suspension is fixed for tests on full-scale models. Models are considerably heavier than the finished vehicle, so that the effect of the air forces and moments on the vehicle position would be unrealistic.

Q14.	Suggest the drag reduction of a commercial vehicle by add-ons.	***4***	***4***	***5***

Ans.

- Tractors are operated with a variety of different trailers. Low drag of the cab alone does not guarantee low drag for all truck-trailer combinations. For high bodies, therefore, a whole range of add-on devices for reducing air drag have been developed.
- **For cab mounting, head and side wind deflectors or adjustable air shields have proved to be effective. The latter are easy to fit, effective and cheap.**
- Devices mounted on the body, for instance fin-like vortex stabilizers on the front wall, which by vortex formation reduce the flow of air between cab and body in crosswinds, or half-balloon-shaped airfoils, help to reduce overall drag.
- For trucks with sharp-edged cabs wind-deflecting devices can reduce drag by up to about 10 per cent, while for low drag versions up to 30 per cent reductions are possible with relative wind from directly ahead. With increasing angle of yaw, appreciably smaller drag coefficients are realized with bulbous fairings on the front of the body than with an air shield.

2 each for any two techniques

Q15.	Explain side wind sensitivity for a road vehicle.	***2***	***3***	***2***

Ans. In side-wind conditions the additional components of side force and yawing and rolling moments develop. The resultant air forces and moments must be balanced by the reaction forces between the vehicle and the road, gripping through the tyres. The resulting tyre slip angles lead to a deviation from the required direction of travel which must be compensated for by the driver via the steering. The above phenomenon, which is often referred to as side-wind sensitivity.

2 marks