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开放式喷射汽车风洞的尺寸和效率

E. MERCKER，R. BLUMRICH，J. WIEDEMANN，F. WITTMEIER
（斯图加特汽车工程与车辆发动机研究所(FKFS)，斯图加特 70569，德国）

摘要：近年来，世界各地汽车企业已建成许多汽车风洞，并在不久的将来会有更多汽车风洞的规划与建设。在风洞规划设计阶段确定的许多功能与参数决定了其整个运行生命周期，并影响建设和运行成本。本文研究通过适当选择3/4开口风洞的试验段几何尺寸，可以使早期的传统风洞中因有限截面发生的流动干扰在很大程度上得到补偿或减少到可忽略不计的程度。研究表明：对于具有不同堵塞度的各种车辆，流动干扰误差出乎意料地可以忽略，因此不需要对试验数据进行修正，这使得汽车风洞试验形成"自由"气流条件；试验阶段的初步尺寸可以比如今常见的情况小很多，也不影响测量结果的准确度，这带来了更低的建设成本，也降低了风洞系统运行的能源需求；自由射流的不稳定性必须被考虑，且射流长度不应该超过某个上限。

关键词：汽车风洞；干扰效应；车辆空气动力学
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Size and Efficiency of Open Jet Automotive Wind Tunnels

E. MERCKER，*R. BLUMRICH* ，*J.WIEDEMANN*，
F. WITTMEIER
(Research Institute for Automotive Engineering and Powertrain Systems Stuttgart (FKFS)，70569 Stuttgart，Germany)

Abstract：In recent years，a number of new wind tunnels for the automotive industry have been built across the world，and more such facilities are planned for the near future. Many decisions made in the early planning phase of the wind tunnel shape the facility throughout its operating life and contribute to both the construction and operating costs of the wind tunnel. The intent of this paper is to outline that with an appropriate choice of the test section geometry of 3/4 open-jet wind tunnels. The flow interferences that occur due to the finite cross section of the jet in a conventional wind tunnel can be largely compensated for or reduced to a negligible extent. It is shown that for a wide range of vehicles with varying degrees of blockage，residual interference becomes surprisingly negligible，so that a correction of the measured quantities is not required and conditions of "free" air flow are generated in the test section. Furthermore，it is shown that the coarse dimensions of a test section can be much smaller than is often the case today without affecting the quality of the measurement results，which leads to lower construction costs，but above all to lower energy requirements for the operation of the system. It is shown that the instabilities of the free jet must also be assumed，which results in an upper limit for the jet length that should not be exceeded.

Key words：automotive wind tunnel；interference effects；vehicle aerodynamics

It is well established that the finite size of wind tunnel test sections，whether 3/4 open-jet or closed-wall，induce force components on an automobile under study that will not occur on the road. These extraneous quantities must be avoided or removed to accurately represent on-road conditions in an unbounded flow field and to ensure that the same results are obtained for the same vehicle in different wind tunnel facilities. The remaining aerodynamic interferences can be influenced by the appropriate choice of geometric dimensions of a wind tunnel test section. To achieve this，there are three different possibilities：

（1）The dimensions of the test section are large enough so that interferences are negligible.

（2）Interferences are calculated on a theoretical base and used to correct the test results.

（3）The dimensions of the test section are weighted against each other in an optimization process so that the net-interference is negligible. The

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第一作者：E. MERCKER(1988—)，男，汽车工程硕士，主要研究方向为车辆空气动力学。

procedure is a multiple parameter variation.

The aim of this study is to ultimately offer the development engineer a test section according to the approach mentioned in (3) whose measurements correspond to those on the road with a high degree of agreement. A similar approach was already proposed by Wickern[1] in 2014 on a purely theoretical basis. In the current paper, the various interference effects are calculated not only using somewhat different potential flow-theoretical approaches, but also using iterative approximation methods that make it possible to effectively differentiate the various influencing parameters in more detail.

A number of scientific publications in recent decades show that interference effects can be calculated reliably on a theoretical base and the resulting distortions can be compensated for by a mathematical algorithm[2-4]. The interference effects on the test vehicle are due to the influence of the nozzle, the collector, the jet expansion and the static pressure gradient of the empty test section.

In order to apply the algorithm, the physics of interference effects needs to be well understood. Thus, for the development engineer concentrating on the optimization of his aerodynamic tasks it would be desirable if the net-effects of the interferences are negligibly small and no correction procedures need to be executed online or by post processing.

In this context, it is interesting to show how the main dimensions of a 3/4 open-jet test section, namely the nozzle cross-sectional area and test section length, have changed over the last 30 years using various existing wind tunnels as examples. In Fig. 1, both parameters are plotted over time. It is discernible that there is a trend towards larger nozzle sizes and test section length.

Since the individual interference effects have different signs, it seems sensible to optimize the geometric dimensions of the various wind tunnel components starting with the test section first. The extent to which such optimization is possible is shown in this paper. Because of the electrical power consumption of the fan, the diffuser angles in different parts of the flow-return circuit, the turning

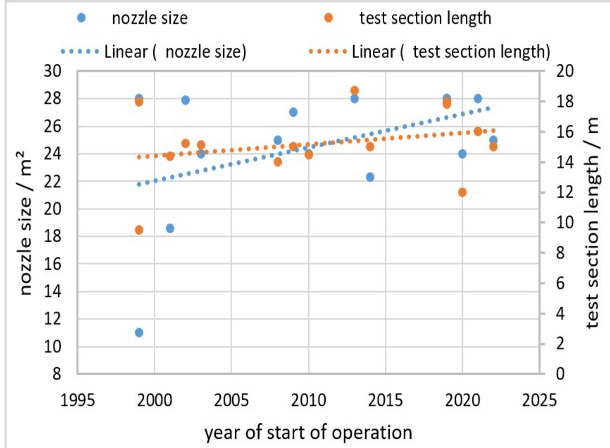

Fig.1 Nozzle size and test section length over time as built

vanes and the pressure losses due to other important internals in the return pipe depend essentially on the geometrical dimensions of the test section. Therefore, this paper focuses on the optimization of the interaction of the test section components. When designing a wind tunnel system from scratch in such a way that the interference effects compensate each other down to an acceptable level, it needs to be shown then that this also remains valid for the entire current and future vehicle fleet to be tested. In this case the construction costs and operating costs, as well the required footprint for wind tunnel building can be considerably reduced in comparison to a larger facility.

1 Jet stability and test section length

In principle, omitting the application of a mathematical approach would lead to wind tunnels with long test sections because the collector-wake interference is reduced then. In addition, the effect of a static pressure gradient already present in the empty test section can be reduced in the proximity of the vehicle in this way. However, in order to ensure stability of the 3/4 open jet of an automotive wind tunnel test section, the cross-sectional area of the nozzle must be increased in the same way, which superficially offers the advantage that the open jet solid-body interference is reduced too.

Moreover, the nozzle effect can be minimized by placing the vehicle at a sufficient large distance from the nozzle exit plane. The remaining overall interference can indeed become small. However, this would definitely be at the expense of construction costs of the facility and operating costs for the wind tunnel in total. Going to the extreme this means that an infinite large wind tunnel generates no interference effect at all. This is exactly the approach which is followed for CFD when road driving is simulated numerically.

If the length of the test section is increased without increasing the size of the nozzle, a new problem is created, which influences the stability of the 3/4 open jet.

A target value for the jet stability is then $L_T/H_D < 3$, where L_T denotes the test section length and $H_D = 4A_N/U_N$ is the hydraulic diameter of the nozzle, with A_N = nozzle area and U_N = wetted circumference of the nozzle. To calculate the jet stability for a 3/4 open jet with ground plane, as commonly used in automotive wind tunnels, the wetted circumference of the nozzle is the sum of the ceiling width and the two sides of the nozzle on which a flow shear layer is formed respectively.

In this context it is remarkable that for the aerodynamic specification of a wind tunnel the stated stability criterion is hardly considered and often not mentioned explicitly in the design documents, although the stability of a free jet is of serious importance for the quality of the measurement results. Additionally, it determines the upper limit of the test-section length.

The background for this statement is the fact that within the 3/4 open jet with ground plane, coherent vortex structures are formed in the shear layer, which resonate with the natural frequency of the flow return circuit of the wind tunnel. Additionally, further downstream in the shear layer, a so-called vortex pairing mechanism takes place, which on the one hand influences the thickness of the shear layer and on the other hand reduces the passing frequency of the vortices floating downstream towards the collector. Both mechanisms lead to lateral flutter of the jet and a prevailing horizontal pumping within the potential-flow core of the jet, whenever a vortex is passing by. In contrast, vertical flutter is largely prevented by the presence of a floor plane.

The effect of the described mechanisms takes place in the low-pass regime of the excitation frequencies and is superimposed on to the vehicle, which in return alters the rms-value of the measured aerodynamic coefficients and which must be avoided. The effect itself grows with the length of the test section in relation to the nozzle area. Some experimental results describing the effect can be taken from the Ref. [5]. A pragmatic solution to the problem is to avoid coherent vortex structures within the shear layers. This can be achieved by installing small vortex generators at the periphery of the nozzle. The disadvantage is, however, that the vortex generators produce noise and negatively influence the static pressure of the empty test section.

Since the range of tasks of automotive wind tunnel has expanded over the last 30 years to include also the aspect of acoustic measurements on vehicles, vortex generators are hardly in use any longer. Therefore, FKFS has gone a different way and developed the FKFS ***besst***® system, a few years ago[6]. The system consists of a series of wall- and ceiling-mounted flow directing elements fixed inside the nozzle. This arrangement creates small longitudinal line vortices (swirls) that continue into the shear layers of the jet and prevent the formation of coherent vortex structures. The nozzle elements have proven to be very effective. Moreover, they showed a slight decrease in background noise level in the test section and additionally, a small generated static pressure gradient may be used to compensate for a possible pressure gradient due to a floor boundary layer control system in the nozzle exit region.

In summary, it can be stated that for the optimization of the test section dimensions, the stability criterion for open jets, as explained above, defines the upper limit for the length of the test section. The remaining interference effects, on the other hand, determine the *necessary* length of the test section. This is important to recognize, since e. g. , the magnitude of the positive collector interference is test section length-dependent and can be partly compensated by a corresponding interference due to a negative open jet-expansion.

In total, the interference effects will be influenced by the size of the nozzle and the collector, the overall length and size of a vehicle, the position of the vehicle inside the test section, the frontal area and the rear end configuration of the test car. Another effect, concerning the empty test section pressure gradient, plays an important role on the necessary length of the test section also. However, this subject will be discussed below.

2 Nozzle-plenum interference

Since the time when the importance of interference effects in open jet wind tunnels was recognized, it was often difficult to quantify the influence of the nozzle on the measurement results. Only by taking into account the simultaneous measurement of nozzle and plenum method to determine the approach flow velocity to the vehicle, it was possible to determine experimentally and by a numerical iteration process the ram effect of the flow into the nozzle due to the presence of the vehicle in the test section[3-4]. Only for small vehicles positioned far enough away from the nozzle exit, the nozzle and plenum method reveal identical results. It is noteworthy that the nozzle method usually assumes lower values for dynamic pressure of the approach flow (and thus a higher drag-coefficient) than with the plenum method. However, depending on the frontal area of the vehicle the plenum method yields a lower dependency on the distance between nozzle and vehicle than the nozzle method. The effective nozzle effect can be determined iteratively using both methods, unless an entire theoretical approach may be chosen[7]. However, the experimental approach offers the advantage that model-related parameters, such as cooling air open or closed, are automatically recorded.

In this context it should be realized that after the optimization process is finalized the measuring position of the vehicle should not be altered, which is the distance between nozzle exit and half the vehicle wheel base at the center of the turntable. The nozzle effect is often the smallest contributor to the interference phenomenon, unless vehicles with a very large frontal area are investigated (blockage ratio > 20%). This is a fact at least for the plenum method, which is often used to determine the tunnel velocity. The reason for this is the fact that the plenum method is less susceptible to interferences exerted by the vehicle on the pressure measurements at the surrounding plenum-wall of the 3/4 open jet. With the nozzle method, on the other hand, the pressure reference points located inside the nozzle can be influenced by the ram effect of the flow for large blockages in the test section. The extent to which this applies can be determined experimentally during the calibration phase of the test section. For this purpose, the pressure difference between settling chamber and nozzle tap (speed hole) is measured with a vehicle installed inside the test section. Then the vehicle is moved in upstream direction step by step with the fan speed kept at constant rpm. As soon as the pressure difference starts to decrease the speed hole is contaminated by the stagnation effect of the vehicle which should be avoided. Note: the described effect should not be confused with the nozzle interference-effect as described above.

3 Collector-wake interference

In some respects, the collector effect works similarly to the nozzle effect. The difference lies in the fact that now the wake of the vehicle triggers an interference effect. Here, the far field wake of the vehicle basically enters the collector at all times and creates interferences at the vehicle just as the vehicle would be measured in a closed test section. However, depending on the distance between the rear end flow separation area of the vehicle and the collector, the near field wake of the vehicle can also partially enter the collector and generate interferences on the vehicle. This occurs due to the fact that the blockage effect (which in this case is a flow gradient effect) deforms the wake and thus changes the pressure distribution at the rear end face of the vehicle. Comparing near field wake and far field wake, it is the far field wake, which is by far the smaller contributor to the interference effect.

The biggest problem to determine the collector effect reliably is connected with the fact that the near wake of vehicles is completely, partially or not at all absorbed by the collector, depending on the test section length and vehicle size. A. Henning[8] proposed an empirical logistic sigmoid function to determine to which degree the near wake is absorbed by the collector with good accuracy. A repeat calculation of a comparison test of different vehicles in different wind tunnels revealed a standard deviation of the corrected drag coefficients of ±1 drag-count, which can be regarded as fully sufficient. The greatest challenge for the optimization process of the test section is the fact that vehicles with a large frontal area usually have a larger vehicle length also, which increases the collector effect. This plus the nozzle effect must in turn be balanced by a correspondingly large solid-body interference effect, which is discussed next.

4 Open-jet boundary interference

The flow in an open-jet wind tunnel over-expands as it passes the vehicle, resulting in a reduced speed at the test object compared with the value measured upstream. Thus, also the drag coefficient is reduced, since it is referred to the undisturbed approach flow velocity. In order to calculate the interference-effect the eccentricity of the vehicle positioned at the tunnel floor has to be considered. To do this a mathematical trick is needed by applying the so-called duplex-model and duplex-nozzle set up. The vehicle and the nozzle are mirrored on the floor plane, which results in a symmetrical model position within a theoretical test section of doubled size. The model is now in the center of a fully open jet, and the infinitely thin tunnel floor is part of the model.

In this way, the so-called tunnel shape factor τ is determined, which influences the solid body interference to a large extent. The factor itself is determined using the so-called fluid dynamic mirror image technique The procedure can most conveniently be taken from the relevant Ref. [9], already published by A. Theodorsen in 1933.

An interesting fact here is that the tunnel shape factor t can be used to influence the magnitude of the interference via the height-to-width ratio of the nozzle. The maximum ratio of t between a square and a rectangular nozzle is about 2, which means that by choosing the nozzle aspect ratio, the jet expansion effect can be doubled and thus, there is a large variability in the effort to keep the other interference effects in balance. Regarding the effect of the vehicle in the test section, it is important that the near-field wake of the vehicle is also included in these considerations, since similar to the solid body of the vehicle, a displacement of the flow by the near-field wake occurs and thus contributes to the jet expansion[7]. Once the tunnel shape factor has been established, it is desirable not to change the height-to-width ratio of a nozzle depending on the external shape of a vehicle. As will be shown later, this is not necessary as the optimization process achieves a low variance of the net-interference for a wide range of vehicles. The reason for this is that as the vehicle size increases, the negative jet expansion effect increases as well, but similarly the positive collector and nozzle effect also grow.

5 Pressure gradient interference

This effect is caused by a gradual pressure rise that occurs as the open-jet flow in the empty test section expands and decelerates into the collector, generating a so-called horizontal-buoyancy effect about the vehicle when placed in the test section. Depending on the length of the test section the interference effect on the solid body of the vehicle and its wake can have a dominant effect on drag, lift and pitching moment[4, 10]. This effect has to be treated differently from all the other effects discussed so far.

In order to calculate the magnitude of this interference effect the concept of a wake sensitivity length has been introduced, which is determined by an iteration process between two repeated test-runs within different pressure gradients[4]. The sensitivity length is than a characteristic measure, which determines the location at which a static pressure in the empty test section is taken to calculate an interference force component. The theory behind this procedure can be found in the literature under the authorship of K. Cooper, E. Mercker and J. Müller[11].

Instead of applying sequential measurements in two different static pressure gradients a more efficient way would be to adjust the intake area of a collector in such a way that the pressure rise in front of the collector is reduced. However, this presupposes that the collector is flexible to a certain extent in the way that the side walls and ceiling can be adjusted such that the static pressure gradient of the empty test section remains constant over the length of the largest vehicle to be tested including the sensitivity length of the near wake. In this way the effect of a static pressure gradient in the empty test section can be neglected for all vehicles.

It is noteworthy that a positive or negative pressure gradient can also occur after the flow exits the nozzle. The reason for this behavior of the jet can be seen in an angularity effect of the flow. The so-called entrainment flow from the surrounding plenum hall into the early shear layer at the edge of the free jet is then disturbed, so that a certain relaxation length is needed to adapt to the surrounding static pressure of the plenum hall. In this context, it is important that a possible static pressure gradient has decayed up to the position of the vehicle front.

Since the effects described can be achieved by fine-tuning the geometry of the collector and nozzle, the effect of a static pressure gradient is not taken into account in our optimization process.

6 Case study for the optimization of 3/4 open-jet interferences

As mentioned above, a multiple parameter variation of the dimensions of the test section is chosen for the analysis in this paper. But the approach would make sense only, if the result is valid for the entire spectrum of current and future vehicle types to be tested in a wind tunnel. The starting point of such considerations are initially vehicles of a van-type with a large frontal area, vehicle length and displacement volume, because then the degree of blockage of the test section and thus, the interferences become largest. The amount of occupancy time spent in the test section is usually rather low for such vehicles and sums up in comparison to other vehicle types to perhaps 10% to 15%, only.

Nevertheless, it is important for a wind tunnel user that such vehicles are also be included in a possible test spectrum. And also, if the optimization process is successful for high blockage vehicles there is hope that it also works for smaller cars, which will be shown further below. In the extreme case of an infinite small model all interferences will finally cancel out.

Starting from a high blockage end for a vehicle selection we choose an existing box shaped van with a frontal area of 5.2 m^2 and an overall length of 6.3 m, as specified by the manufacturer, which we denoted as Van-4 in our further discussion. The vehicle has a width of 2.1 m and a height of 2.6 m (e.g., raised car roof for more loading space). This reveals an aspect ratio of 0.8 (width to height ratio of car) for the vehicle. As a next step, the inverse of this aspect ratio is transferred for flow symmetry reason to the nozzle cross-sectional area and is used to determine τ, the tunnel shape factor.

The starting point of our iteration process is carried out with the described vehicle. At a later stage it needs to be proved to what extent the assumptions made have an impact on different vehicles and whether a negligible net-balance of interference effects is achievable. A satisfactory result would be a final outcome with an absolute bandwidth of ± 1.5 drag-counts for the net-interference for all cars investigated.

As a next step, it is important to determine the nozzle exit area, as this determines the blockage ratio on the one hand and with the stability criterion of the free jet, the test section length can be derived iteratively.

For this purpose, we again use Van-4, which, as the largest vehicle examined, provides us with an initial estimate of the necessary test section length. It is determined from the vehicle position in the test section, the vehicle length, the sensitivity length of the near field wake and the relaxation length for the static pressure of the empty test section. The variable parameter in this process is the distance from the nozzle to the center of the vehicle. In anticipation of a detailed analysis that includes the nozzle effect, the collector effect and the jet expansion effect, Fig. 2 shows the net.

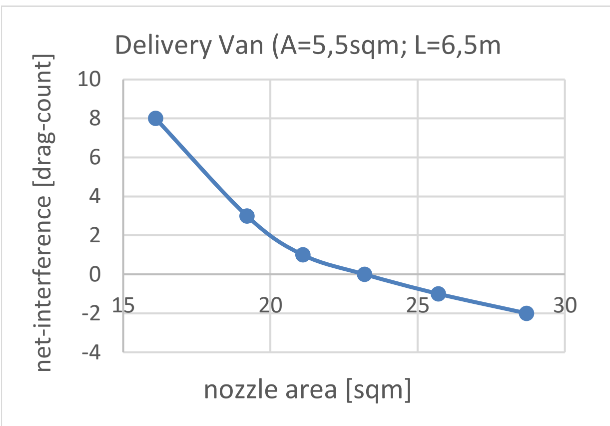

Fig.2 Net-interference versus nozzle area: Van-4; model center at 4.5 m from nozzle; collector-nozzle ratio 1.5; test section length 12.7 m; nozzle aspect ratio 0.8

influence for the nozzle, which assumes a value of zero for an optimal cross-sectional area of 23. 2 m^2. The vehicle center was placed at 4. 5m downstream of the nozzle and the area ratio of collector to nozzle was assumed to be 1. 5, a typical value for wind tunnels of that size.

Assuming the stability criterion $L_T/H_D<3$ of a 3/4 open jet, the test section length is a consequence of the cross-sectional area of the nozzle and the corresponding hydraulic diameter with an aspect ratio of 0. 8 for the nozzle. In our case, it turns out that after a detailed optimization process the length of the test section is $L_T=$ 12. 7 m which results in a sufficient jet stability limit of $L_T/D_H = 2.7 < 3.0$. This result may be taken from Fig. 3 for the example of three different cars (vehicle details are denoted in Tab. 1).

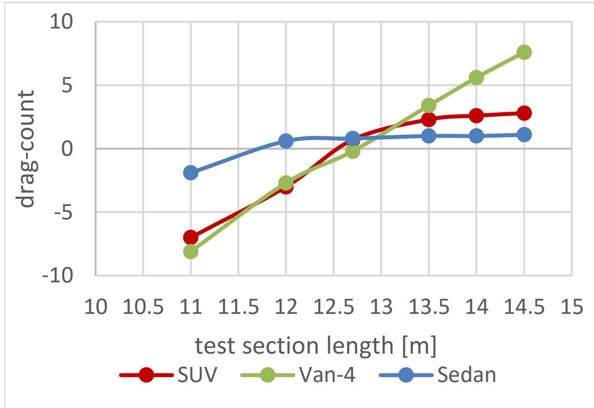

Fig.3 Net-interference effect versus test section length with nozzle area 23.2 m^2: model center at 4.5 m from nozzle; collector-nozzle ratio 1.5; nozzle aspect ratio 0.8; (+) decrease drag

A detailed analysis of the model position can be depicted from Fig. 4, which reveals the net-interference for three different cars versus model position denoted by the distance between nozzle and the center of the model. Also, for the following figures the mathematical sign convention indicates that positive drag-counts reduces the measured drag and vice versa. The optimization process is shown for the example of a SUV (hatch back), Van-4 (square back) and a sedan (notch back). The optimal model position for the three vehicles mentioned above (and the other cars not shown) are obtained from the intersection of the net-interference curves versus the distance to the nozzle. The best correlation is obtained at a distance of 4. 5m from the model center to the nozzle, which is used for further considerations.

A detailed view on how the individual interference parameter develop versus model position is displayed in Fig. 5—Fig. 7 for the example of an SUV, a large delivery-van and a middle-class sedan. Apparently, for the SUV (see Fig. 5) the net-interference is practically insensitive to the model center position between 3. 5 m and 5. 5 m from the nozzle.

For the delivery-van (Fig. 6) a shorter distance of the model center to the nozzle by less than half a meter increases the net-interference and already

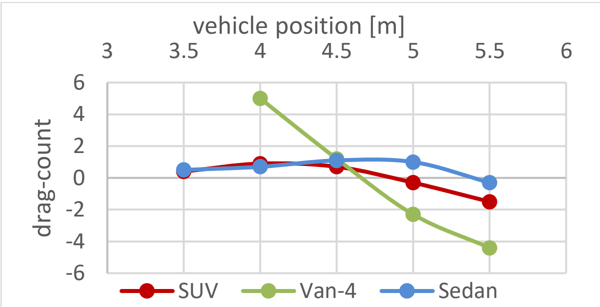

Fig.4 Net-interference effects versus model position for nozzle area 23.2 m²: SUV; Van-4; Sedan (notch back); test section length 12.7 m; collector-nozzle ratio 1.5; nozzle aspect ratio 0.8: (+) decrease drag

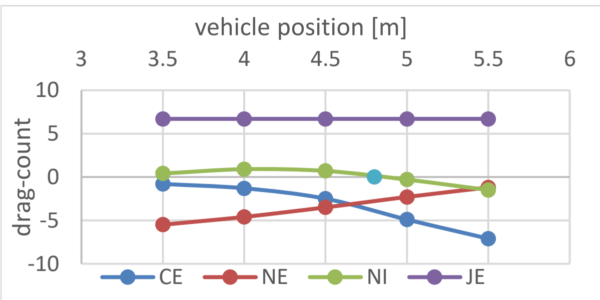

Fig.5 SUV interference effects versus model position for nozzle area 23.2 m²: CE collector effect; NE nozzle effect; NI net-interference effect; JE jet-expansion effect; test section length 12.7 m; collector-nozzle ratio 1.5; aspect ratio 0.8: (+) decrease drag

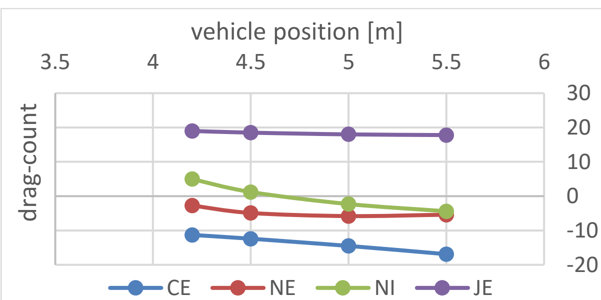

Fig.6 Van-4 interference effects versus model position for nozzle area 23.2 m²: CE collector effect; NE nozzle effect; NI net-interference effect; JE jet-expansion effect; test section length 12.7 m; collector-nozzle ratio 1.5; nozzle aspect ratio 0.8; (+) decrease drag

exceeds our initially defined limits. It should be emphasized that for this vehicle the distance to the nozzle was limited to 4.2 m in our optimization process, since, in order to calculate the nozzle effect, the potential-flow model used to replace the physically vehicle protrudes into the nozzle and blockage effects as they occur in a closed test section come into operation. This fact limits the execution of our optimization process. For the middle-class sedan (see Fig. 7) the net-interference varies over the range of model positions investigated, but stays within our limits.

In order to understand the iteration process, it should be mentioned that when varying the parameters, one variable was changed at a time and then applied to all the vehicles examined. The iteration process is only completed after the stability criterion for the free-jet has been fulfilled and the net interference stays within the defined limits.

A further detailed break-down of all existing cars of this study can be taken from Tab. 1. When selecting the vehicles, care was taken to ensure that a wide range of vehicles of different types and sizes were available. The vehicles from the sports car to Van-4 are all cars produced by European manufactures. In addition to the vehicle types and their tail configurations, Tab. 1 (yellow-shaded) also shows the main dimension of the selected vehicles and the blockage ratio (vehicle frontal area to nozzle area). The centers of the vehicles were positioned at 4.5 m downstream of the nozzle and the test section length was 12.7 m.

The right side of Table1 (see next page) display the detailed analyses of the different interference effects in drag-counts and the final results, again in drag-counts, of the residual net-interferences are shown in the last column to the right (blue-shaded). The effect of a possible pressure gradient in the empty test section does not have to be assumed with an appropriately designed collector and a sufficient test section length, since a zone of pressure relaxation in front of the collector would be decayed in upstream direction by the end of the sensitivity length. This is what we assume in our considerations. However, if a vehicle is placed inside the test section, the combined far-field and near-field wake effect of the vehicle triggers another interference effect at the solid walls of the collector, which is comparable to the blockage effect in a closed wall wind tunnel. This effect reflects back to the vehicle in upstream direction and changes the forces on the measured object as described above.

In summary, the collector effect is smallest for small vehicles because it is the far field wake which is involved only, but eventually outweighs the nozzle effect for larger vehicles when the plenum method is used and the near wake interacts with the collector. Finally, nozzle and collector effect together are compensated by a growing jet expansion effect which results in a small overall net-interference effect, even for the largest vehicle investigated.

The same result would be obtained by using the nozzle method. However, in this case it is mandatory to determine the incident flow with both methods, the nozzle method and the plenum method. Since all other interference influences remain the same regardless of the method used, the resulting difference in drag coefficient between both methods must be included in the balance of the net-interference summation for the nozzle method. The use of the nozzle method alone to determine the approach speed is not advisable as there is no counterpart of interference effects that could compensate for the nozzle effect generated by the nozzle method. In this context, it is perhaps worth noting that for a van with a blockage ratio of >20%, the difference in drag between nozzle and plenum methods can easily grow to over 40 drag-counts.

Tab. 1　Vehicle parameter and results from interference optimization

RE	VT	FA/ m^2	OL/ m	Vol/ m^2	BR/ %	JE drag-count	NE drag-count	CE drag-count	Net−I drag-count
FB	Sports Car	2.01	4.69	5.0	9	3.4	−2.5	−0.3	0.6
FB	Small Sedan	2.14	4.10	6.5	9	4.0	−2.3	−0.3	1.4
NB	Sedan	2.20	4.70	6.5	10	4.3	−2.8	−0.5	0.6
HB	Kombi	2.34	4.90	7.7	10	4.9	−3.1	−1.1	0.7
WB	Minivan	2.46	4.50	7.0	11	5.5	−3.1	−1.2	1.2
HB	SUV	2.87	4.90	8.5	12	7.0	−3.6	−3.0	0.4
WB	Van−1	3.29	4.90	11.4	14	8.6	−3.4	−4.8	0.5
WB	Van−2	4.10	6.00	16.9	18	12.4	−3.9	−9.2	−0.8
WB	Van−3	4.60	6.00	19.4	20	15.0	−4.6	−10.4	−0.0
WB	Van−4	5.20	6.30	23.5	22	18.5	−4.9	−12.4	1.2

Note: RE rear end configuration of vehicle (FB fast back; NB notch back; HB hatch back; WB wagon or square back back); VT vehicle type; FA frontal area; OL vehicle overall length; Vol vehicle volume; BR percentage blockage ratio; JE (brown) jet expansion effect (drag-counts); NE nozzle effect for plenum method (drag-counts); CE collector effect (drag-counts); Net−I (blue) showing drag-counts of net-interference; Mathematical sign convention for drag-counts: (−) interference increases drag-coefficient and must be subtracted, (+) interference decreases drag-coefficient and must be added; Model position at 4.5 m from nozzle; Test section length 12.7 m.

7　Summary and conclusion

A parameter variation of the characteristic dimensions of an 3/4 open jet test section was executed. Test cases were a number of typical vehicles of today covering a range of cars with small frontal area and short overall length up to delivery-vans with a total length of 6.3m and a frontal area of 5.2 m^2. The optimization process revealed that for a nozzle cross-section of 23.2 m^2 and a test section length of 12.7 m the residual net-interference effect for all cars investigated was in a band-width of less than ±1.5 drag counts if the model center was placed at 4.5m downstream of the nozzle exit. Consequently, it is not necessary to change the length of the test section by moving the collector or to adjust the measuring position for vehicles with different dimensions. Furthermore, the results were obtained with a fixed nozzle cross-sectional area and an unchanged aspect ratio. With regard to the requirement not to carry out interference corrections, this result can be regarded as completely sufficient.

For the optimization process it was necessary to determine the nozzle interference with the nozzle method and the plenum method simultaneously, similar to the procedure of applying a blockage correction scheme in a 3/4 open test section. However, since the direct assessment of interferences is subsequently no longer necessary due to a negligible overall net-interference, the plenum method alone can be used for evaluating the tunnel speed if the test section components are optimized and a vehicle is placed inside the test section.

Finally, the question should be answered as to why it is only nowadays that it has been possible to design a wind tunnel that is virtually interference-free. The answer clearly lies in the introduction of a logistic sigmoid function specified by A. Henning[8] for the near wake. With that, it was possible to balance the effect of the vehicle′s near-field wake and far-field wake with great accuracy for different vehicle lengths and rear end configurations.

The presented optimization process was carried out exemplarily on the example of the drag coefficient. In the case of the flow about a vehicle, the orientation and the absolute value of the resulting force vector do not represent the determining variable for the method presented. Rather, it is the dynamic pressure of the approach flow that scales the flow velocity to the road conditions by suitable procedures. The optimization process therefore also applies to all other velocity-related aerodynamic coefficients. If the measured and the resulting coefficient are identical afterwards, the condition as measured on the road is achieved.

8 Future perspective

The presented optimization process may have given the impression that the resulting test section dimensions are the only optimum for the design of a wind tunnel. But this statement is biased! If one were to aim for a smaller nozzle cross-sectional area for financial or spatial reasons, a shorter test section would also have to be chosen for reasons of flow stability. Even for such a situation, an optimum of the net interference may be found that corresponds to the given specification. However, what probably would not succeed is that the optimal design of the test track does remain valid for the large variety of vehicles at the same time, as is the case in the study presented here. Nevertheless, with the optimized design parameters of the test section, we have thus laid the foundation for a truly "tolerant" open-jet wind tunnel for automotive testing.

References:

[1] WICKERN G. A theoretical approach towards the self-correcting open jet wind tunnel [C]// SAE paper 2014-01-0579, 2014.

[2] MERCKER E, WIEDEMANN J. On the correction of interference effects in open jet wind tunnels [C]// SAE paper 960671, 1996.

[3] MERCKER E, WICKER N, WIEDEMANN J. Contemplation of nozzle blockage in open jet wind tunnels in view of different Q-determination Techniques [C]// SAE paper 970136, 1997.

[4] MERCKER E, COOPER K. A two-measurement correction for the effects of a pressure gradient on automotive, open jet, wind tunnel measurements [C]// SAE paper2006-01-0568, 2006.

[5] SCHÖNLEBER C. Investigation of transient interference effects of open-jets for automobiles (translation) [D]. Stuttgart: IVK University of Stuttgart, 2019.

[6] BLUMRICH R, WIDDECKE N, WIEDEMANN J, *et al.* New FKFS technology at full-scale aeroacoustic wind tunnel of Stuttgart University [J]. SAE International Journal of Passenger Cars: Mechanical Systems, SAE paper 2015-01-1557, 2015.

[7] WICKERN G. On the application of classical wind tunnel corrections for automotive bodies [C]//SAE 2001 World Congress. SAE paper 2001-01-0633, 2001.

[8] HENNING A, Widdecke N, Wiedemann J. A study on collector effects in open-jet wind tunnels [C]// 11th Conference on Vehicle Aerodynamics. Haus der Technik, 2014.

[9] THEODORSEN T. The theory of wind-tunnel wall interference 18 [R]. Annual Report, NACA 1933: Report No. 410.

[10] MERCKER E, COOPER K, FISCHER O, *et al.* The influence of a horizontal pressure distribution on aerodynamic drag in open and closed wind tunnels [C]// SAE 2005 World Congress & Exhibition. Detroit: SAE paper, 2005.

[11] COOPER K R, MERCKER E, MÜLLER J. The necessity for boundary corrections in a standard practice for the open-jet wind tunnel testing of automobiles [J]. SAGE Journal of Automotive Engineering, 2017, 231(9):095440701770128.