

Comparison of the conformity of aerodynamic resistance in Europe and the US

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Introduction

While the European Commission is currently working towards a new test procedure to determine CO₂ emissions via the VECTO simulation model, the US EPA and NHTSA have reviewed and finalized Phase 2 of their comprehensive Heavy-Duty National Program to reduce greenhouse gas emissions (GHG) and increase fuel efficiency for on-road heavy-duty vehicles^{1,2}. Similar to VECTO, also the US have chosen a simulation approach to determine CO₂ from heavy-duty vehicles by developing the GEM model (Greenhouse Gas Emissions Model). This was developed by US EPA as a means for determining compliance with EPA's GHG emissions and NHTSA's fuel efficiency standards, for Class 7 and 8 combination tractors and Class 2b-8 vocational vehicles.

Both the VECTO and the GEM model use input files that provide data on relevant vehicle, driveline and engine characteristics such as engine efficiency maps, gear ratios, tire rolling resistance, vehicle mass and many more. All of these inputs are defined, and where appropriate, a test procedure is developed to determine them in an accurate and reproducible way. One of the most important inputs in terms of its influence on fuel consumption is the vehicle's aerodynamic resistance, normally expressed as the product of the drag coefficient C_d and the frontal area A . Since it is rather complicated to measure the aerodynamic resistance, both the US and Europe have included detailed test procedures. In the US this is based on a coastdown test as a reference method, while Europe has chosen for a Constant Speed Test (CST).

To ensure that production vehicles are conforming to the test results measured on a (pre-production) vehicle, both regions have an enforcement mechanism installed to confirm the aerodynamic resistance. In Europe these are the Conformity of Production requirements, and in the US there are Selective Enforcement Audits (SEA). The value of the $C_d.A$ measured at type approval is not only depending on the aerodynamic performance of the vehicle, but may also be influenced by the use of potential tolerances and flexibilities within the test procedure. Therefore, the stringency of the enforcement mechanism against which the $C_d.A$ is verified also has an influence on the type approval value. This paper will evaluate the confirmation procedures applied in the US and Europe to highlight the main differences, the allowed tolerances and other relevant details. As the US EPA has performed a thorough work to improve their test procedures towards Phase 2³, Europe might benefit from their review.

¹ See: "Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles—Phase 2, Regulatory Impact Analysis" at

<https://nepis.epa.gov/Exe/ZyPDF.cgi/P100P7NS.PDF?Dockkey=P100P7NS.PDF>

² Official publication of The Phase 2 GHG rule has been the Federal Register can be found at

<https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-and-related-materials-greenhouse-gas-emissions>

³ See: "Additional Discussion of Selective Enforcement Audit and Confirmatory Testing for Aerodynamic Parameters for Combination Tractors and for Trailers" at

<http://www.noticeandcomment.com/Additional-Discussion-of-Selective-Enforcement-Audit-and-Confirmatory-Testing-for-Aerodynamic-Parameters-fn-355836.aspx>

Test procedure in the US

The new HD Phase 2 standards for combination tractors and for trailers require that manufacturers of tractors and trailers conduct testing to determine aerodynamic drag values which act as inputs for the GEM simulation model. The procedures may also be applied to determine the influence of options intended to reduce the aerodynamic drag of the vehicle. The EPA has introduced an improved version of the Phase 1 test procedures in 40 CFR 1037.521⁴ for measuring aerodynamic parameters. These Phase 1 and Phase 2 procedures specify how to measure $C_d.A$ by coasting down an actual vehicle.

While the coastdown method is still applied as the reference test method, manufacturers are also required to use an alternate method such as scaled wind tunnels and computational fluid dynamic (CFD) simulations. This will not only allow for easier certification of all vehicle configurations, but can also be applied to determine the $C_d.A$ at a yaw angle of $\pm 4.5^\circ$, which is selected by the EPA as the representative average wind condition (yaw angle is the apparent angle at which the air hits the vehicle, formed by the combination of the forward moving speed of the vehicle, and the wind speed and direction). The manufacturer has to demonstrate that the alternate method yields similar or better results as the coastdown method, and a correction factor $F_{alt-aero}$ is certified to convert the results from any effective yaw at a coastdown run to the surrogate angle of $\pm 4.5^\circ$. EPA has also included a test procedure for constant speed testing, but that is not expected to be applied much as alternate method since it does not facilitate easy testing and certifying in a simulated environment.

When the $C_d.A$ of a vehicle has been measured and corrected towards the average wind condition at $\pm 4.5^\circ$ yaw angle, the value will be categorized according to the vehicle class and a binning system. The GEM input is determined by the average value of the bin to which the vehicle was certified, not the actual value of the $C_d.A$. The table below shows the bins for Class 8 vehicles, and the tolerance from the average bin value to the upper and lower boundaries of the bin. As can be seen, these tolerances range from roughly -4% to +4% for this particular vehicle class.

Class 8										
	Day cab, High roof					Sleeper cab, High roof				
Bin	Lower	OEM value	Upper	Lower tol.	Upper tol.	Lower	OEM value	Upper	Lower tol.	Upper tol.
I	>7,2	7,45	-	-3,4%	-	$\geq 6,9$	7,15	-	-3,5%	-
II	6,6	6,85	7,1	-3,6%	3,6%	6,3	6,55	6,8	-3,8%	3,8%
III	6	6,25	6,5	-4,0%	4,0%	5,7	5,95	6,2	-4,2%	4,2%
IV	5,5	5,7	5,9	-3,5%	3,5%	5,2	5,4	5,6	-3,7%	3,7%
V	5	5,2	5,4	-3,8%	3,8%	4,7	4,9	5,1	-4,1%	4,1%
VI	4,5	4,7	4,9	-4,3%	4,3%	4,2	4,4	4,6	-4,5%	4,5%
VII	-	4,2	$\leq 4,4$	-	4,8%	-	3,9	$\leq 4,1$	-	5,1%

Table 1 – Bin values for Class 8 vehicles, and tolerances between the average bin values and the upper/lower bin boundaries

Air drag testing is done under the responsibility of the manufacturer, but the EPA may also perform 'confirmatory testing' at pre-production vehicles to evaluate the declared aerodynamic drag. Though during Phase 1 there were no direct consequences specified if the results could not be confirmed, for Phase 2 these will be tighter. Since there are large numbers of vehicle configurations, confirmatory testing is likely to focus mainly on the equivalency of the alternate method and the accuracy of the correction factor $F_{alt-aero}$ since that has consequences for all vehicles that are certified according to the alternate air drag measurement method.

⁴ See <https://www.law.cornell.edu/cfr/text/40/1037.521>

Once the vehicle has entered into production, the manufacturer needs to conduct SEA tests to prove the compliance of the vehicles to the bin of the certified vehicle. Selection of vehicles for SEA testing is controlled by the EPA. Acknowledging that the test-to-test variability is high for coastdown testing, the focus is more on measuring a sufficient amount of runs instead of measuring a lot of vehicles. Compliance determination is therefore based on average values of at least 24 coastdown runs in opposite directions and the statistical confidence interval. Air drag compliance is only observed against the bin for which the vehicle is certified, not to the value that was determined during the certification.

Every vehicle configuration has its own $C_d.A$ bin value that it certifies to, there are no vehicle families for which only a parent vehicle is certified. Therefore, each vehicle configuration may be selected for an SEA test.

Test procedure in Europe

Also in Europe the manufacturer of a vehicle has to certify the $C_d.A$ of a vehicle by measuring an actual vehicle, and this value is used as an input for the VECTO simulations⁵. In contrast to the test method in the US, Europe has chosen to only allow the constant speed test (CST) to determine the air drag. In this test procedure, the vehicle is tested at two constant speeds, a high and a low one. The total resistance at these speeds is measured, and the difference between the two allows the aerodynamic resistance to be isolated from the rolling resistance of the wheels and the driveline. The yaw angle during the test is calculated from the results, and calculated back to zero yaw (i.e. no crosswind) via generic correction functions for the vehicle categories. The $C_d.A$ at zero yaw angle is then corrected by these correction functions to reflect a generic average crosswind of 3 m/s. This is the air drag that VECTO will use for its calculations.

Generally, the coastdown method is rather sensitive to small influences during the test, such as changes in the track alignment and variations in wind speed and direction, which lead to a poor repeatability and reproducibility of this method⁶. The only way to arrive at a reasonable accurate aerodynamic drag is to cancel out these influences by increasing the number of runs. However, not all influences can be eliminated, such as the smoothness of the test track surface and changes in the wind flow due to obstacles near the track. Also the role of tarmac temperature on the rolling resistance is not yet fully understood. The CST is less sensitive for external influences, as they are leveled out during the measurement itself by maintaining the constant speeds for a longer period. According to the Regulation Impact Analysis by the EPA¹ a test on three Class 8 Sleeper Cab tractors with trailer showed that the standard error on $C_d.A$ for the coastdown method can be reduced to below 1% if the number of coastdown runs in opposite directions is higher than 20. They also evaluated a constant speed method, which showed standard errors ranging from only 0.5 to 0.8% on five vehicle configurations.

The CST method was also evaluated by the JRC of the European Commission (with support from industry), and the results were reported in an SAE paper⁷. They concluded:

⁵ The detailed test procedure in draft is included as Annex V, and is available for VECTO Editing Board members at the applicable CIRCABC folder under Library > 2016.09.19 - Editing board 8th meeting > 20160908_Air-drag_distributed.docx

⁶ Repeatability refers to obtaining the same results by repeating the test at the same track and by using the same test equipment, while reproducibility refers to the ability to replicate the results on another track by using other (yet qualified) test equipment

⁷ SAE 2014-01-0595 by G. Fontaras et al, An Experimental Methodology for Measuring of Aerodynamic

“The results of measurements performed on two HDVs for assessing the proposed methodology suggest good characteristics in terms of measurement sensitivity, precision, reproducibility and robustness. The repeatability standard deviation was calculated in the order of 2% of the air drag value measured while the reproducibility standard deviation was in the order of 2.5%. The results obtained so far fulfills the need of the CO₂ monitoring procedure for an air drag calculation method that will be in the position to accurately capture the characteristics and advantages of each vehicle body.”

The air drag testing for certification is done under the responsibility of the manufacturer, and shall be witnessed by a representative of the technical service (TS) and/or type approval authority (TAA). In Europe there is no binning system applied as in the US, the measured air drag is corrected towards the average generic crosswind of 3 m/s and used directly as input to the VECTO calculation.

Manufacturers have to perform tests on their production vehicles to prove the Conformity of Production (CoP) to the certified air drag value. CoP testing is done under the responsibility of the manufacturer and is foreseen to be witnessed by another TS/TAA than that which certified the air drag at type approval. Until today, the role of the TS/TAA in e.g. CoP emission tests was limited to rubberstamping the result, witnessing a test only in special occasions.

Tolerances on the certified aerodynamic resistance

We will now zoom in on how the certified air drag value is being confirmed in both regions, and look at the tolerances that apply between the original certified vehicle and the production vehicle.

Confirmation in the US

Basis for the confirmatory tests and SEA's is the bin according to which the vehicle was certified. Hence, the tolerance for a particular vehicle depends where it is positioned within the bin. As seen in Table 1 this ranges from 0% if it is equal to the top of the bin to roughly 8% if it is close to the bottom of the bin. Understandably, the EPA will tend to select vehicle configurations that are certified at an air drag value close to top of the bin. This requires manufacturers to manage how conservative or confident they are in their bin declarations. Both for the confirmatory testing and the SEA's the procedure is to coastdown the vehicle at least 24 times (12 runs in each direction) – see 40 FR 1037.305 for details⁸. From these test results the mean C_dA is determined and corrected towards the average wind condition at a yaw angle of ±4.5°, and the statistical confidence interval is calculated according to the following formula:

$$Confidence\ Interval = \frac{1.5 \times \sigma}{\sqrt{n}} + 0.03$$

where :

σ = the standard deviation

n = the total number of coastdown runs

The air drag value is confirmed if the statistically significant mean estimate (SSME, i.e. mean ± confidence interval) is *entirely* below the top of the bin to which the vehicle was certified, and the vehicle is considered to pass. Similarly, if the SSME is *entirely* above the top of the bin, the vehicle is considered to fail. If no pass or fail is concluded, more coastdowns have to be performed up to a maximum of 100. If at that point the SSME is still not conclusive on a pass or fail, the vehicle is

Resistances of Heavy Duty Vehicles in the Framework of European CO₂ Emissions Monitoring Scheme, March 2014

⁸ See the final rule in Federal Register/ Vol. 81, No. 206 / Tuesday, October 25, 2016 / Rules and Regulations at <https://www.gpo.gov/fdsys/pkg/FR-2016-10-25/pdf/2016-21203.pdf>

considered to pass. A third option is that a manufacturer concedes failure at an earlier stage. Even though the EPA acknowledges the relatively large test-to-test variation in coastdown testing, they claim their approach to be such that “where a manufacturer acts in good faith for certification and uses good engineering judgment throughout the process, false failures for *individual vehicles* would be rare and false failures for a *family* would not occur.”³ In other words, they consider this evaluation of the pass/fail criteria would not bring injustice to the manufacturer by accidentally failing a vehicle that would actually be compliant.

In summary, between the certified air drag value and the measured value of a production vehicle the following tolerances may apply in the US:

- Positive tolerance between the $C_{d,A}$ of the vehicle and the top of the bin value, ranging from 0 to $\pm 8\%$ tolerance.
- Negative tolerance on the evaluation strategy of the SEA, since the confidence interval needs to be entirely below the upper bin value. The tolerance depends on the number of coastdowns, since the confidence interval will normally reduce by increasing the test volume.

This is illustrated in the Figure 1, with the orange arrow representing the maximum tolerance in the case that 100 coastdowns are performed for the SEA or Confirmatory test. If the $C_{d,A}$ of a vehicle is close to the top of the bin, the tolerance will be smaller, and vice versa. At the same time, the tolerance depends on the statistical pass/fail decision built into the SEA: since it needs to be confirmed that the whole confidence interval is below the top of the bin, the space between actual $C_{d,A}$ and the bin border is reduced. In some occasions, it may even be negative as is illustrated by the ‘24 coastdown runs’ bar. If additional coastdown runs are performed, this space will gradually increase, and at 100 coastdown runs the total tolerance span will be available. From this figure we learn that the uncertainty of the coastdown measurement is at the manufacturer’s expense, at least until 100 coastdown runs are performed to confirm the certified air drag.

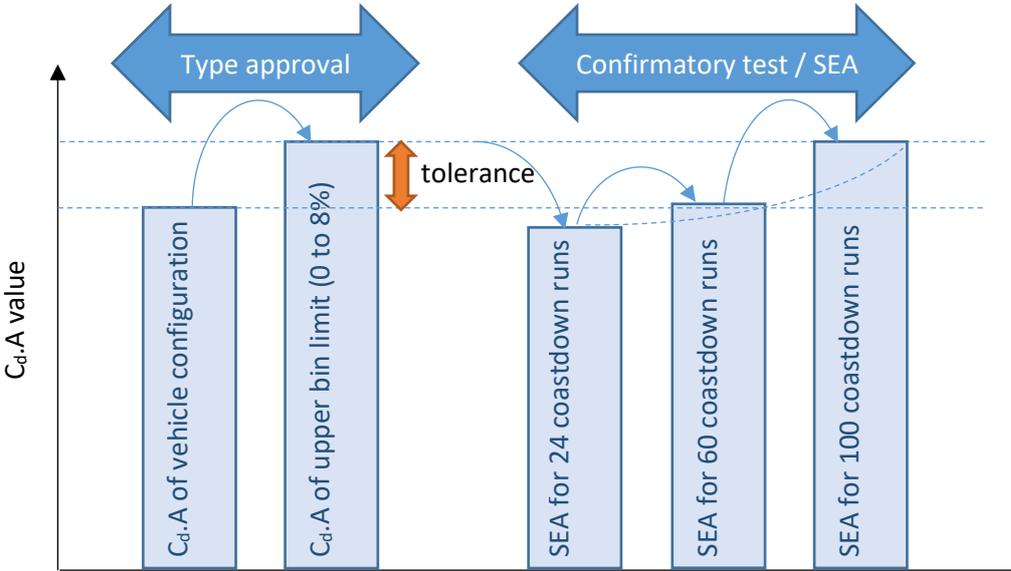


Figure 1 – Graphical representation of the tolerance for a vehicle manufacturer in the US

If a vehicle fails, the manufacturer has to coastdown two additional vehicles. This can be the same vehicle configuration or an alternative configuration within the family. For each vehicle that fails, two

additional vehicles have to be tested, up to a maximum of 11. More than 50% of the vehicles should pass, otherwise the vehicle family is considered to fail as a whole and the certificate is suspended.

Confirmation in Europe

The details of the CoP requirements are outlined in Appendix 7 of Annex V of the draft test procedure⁵. Basis for evaluating the CoP test result is the air drag value of the certified parent vehicle. The parent vehicle should have the worst-case aerodynamic drag of all vehicles for which it serves as the parent. Vehicles for which the air drag value was ‘transferred’ from other vehicle classes are not subject to CoP testing, but the text seems to imply that also ‘child’ vehicles below the parent vehicle can be selected. Paragraph 4.5 in the draft procedure specifies the vehicle selection as follows:

“The first two vehicles per OEM and year to be CoP tested shall be selected from the two biggest families or cluster in terms of vehicle production. Additional vehicles shall be selected by the Technical Service.”

From this requirement it is not clear who will decide for these “first two vehicles” which specific vehicle is selected from the family or cluster. It might seem obvious that normally a parent vehicle is selected, but is important that also child vehicles can be selected to confirm that the parent vehicle indeed has the worst-case air drag. A child vehicle that has a lower air drag would pass the CoP test more easy, but this may not be seen as an additional tolerance because the vehicle was certified at the higher $C_{d,A}$ of the parent vehicle, so to the disadvantage of the manufacturer.

The criterion for passing the CoP test is the certified air drag value of the parent vehicle plus a tolerance of 0.2 m^2 to account for variance within the production and for the uncertainty in the selection of the worst-case vehicle in the family as the parent vehicle. This means a tolerance of about 3% for typical truck $C_{d,A}$ values. On top of that there is an additional margin of 10% “representing the reproducibility range of a constant speed test”⁵. There are no statistical evaluation criteria included (yet) for the case that a vehicle fails the test, while in other technical annexes this is clearly specified. This seems like a temporary omission, but for now it will be assumed that the outcome of the CST for CoP results directly into a ‘pass’ or ‘fail’ without specifying any consequences.

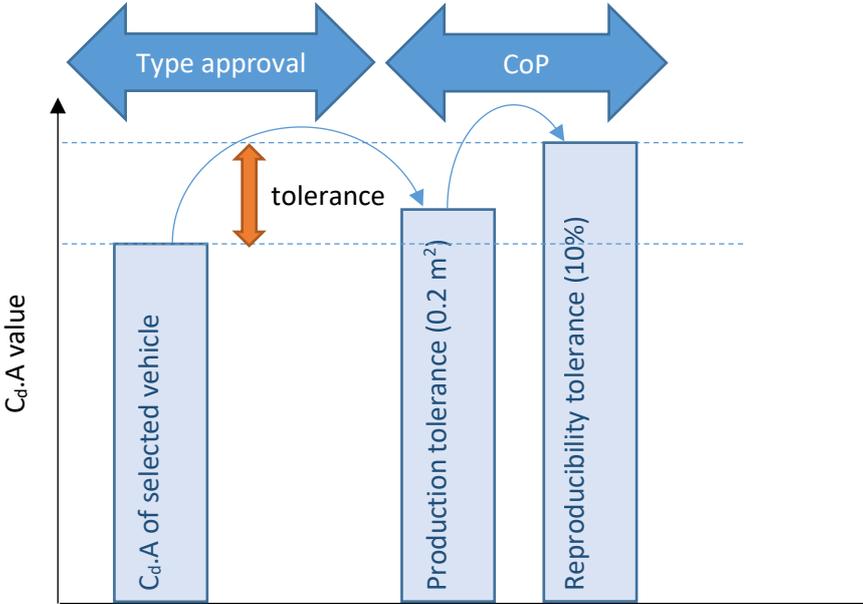


Figure 2 – Graphical representation of the tolerance for a vehicle manufacturer in Europe

Figure 2 illustrates the tolerances that are applicable in Europe for the CoP test. From this figure we learn that the uncertainty in the CoP test procedure is used to the benefit of the manufacturer.

Comparison of tolerance versus procedural differences

Looking at the test procedures and tolerances in the US and Europe, we observe that the coastdown method applied in the US has worse repeatability and reproducibility than the CST method in Europe. To reduce the uncertainty this introduces to the measurement of $C_{d,A}$, the amount of coastdown tests is increased to a minimum of 24. Despite the higher uncertainty level, demonstration of confirmation in the US is based on a *negative* tolerance since the whole range of the statistically significant mean estimate needs to be below the top of the bin value (unless an 'inconclusive' result is reached after 100 coastdowns). This negative tolerance will decrease with a higher number of coastdowns and a better test repeatability. Compared to the situation in the US, the European CoP limit seems much more relaxed by offering an absolute tolerance of 0.2 m^2 and an additional 10% tolerance to account for the reproducibility of the CST method.

Effectively this means that the uncertainty caused by the repeatability of the measurement method works towards the benefit of the manufacturer in Europe, while the US considers this towards the disadvantage of the manufacturer. Furthermore, the claimed 10% of uncertainty seems rather high against research results showing a standard error of 1.8% at maximum¹, or a standard deviation on the reproducibility that was proven to be limited to 2.5%⁷. Considering that this reproducibility level was achieved at a time where there was not yet much experience on aerodynamic drag testing, it might even be further reduced once more experience is gained throughout the years that the HDV CO₂ legislation is in force.

Recommendations

Based on the comparison of the test procedures, the confirmation testing and the applied tolerances, we come to the following recommendations for the European CoP requirements in Appendix 7 of Annex V:

- Delete the absolute tolerance of 0.2 m^2 from the CoP limit. It should be clear that the manufacturer is responsible for nominating which vehicle should act as the parent of the family, and it is not justifiable that any uncertainty towards that selection should be carried by the legislator. Furthermore, if a manufacturer feels that a certain variance applies to his vehicle production, he should add the necessary tolerance to a higher declared air drag (see the next bullet point).
Also note that this absolute tolerance would not necessarily apply to all vehicles (e.g. a single vehicle without variants), but is nevertheless awarded in each CoP test. Manufacturers that do not need this tolerance could potentially use flexibilities in the test procedure to obtain a lower air drag value, resulting in an artificial lower CO₂ result from VECTO. The absolute 0.2 m^2 would translate into a relative tolerance of about 3% for average vehicles.
- In the current proposal, the measured air drag by the CST test procedure directly serves as input for VECTO. The manufacturer should have the possibility to declare a slightly higher $C_{d,A}$ to account for uncertainties to which vehicle should be tested as parent vehicle, and/or for variations in the production, as outlined in the previous bullet point. The higher declared air drag should then serve as the official air drag value for all vehicles in that air drag family.
- Revise the 10 % reproducibility tolerance in the CoP limit to reflect the state of the art in CST measurement technology and the experience gained up to now in the tests that have taken place. Based on the evidence mentioned in this paper, the 10% tolerance should clearly be adjusted downwards. We suggest that a maximum tolerance of 5% would be sufficient, which is 2 times the

standard deviation found in the JRC study⁷. Assuming a normal distribution of the uncertainty associated to the reproducibility, this would mean that more than 97.5% of the single vehicle tests would result in a 'pass' decision. This number increases further to nearly 100% if a 'fail' test result is followed by successive tests for confirmation of the fail decision.

- For CoP of vehicle families we recommend that both parent and 'child' vehicles can be selected for testing, and that the selection is controlled by the TS/TAA. Choosing the parent vehicle seems the most challenging since the tolerances are expected to be the smallest. However, also 'child' vehicles should be checked by CoP, especially if there are reasons to question if the parent vehicle actually has the worst-case air drag. This is already largely in line with the text of Appendix 7, but there is still some unclarity in the vehicle selection for CoP.
- Appendix 7 of Annex V should be complemented with statistical evaluation criteria for a pass/fail decision. At this moment it is not clear what should be done if a vehicle fails to meet the CoP limit specified in paragraph 2. In the other technical annexes on component testing three further components have to be checked and should meet the criteria. If they also fail, a plan of remedial measures needs to be established by the manufacturer (as is already the case in the legislation today).

For these recommendations we feel the following principle should apply, even though we acknowledge the complexity to strike a balance between the two:

While no vehicle or family should unjustly fail the CoP, no unnecessary tolerance should be provided to make it unjustly pass.

We expect these recommendations will assist towards finding that balance.