Testing the dynamic behaviour of vehicles: Normalisation of test conditions by use of multi linear regressions

Patrick DUPONT
Head of Running Conditions Section
Track Engineering Department
SNCF - Direction de l'Ingénierie
6 Avenue François Mitterrand
93574 LA PLAINE SAINT DENIS
FRANCE

Abstract

The international test protocols used for the assessment of the on-line dynamic behaviour of railway vehicles (UIC Code 518, EN 14363) specify a set of test conditions, describe data processing rules and give limit values for defined assessment quantities.

Following years of practice on various networks, it is widely accepted that a strict compliance with the test conditions as specified in these documents is virtually impossible, or at least not economically practicable: this would indeed lead to the performance of test runs on specific railway lines chosen for this purpose, far from each other etc., which would increase complexity, duration and costs of tests.

In practice, many test bodies purely disregard part of the test requirements (assumed as « impossible to fulfil »). This may be acceptable on a national basis, where partners (NSA, Infrastructure manager, operator, test institute...) share a common view of the characteristics of their network and the resulting test conditions considered as « necessary and sufficient ».

But such deviations are not acceptable for an authority (notified body or NSA) asking for a strict application of the rules, or when acceptance is sought on another network (interoperability or bilateral cross acceptance) where the reference conditions of track or operation may differ. Usually, tests have to be duplicated or at least complemented.

The aim of the present work is to define a way to normalise vehicle test conditions, in order to assess the dynamic quantities (forces, accelerations) at the specified target conditions: track radius, speed, cant deficiency, track quality etc.

Real test data from various types of vehicles were analysed versus test conditions, using multi linear regressions allowing to:

- identify the test conditions which are the most influential on the vehicle behaviour,
- establish correlation rules between input (test conditions) and output (test results) quantities,
- use them to upgrade the estimated values to target conditions specified in UIC 518 / EN 14363.

A general correction method is proposed, either based on the use of « universal » coefficients or, more often, of the own correlation rules of the vehicle considered. In this way, it will be possible to evaluate the dynamic parameters of any vehicle at the requested reference conditions, even when these have not been exactly met during the test process. A fair comparison of vehicles will be made possible, avoiding any suspicion about the validity of the tests for acceptance in any other country.

Key words

test conditions, test results, linear regressions

1. Test performance and assessment for the acceptance of vehicles dynamic behaviour

Before its introduction in commercial service, any new or modified railway vehicle is submitted to the examination of its dynamic behaviour. In Europe, this assessment is usually carried out by submitting the vehicle to a series of on-line tests performed according to one of the following documents:

- UIC Code 518 (latest issue: 4^{th} edition - September 2009),
- EN 14363 (latest issue: December 2005 - currently undergoing full revision).

Both documents will be considered here as equivalent, their discrepancies being the result of different stages of evolution of an identical set of rules. They specify how to perform and assess the dynamic tests, and describe in particular:

- the test conditions to be performed,
- the quantities (forces and/or accelerations at various locations on the vehicle) to be measured,
- the signal filtering and processing rules to be applied, in order to derive the « estimated values » representing the expected behaviour of the vehicle in reference operating conditions,
- the limit values to which these estimated values shall be compared for vehicle acceptance.

A summary of these rules is given hereafter, limited to what is necessary for a correct understanding of the issues addressed in this paper. To make the description as clear as possible, simplifications have been made on some details.

a. Test conditions

According to its nature, design and use, a vehicle may need to be tested empty and loaded, in normal and degraded modes, in one or both running directions. The following conditions apply for every of these vehicle testing configurations.

Test conditions are based on the maximum speed (V_{lim}) and cant deficiency (I_{adm}) expected in service. The useable parts (fulfilling the requirements recalled hereafter) of the test runs have to be classified into 4 test zones defined as:

- zone 1: tangent track - minimum 10 km partitioned into 250 or 500 m track sections,
- zone 2: large radius curves - minimum 5 km partitioned into 100, 250 or 500 m track sections,
- zone 3: small radius curves (radius 400 m ≤ R ≤ 600 m) - minimum 50 sections of 100 m each,
- zone 4: very small radius curves (250 m ≤ R < 400 m) - minimum 25 sections of 70 m each.

Additional test conditions to be fulfilled on each of the individual track sections making up these test zones are the following:

- on zone 1: test speed shall be V_{lim} + 10% (tolerance +/- 5 km/h),
- on zone 2: test speed shall be between V_{lim} and V_{lim} + 10% (tolerance +/- 5 km/h),
  cant deficiency shall be in the range $0{,}70.I_{adm} \leq I \leq 1{,}15.I_{adm}$,
  with at least 20% of the track sections above $1{,}05.I_{adm}$,
- on zone 3: the mean radius R_m of the track sections used shall be between 450 and 550 m,
  cant deficiency shall be in the range $0{,}70.I_{adm} \leq I \leq 1{,}15.I_{adm}$,
  with at least 20% of the track sections above $1{,}05.I_{adm}$,
- on zone 4: the mean radius R_m of the track sections used shall be between 280 and 350 m,
  cant deficiency shall be in the range $0{,}70.I_{adm} \leq I \leq 1{,}15.I_{adm}$,
  with at least 20% of the track sections above $1{,}05.I_{adm}$.

These requirements regarding length and number of track sections, radius, speed and cant deficiency are usually the main conditions taken into account when preparing the test campaign. Their purpose is to explore the parts of the expected operating range assumed to be the most critical:

- maximum speed of the vehicle (zones 1 and 2), in order to assess the risk of instability (zone 1) and to evaluate track forces and carbody accelerations at top speed (mainly zone 2),
- maximum cant deficiency (zones 2 - 3 - 4), generating high levels of forces (lateral and vertical) on the outer rail and on the track itself,
- very small radii (zone 4), where lateral forces and wheel climb ratio Y/Q may become critical.

Beside these basic requirements, two aspects are also specified: contact conditions and track quality.

Requirements about wheel/rail contact conditions are now directly expressed in terms of equivalent conicity (Tanγ_e) on test zone 1 (high values to assess the risk of instability and low values to explore low frequency carbody motions) and radial steering index (q_E) on test zone 4 (to make sure that the sample includes sections with both easy and difficult curving possibilities, resulting in low and high values of the lateral forces and the Y/Q ratio). Experience in this field remains however limited.

As regards track quality, the current specifications are based on the distributions, among the track sections used for the evaluation, of the standard deviations of longitudinal level (Z_s) and lateral alignment (Y_s) of the track. The requirement is that, on each test zone and separately for each of these two parameters, at least 50% of the track sections have a quality worse than QN_1, including at least 10% with a quality worse than QN_2. QN_1 and QN_2 are defined for various classes of V_{lim} speed.

b. Quantities to be measured

The so-called normal method is based on the measurement of wheel/rail contact forces Y (lateral) and Q (vertical), of which the following assessment quantities are derived:

- ΣY, total force exerted laterally on the track by a wheelset (track shift force),
- Y/Q ratio, used to assess the risk of derailment by wheel flange climbing,
- Y_{qst}, mean value of lateral curving force exerted on the outer rail in curves,
- Q, maximum vertical force exerted on the outer rail in curves,
- Q_{qst}, mean value of vertical force exerted on the outer rail in curves.

The first two (ΣY and Y/Q) are considered as safety relevant, others are used to assess track fatigue.

In addition, lateral accelerations are measured on the bogie frame (above the wheelsets), and lateral & vertical accelerations are measured in the carbody (above bogie pivots). Carbody accelerations are used in the normal method to assess « running behaviour ».

Alternative methods, defined as « simplified », are described in UIC 518 and EN 14363, mostly based on these (bogie frame and carbody) accelerations. But, although the same methods could be applied to accelerations, the present paper only focuses on the influence factors of wheel/rail forces assessed in the frame of the normal method as safety and track fatigue criteria.

c. Signal processing

The process described hereafter shall be repeated for each vehicle configuration (load case, normal or degraded mode, running direction…), test zone (1 to 4), measuring point and assessment quantity.

The first stage of the statistical process determines a representative value of the assessment quantity on each of the N track sections making up a test zone. In a second stage, these N individual values are used to calculate the estimated value of this assessment quantity on this test zone.

For « maximum » assessment quantities (ΣY, Y/Q and Q), the 99,85% value (and/or the absolute value of the 0,15% value of a negative signal) of the filtered signal on each track section is picked out:

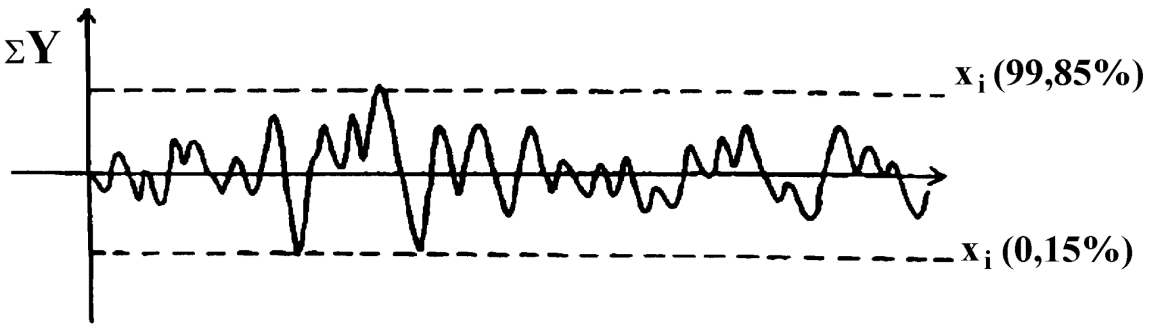

Figure 1 - Extraction of 0,15% and 99,85% values on a track section

For the whole test zone, when a one-dimensional statistical process is used, the maximum estimated value is defined as « mean + 3 standard deviations » of the N individual values (2,2 standard deviations only in the case of Q - track fatigue quantity).

For « quasi static » quantities (Y_{qst} and Q_{qst}), the 50% value of the filtered signal on each track section is used and the estimated value on the test zone is defined as the mean of these N individual values.

d. Limit values (axle load ≤ 22,5 tonnes)

The limit values for safety and track fatigue assessment quantities are the following:

$(\Sigma Y)_{lim}$ = $(10 + P_0/3)$ kN P_0 being the static axle load in kN

$(Y/Q)_{lim}$ = 0,8

$(Y_{qst})_{lim}$ = 60 kN (in UIC 518:2009: $30 + 10500/R_m$, with R_m the mean radius of track sections used)

$(Q_{qst})_{lim}$ = 145 kN

$(Q)_{lim}$ = $(90 + Q_0)$ kN with limitation according to V_{lim} speed Q_0 being the static wheel load in kN

2. Current practice and difficulties

From the summary given above, it is obvious that defining a test programme meeting all the required test conditions is a very hard task. Indeed, on a given network, it is usually possible to find test lines fulfilling either of the requirements stated in UIC 518 or EN 14363. But the difficulty lies in the fact that these requirements shall be fulfilled simultaneously, on a certain number of individual track sections.

The combination of track radius (R), test speed (V) and test cant deficiency (I) is usually achievable on most networks, but the compilation of the minimum number of valid sections for every test zone may require running on various lines, sometimes far from each other (with an impact on test duration and cost). In some countries, legal requirements even make it difficult to perform the over-speed runs requested (which, for some vehicle types, implies to exceed the local top speed of the line).

Requirements on track quality come in addition, with 2 difficulties. The first is that the test programme, as already said, is primarily designed in order to meet the above-mentioned requirements (minimum number N of sections acceptable in terms of R, V and I), the track quality being then « taken as it is », be it valid or not (…usually not!). The other is that, even when special attention is paid to track quality, it is noted that the track quality distributions requested (50 % sections ≥ QN_1, including 10 % ≥ QN_2) are very demanding, because the QN values are in many cases (especially regarding alignment Y_s) higher (worse track quality) than representative values of most European networks. For both reasons, specifications about track quality are often regarded as not practicable and are merely ignored, whereas track defects are known to have a prominent influence on the dynamic response.

This is obviously one of the fields where the present work could help greatly, until the QN numbers, now under examination, are revised (and, in a second stage, replaced by another method to describe the quality of test tracks).

Beside the non compliance to various test specifications for the reasons quoted above, we shall also consider the requirements which, even when complied with, allow a rather wide range of acceptable test conditions, potentially leading to diverging results as regards the acceptance of a vehicle.

This initially came to evidence for the evaluation of Y_{qst} for locomotives (see 5.a), where the possible range for the mean radius R_m of track sections on test zone 4 (280 m ≤ R_m ≤ 350 m) lead to a possible spread of 10 kN in the estimated Y_{qst}. So the same vehicle could be found acceptable (Y_{qst} ≤ 60 kN) if the mean radius of sections in test zone 4 was in the upper part of the allowed range, or unacceptable if this radius was in the lower part of the range.

This observation, that acceptance or rejection of a vehicle could depend on its test conditions rather than on its own capability, led to the proposal by UIC Project Group in charge of the revision of Code 518 of a new expression of the Y_{qst} limit value, now also adopted by European Rolling Stock TSI (Technical Specification for Interoperability): $(Y_{qst})_{lim} = 30 + 10500/R_m$.

CEN TC256 Working Group 10 should transfer this new formulation into the revised EN 14363, although the correction according to R_m should be introduced during the estimation of Y_{qst} rather than into the limit value. Indeed, it looks sensible to keep the limit absolute, related to the resistance of the track which obviously is a matter of components strength and not of curve radius.

3. Scope and benefits of the present work

According to EN 14363:2005 and UIC 518:2009, it is now compulsory for quasi static quantities and optional for maximum quantities to use a two dimensional statistical procedure. This way, the dynamic behaviour of the vehicle can be assessed in perfectly normalised conditions regarding cant deficiency, which is indeed one of the most influent parameters on various assessment quantities.

UIC work on the lateral force Y_{qst} of locomotives (see 5.a) showed that it was possible to neutralise the influence of track radius variations, allowing a more absolute assessment of this quantity and more objective comparisons between vehicles, possibly tested in different ranges of curve radii.

The aim of the present work is to investigate whether such normalising procedures could be extended to any assessment quantity, in order to compensate for the variability of all relevant test conditions (including track quality). This variability may be the result of allowances in the assessment procedure (ranges of values being specified rather than single target values) or deviations from this procedure.

The possible use of the methods to be developed could be the following:

- when the value specified for one of the relevant test conditions (radius, speed, cant deficiency, track quality…) was not achieved during a vehicle test, the estimated values of the assessment quantities affected by variations of this parameter could be recalculated for the specified value,
- when the possible range to be achieved for a parameter (radius in the case of Y_{qst}, for example) is so wide (and this parameter so influent) that testing at one or the other end of this range could result in diverging conclusions, the estimated values of the assessment quantities affected by variations of this parameter could be adjusted to a specific value of the parameter (in this range).

The correction should, for the reason stated at the end of point 2, be applied during the second stage (test zone) of the determination of an estimated value, before comparison with the limit value. It could be applied uniformly to all vehicles, or with variations according to vehicle type or characteristics, or even be based on coefficients derived from a specific study of each vehicle. This question will be developed at the end of this paper.

By allowing the use (after careful recalibration) of test data not strictly complying with specifications, such an approach offers numerous potential benefits:

- economy: avoids scrapping test data (the collection cost of which is always high) and sometimes repeating the test,
- accuracy: provides a tool to estimate the dynamic values in precise test conditions, rather than use the values corresponding to slightly (or even largely…) inadequate conditions,
- confidence: real test data is used as the input, and (probable conclusion) adjusted according to its own statistical evolution rules; this may be safer than using a mix of test and simulation results,
- reduced severity: the correction thus achieved has not the punishing effect of the correction factors proposed by Appendix H.3 of UIC 518:2009 when the number of valid test sections is not sufficient and the values are estimated from a reduced sample, with the same confidence level.

Note: some of these benefits, of course, are exclusive of each other. As an example, in a given case, the first one (economy) shall be considered by honest people (who would ignore improper data) and the second one (accuracy) by less regarding people (who would use such data without correction)!

4. Principles of the work

Considering the influence of mean radius R_m on the estimated value of Y_{qst}, evidenced by UIC work, CEN TC256 Working Group 10 decided, in the frame of the ongoing revision of EN 14363, to explore the respective influences of variable test conditions on the test results (to start with: ΣY, Y_{qst}, Q, Q_{qst}).

The basis for this work is the performance of multi linear regressions of vehicle test results (output) against test conditions (input), conducted and analysed as explained hereafter.

The aim is to use the results of such regressions in the adjustment of the initial estimated values, when the overall test conditions did not meet the target values of radius, cant deficiency, track quality.

a. Data

The starting point is a table (under EXCEL or another suitable format) of test conditions and results, including the following data (with one line per track section and as many columns as available input parameters or output quantities):

- identification of each test track section: run n°, start km, end km,
- track layout of each section: radius R, cant D, curvature1/R (or 1000/R),
- test running conditions on each section: speed V, cant deficiency I,
- track quality on each section: lateral, vertical (standard deviations), gauge (mean value),
- other available quantities: equivalent conicity $Tan\gamma_e$, radial steering index q_E, friction coefficient…,
- statistical values of the assessment quantities on each track section:
  - 99,85 % values for « maximum » quantities (ΣY, Y/Q, Q),
  - 50 % values for « quasi static » quantities (Y_{qst}, Q_{qst}).

b. Method of analysis

For every assessment quantity under investigation, the analysis uses a multi linear regression tool to determine a regression rule of the following form, using all the available information:

$X = a_0 + \Sigma a_i.x_i$ (i = 1, 2… n)

X being the assessment quantity under investigation (99,85 % or 50 % value)

and the x_i being the available input parameters.

This regression rule is associated to various statistical figures describing the relevance of the formula:

- global regression coefficient R^2 (should be as near to 1 as possible),
- standard deviation (in kN) of the part not explained by the regression,
- Student coefficient t_i of each parameter i (same sign as the associated coefficient a_i).

It is usually assumed that there is a significant influence of a parameter when the associated Student t_i is, in absolute value, higher than 2. In other words, a regression rule as expressed above should only be used when all the t_i associated to the parameters used in this expression are greater than 2. However, it immediately appears (after performing the first round of regression) that most Student t_i do not reach this minimum.

So a sensible way to carry on the analysis consists in removing the parameter associated with the lowest t_i (in absolute value) and use the regression tool again. A new formula is obtained, with new coefficients a_i associated to new Student t_i. Usually, at this early stage, very little information is lost: the global R^2 decreased (and standard deviation increased) only marginally, whereas the Student t_i of the remaining (n - 1) parameters improved a little.

The same process is then repeated, after elimination of the remaining parameter associated with the lowest t_i (in absolute value), until all Student t_i are greater than 2 (in absolute value). In favourable cases, about 2 or 3 input parameters remain in the expression, and the global R^2 has not decreased too much since the beginning, because the parameters which have disappeared during the process were either of little influence on the force studied, or closely correlated to the remaining parameters.

Such a formula, using a reduced number of input parameters (statistically independent) associated to high Student t_i and retaining a rather high global R^2, can be used with relevance to estimate the force investigated as a linear combination of the appropriate test conditions.

c. Representation and harmonisation of results

Experience gathered over a long period and from the analysis of numerous tests showed it was necessary to adapt the process described above. Indeed, if from a scientific point of view it looks sensible to leave statistics identify the most appropriate representation of the influences, this usually results in heterogeneous formulae:

- the representations may use inter-correlated influence factors, which is not appropriate because in such a case their real influences interfere (coefficients in the regression may be shifted from one parameter to the other without altering the precision of the regression),
- they may also use irrational parameters, making the physical understanding of the phenomena difficult and the interpretation hazardous,
- the influence factors may vary from one vehicle to another, making comparisons impossible as well as the definition of common correcting rules.

This is why it has been chosen, in the 1st stage of the work, to « force » in some way the regressions, by seeking expressions of the forces under investigation as linear combinations of:

- 1 parameter representing track layout. Among the possible options (radius, curvature and cant), cant soon disappeared and **curvature 1/R** was finally preferred to radius, as providing a better representation of the increasing forces in sharp radii,
- 1 parameter representing running conditions; speed should be the right option for the behaviour on tangent track (not studied here); for curves **cant deficiency I** usually appears to be a better choice (and has already been, for many years, the parameter used in two dimensional analyses),
- 1 parameter representing track quality (for « maximum » quantities only, as it is physically obvious that « quasi static » quantities are independent on local defects of the track). It occurred that the **standard deviation of lateral defects Y_s** usually provided better results than vertical Z_s. This is easily understandable for lateral forces (ΣY), obviously more influenced by lateral defects, but regressions carried out on vertical forces Q provided results not significantly better with Z_s than with Y_s. Various explanations may be sought, such as a roll movement due to lateral defects, influencing the balance of vertical forces between both wheels. It shall also be noticed that lateral and vertical quality of the track, when examined using standard deviations over a certain length, are closely correlated together, which makes the use of any parameter (Y_s or Z_s) rather neutral. This is why, in order to allow a more homogeneous representation, Y_s has been retained for the analysis of both lateral and vertical forces.

Other parameters, when available, have sometimes provided very good results, adding a relevant « plus » to the comprehension of the physical phenomena and the validation of what the optimal test conditions should be. Among these, we may first of all quote the friction coefficient μ, unfortunately not directly accessible during tests (and out of control during operation), but which may be roughly approximated by the Y/Q ratio on the inner wheel of the guiding wheelset. Very recent analyses also showed the relevance of the newly defined radial steering index q_E, when analysing lateral forces or the Y/Q ratio in sharp radius curves. Some words will be said at the end of this paper, but lack of data did not allow a systematic use of these additional parameters in the frame of the present work.

So, at this stage, « quasi static » quantities will be approximated by regression rules of the form:

Y_{qst} or Q_{qst} = a + b/R + c.I

and « maximum » quantities will be approximated by regression rules of the form:

ΣY or Q = a + b/R + c.I + d.Y_s

5. First results

a. Locomotives - Study of Y_{qst}

In the frame of the revision of UIC Code 518, the curving force Y_{qst} of locomotives in small and very small radius curves (250 to 600 m) was analysed. The results are summarised in the following tables.

For a first set of locomotives, tested in Italy (4 types, the first of which was tested with new and worn wheel profiles), the $(Y/Q)_i$ ratio on the inner wheel, used to approximate the friction coefficient μ, was available as a mean value over every track section, together with curvature 1/R and cant deficiency I.

The results are really outstanding: as the first table shows, it is clear that these 3 parameters 1/R, I and $(Y/Q)_i$ explain most of the variability of Y_{qst}, R^2 values being all above 0,80.

Locomotive	IT1 new	IT1 worn	IT2	IT3	IT4	Mean
Global R^2	0,84	0,88	0,81	0,87	0,87	0,85
Standard error	3,40	2,76	3,20	3,44	3,30	3,22
Nb sections	252	248	263	266	229	252
a (constant)	-2,84	-7,23	-8,96	-13,31	0,69	-6,33
b (1/R)	9742	7481	5522	9045	6754	7709
c (I)	0,008	0,076	0,063	0,050	0,049	0,049
d $(Y/Q)_i$	56,8	45,5	96,8	94,5	64,2	71,6
Student t_a	-1,28	-4,17	-3,65	-5,76	0,34	-2,91
Student t_b	17,29	14,77	10,98	17,10	11,48	14,32
Student t_c	0,50	5,97	3,60	3,23	3,44	3,35
Student t_d	21,61	23,85	22,67	31,88	22,54	24,51
$\sigma(1/R)$	0,00045	0,00045	0,00046	0,00045	0,00046	0,00045
$\sigma(I)$	15,0	16,0	12,1	15,1	16,7	15,0
$\sigma(Y/Q)_i$	0,088	0,104	0,051	0,073	0,091	0,081
$b.\sigma(1/R)$	4,4	3,3	2,5	4,0	3,1	3,5
$c.\sigma(I)$	0,1	1,2	0,8	0,8	0,8	0,7
$d.\sigma(Y/Q)_i$	5,0	4,7	4,9	6,9	5,9	5,5

Table 1 - Locomotives - Expression of $Y_{qst} = a + b/R + c.I + d(Y/Q)_i$

Student t values for $(Y/Q)_i$ are above 20, which shows that the influence of this parameter is even stronger (and constant) than that of curvature (also obvious, with Student t above 10).

Cant deficiency comes only third... although it is currently specified in EN 14363 as the normalising parameter in a two dimensional evaluation! This could at first be explained by the rather limited range of evolution of I (contrived by imposed test conditions) as compared with the more open range of radii taken into account (250 to 600 m), but additional studies confirmed this trend.

The relative influences of these 3 parameters can be compared using the product of their coefficient in the regression (b, c and d respectively) and the standard deviation of each of these parameters; resulting values are 5 - 6 kN for friction, 3 - 4 kN for curvature and less than 1 kN for cant deficiency.

The analysis was extended to 3 locomotives tested in France, but without use of $(Y/Q)_i$; the next table confirms the first results as regards the relative influences of curvature and cant deficiency, the first always being more important than the second. The lack of information when losing $(Y/Q)_i$ is obvious when considering the global R^2 values obtained on the Italian locomotives, now around 0,50.

Locomotive	FR1	FR2	FR3	IT1 new	IT1 worn	IT2	IT3	IT4
Global R^2	0,69	0,59	0,10	0,54	0,59	0,44	0,36	0,56
Standard error	4,06	5,39	8,86	5,75	5,03	5,52	7,59	5,95
Nb sections	94	88	93	252	248	263	266	229
a (constant)	14,80	28,37	20,08	14,69	-0,24	21,62	17,21	2,42
b (1/R)	9649	10227	6157	14203	12975	9968	12055	13204
c (I)	0,186	0,027	0,109	-0,039	0,021	0,061	0,039	0,075
Student t_a	3,48	6,06	2,16	4,20	-0,08	6,11	3,71	0,66
Student t_b	8,29	10,88	1,72	15,99	15,79	12,48	10,50	14,27
Student t_c	4,83	0,91	1,75	-1,46	0,93	2,04	1,14	2,94

Table 2 - Locomotives - Expression of $Y_{qst} = a + b/R + c.I$

Considering (after the previous study) that cant deficiency was not so influent, an extended sample of locomotives (including some for which the individual values of cant deficiency were not available) was analysed using only curvature (single regression). The results are shown in the next table.

Locomotive	FR1	FR2	FR3	IT1 new	IT1 worn	IT2	IT3	IT4	DE1	DE2	DE3	SJ1
Global R^2	0,61	0,59	0,07	0,53	0,58	0,43	0,35	0,54				
Standard error	4,52	5,38	8,96	5,77	5,03	5,55	7,59	6,05				
Nb sections	94	88	93	252	248	263	266	229				
a (constant)	32,38	32,23	29,79	10,42	2,18	27,88	21,66	11,45	33,00	28,00	48,00	9,71
b (1/R)	12871	10306	8572	13662	13347	10543	12591	14259	9840	12620	6960	12792
Student ta	13,15	16,04	3,96	5,43	1,27	15,72	8,73	5,54				
Student tb	12,11	11,02	2,57	16,88	18,59	14,02	12,03	16,44				

Table 3 - Locomotives - Expression of $Y_{qst} = a + b/R$

The evolution of R^2 values between Tables 2 and 3 shows that little information was lost, curvature being much more influent here than cant deficiency. It may also be noticed that the coefficients for 1/R are fairly close to each other, which allowed UIC Study Group in charge of the revision of Code 518 to derive from this study a new expression of the limit value:

$\mathbf{(Y_{qst})_{lim} = 30 + 10500/R_m}$, R_m being the mean radius of test sections.

When Y_{qst} is estimated using a 2-dimensional analysis according to cant deficiency (as requested now in UIC 518 and EN 14363 for all quasi static quantities), this allows a normalisation of test conditions regarding both radius and cant deficiency. However, the present study shows that it would be highly desirable to include also friction in such a normalisation. Work in this field is still ongoing.

It must also be said that this study, based on locomotives only (being the most critical type of vehicle in terms of Y_{qst}), would lead to different coefficients for other types of vehicles (multiple units, freight wagons…), as will be shown later in this paper. So the limit value stated above should be considered as a first step towards normalisation, but still to be improved.

b. Extension to other vehicles and quantities

In the frame of CEN WG10, the work carried out on Y_{qst} for locomotives was extended to other assessment quantities (ΣY, Q, Q_{qst}) and other types of vehicles (multiple units and freight wagons). The idea was to investigate whether the rather promising results obtained could be generalised, thus providing a way to normalise test results to target conditions which may be difficult to achieve.

This work was performed using the test results of 7 vehicles tested in France:

- 3 locomotives (1 BB + 2 CC),
- 1 standard design EMU (powered - leading - and non powered bogies),
- 1 articulated DMU (powered - leading - and non powered - Jacobs - bogies),
- 2 freight wagons (fitted with 2 2-axles bogies).

With the exception of the non powered bogies of the EMU and DMU, the investigations were made on the first (leading) wheelset of the vehicle, where the forces are usually the highest. As explained in section 4.c, the regression rules investigated are of the form:

$\mathbf{Y_{qst}}$ **or** $\mathbf{Q_{qst}}$ **= a + b/R + c.I** for « quasi-static » quantities,

$\mathbf{\Sigma Y}$ **or Q = a + b/R + c.I + d.Ys** for « maximum » quantities.

The analyses are summarised in tables of results, not reproduced here, but similar to those presented in section 5.a. The main conclusions are given hereafter, for each assessment quantity.

c. Sum of guiding forces ΣY_1

The regression is rather good on both CC locomotives ($R^2 = 0,69$) and on both bogies (0,64 and 0,58) of the articulated DMU, but much poorer ($0,17 \le R^2 \le 0,30$) on the EMU and the freight wagons.

Using the same criteria as in 5.a (Student t values for the significance of a parameter and product « coefficient x standard deviation » of this parameter to characterise its influence on ΣY_1 variations), we can say that there is always a positive correlation of ΣY_1 with cant deficiency and track defects (ΣY_1 increases when cant deficiency increases or when track quality deteriorates). The share of both parameters in the variability of ΣY_1, assessed by « coefficient x standard deviation » index, is similar (about 2,2 kN each, as an average on the 9 investigated bogies).

As regards curvature, the influence is clearly positive on the vehicles (locomotives and DMU) providing good regressions, but appears to be very uneven on the EMU and wagons. On the former, the « coefficient x standard deviation » index of 1/R is similar to that of cant deficiency or track quality.

Talking now about the coefficients of the regression (sensitivity of ΣY_1 to the variations of curvature, cant deficiency and track quality), and considering the locomotives, the orders of magnitude are:

- 5300 kN/(m^{-1}) for curvature variations,
- 0,17 kN/mm for cant deficiency variations,
- 9 kN/mm for track quality variations (measured by standard deviation of lateral alignment).

For the other vehicles the sensitivity of ΣY_1 to cant deficiency variations is usually around 0,14 kN/mm and its sensitivity to track quality around 4 kN/mm only for multiple units …but 12 kN/mm for wagons! The influence of curvature is too unstable to be quoted.

d. Guiding force Y_{qst1}

The results found on the locomotives (none of which was among those studied in 5.a) are rather good (global R^2 of at least 0,50) and fully confirm the conclusions of section 5.a:

- strong and stable influence of curvature:
    - very high Student t values, largely above 10,
    - similar sensitivity coefficients, around 10500 kN/(m^{-1}), consistent with the new limit,
    - « σ.coef » index around 5 kN,
- secondary influence of cant deficiency:
    - positive but lower Student t values,
    - positive but uneven sensitivity coefficients,
    - « σ.coef » index around 1 kN.

But the results on the EMU, DMU and wagons are really inconclusive:

- most Student t values are around zero (except some values on multiple units),
- sensitivity coefficients are low and uneven,
- « σ.coef » indices never reach 2 kN (except for curvature on the trailing bogie of the EMU: 4 kN).

As a conclusion, the analysis and the values reported in section 5.a are confirmed for locomotives, but cannot be extended to other vehicle types, on which the influence factors of the guiding force Y_{qst}, if any, remain to be determined.

For all vehicle types, the influence of friction, identified on Italian locomotives as being even stronger than the influence of curvature, should be investigated. Other parameters (such as the radial steering index q_E) might also be relevant in the generation of Y_{qst}.

e. Vertical force Q_1

Although virtually all correlations are positive (Q increases when curvature, cant deficiency or track defects increase), the results are about the same as for ΣY_1: rather good for locomotives and rather uneven for multiple units and freight wagons.

For the 3 most conclusive cases (CC locomotives and leading bogie of the DMU), we find an evenly distributed influence of curvature, cant deficiency and track quality, with Student t values around 7 and « σ.coef » indices between 1 and 6 kN. The coefficients of 1/R, I and Y_s in the regression, however, differ from a vehicle to another, making it difficult to derive common rules.

An unexpected result of these studies, though not incidental because this is a constant trend, is that Q forces are depending on the curve radius; in fact, when examining together the regressions for both wheelsets of the bogie we find that:

- when curvature increases, the load on the outer wheel of the first wheelset increases, whereas the outer wheel of the second wheelset unloads of a similar quantity; on average, on the 9 bogies investigated, the coefficient is about +/- 4000 kN/(m^{-1}),
- the influence of cant deficiency is rather evenly shared on both wheelsets, with mean coefficients of 0,17 and 0,20 kN/mm respectively,
- the influence of track defects is also rather evenly shared, with coefficients around 7 kN/mm.

As expressed above, these coefficients are only mean values, the individual figures being scattered, with a more stable influence of cant deficiency, then track defects, then curvature, and the regression being more reliable in the case of locomotives …as for the other quantities.

f. Vertical quasi-static force Q_{qst1}

The usual conclusions apply: locomotives provide the best regressions, although the leading bogie of the DMU also stands out, and even the freight wagons show some consistency here!

The results are consistent with the analysis of Q_1 regarding the positive correlation with curvature (opposite effect on the second wheelset) and cant deficiency, with similar influences.

Note: the UIC study carried out for the extension of the axle load to 25 tonnes had led to the following theoretical formula, validated by test results:

$\mathbf{Q_{qst} = Q_0.(1 + 2,3.h_G.I/e^2)}$ where: Q_0 = static wheel load in kN

h_G = height of centre of gravity above rails

I = cant deficiency

e = distance between rolling circles (1500 mm / standard gauge)

The accuracy of this formula has been checked on various vehicles, but with the previous definition of Q_{qst} (where all outer wheels of a bogie are combined). In a separate assessment of wheelsets 1 and 2 the influence of curvature (positive on the first wheel, negative on the second) shall be included.

6. Conclusion - Possible applications and next steps

These studies on the influence factors of Y and Q forces showed differences between vehicle types, locomotives usually providing better results than multiple units and - even more - freight wagons.

In favourable cases, linear regressions of test results allow the estimation of the forces investigated (ΣY, Y_{qst}, Q and Q_{qst}) as linear combinations of curvature 1/R, cant deficiency **I** and track quality Y_s. These regressions open the door to possible recalculations of the estimated values of these quantities for target (specified in EN 14363) values of the relevant test conditions.

In some cases the regression rules may be consistent enough to derive general normalisation rules, which can take the form of:

- a common correction coefficient, which can be used to correct the original estimated value by adding a term « coefficient x missing amount of the influencing factor », before comparison with the limit value,
- or a limit curve (such as $\mathbf{30 + 10500/R_m}$), including the most important influencing parameters.

In such a situation, it is not even necessary to perform a specific analysis for the vehicle considered; this is the approach proposed for Y_{qst} on locomotives (but not valid for other types of vehicles).

However, even when the regressions found allow a sensible representation of the vehicle behaviour, usually this expression is only applicable to this vehicle, because similar studies on various vehicles lead to too different coefficients. In this case the correction proposed above in order to upgrade the estimated values to target test conditions remains possible, but shall be made using the coefficients (b, c, d…) determined by a specific analysis of this vehicle's results.

If the regression rule obtained is: $a + b/R + c.I + d.Y_s$

the correction to be applied is: $b.(1/R_t - 1/R_m) + c.(I_t - I_m) + d.(Y_{st} - Y_{sm})$

where index « t » refers to target conditions (EN 14363) and index « m » to the mean conditions achieved during the test (or possibly the 90% value when talking of Y_s).

Then, there are cases where no useable regression can be found ($R^2 \approx 0$), which was often the case in the present study for freight wagons for example. In such a situation, no sensible correction can be applied; however, a low R^2 being associated with low regression coefficients, no correction needs to be applied, and it can be assumed that testing in the target conditions would have produced similar estimated values.

The implementation of these principles, the advantages of which have been described in Section 3, necessitates a confirmation of the first results, exploring:

- the feasibility of the process described (linear regressions of vehicle test results → determination of regression coefficients → correction of the original estimated values),
- the possibility to define, in limited cases, common coefficients,
- the influence of other parameters, some of which look promising (friction, radial steering index).

This is expected to be done in the frame of CEN TC256 WG10, based on the study of more test results from different types of vehicles tested in different countries.