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1 **PAVING THE WAY TO USE WIM SYSTEMS FOR DIRECT ENFORCEMENT IN FRANCE**

2

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ABSTRACT

This paper presents an overview of a National project carried out in France since 2014. The project aimed assessing the feasibility of using high-speed WIM systems for direct enforcement of overloads, and to prepare their certification.

Specifications are proposed for a type-approval procedure, taking into account the requirements of the Ministry of Transport. They follow the International Recommendation R-134 of the OIML, with a few adaptations and derogations. Field tests were carried out over 3-4 years on a motorway with two WIM systems and more than 1,500 trucks and 330 vans from the traffic flow. The accuracy of these systems was assessed both by a statistical approach (COST323) based on tolerance intervals and confidence levels, and a metrological approach based on maximum permissible errors (OIML). Both WIM systems meet the COST323 accuracy class A(5) for trucks and class B(10) for vans, all with fully loaded vehicles. Therefore, the feasibility of using high-speed WIM for direct enforcement was shown. The next step will be the type-approval of the instruments. Finally, a closed test track (Transpolis, near Lyon) was proposed to carry out type-approval tests. Measurements with two instrumented vehicles were done in 2019-2020, in order to assess the maximum variations of the axle impact forces, and to compare them with the measurements on the motorway and with the tolerances of the expected accuracy classes. The closed test site is technically qualified to welcome type-approval tests of WIM systems or direct enforcement.

The project paves the way for direct enforcement by WIM.

Keywords: Weigh-In-Motion (WIM), Direct Enforcement, Overloads, Heavy Commercial Vehicles.

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INTRODUCTION

Trucks are carrying more than 75% of the goods on the road in the European Union (EU), and even almost 80% in some Member States, like in France. This mode share is slightly increasing over time, because of its efficiency and flexibility. Heavy good vehicle weights and dimensions increase since several decades, to face the increasing demand of goods volume, to reduce the congestion and the CO2 emissions (1). The European Directive 96/53EC (2) lays down the maximum authorized weights (in international traffic) and dimensions (in national and international traffic) of heavy vehicles in the EU. The common maximum weight for 5 and more axle vehicles is 40 t. However, the Member States may authorize higher weight limits for national traffic, and many of them did that. E.g. Scandinavian countries (Finland, Sweden) allowed the European Modular Systems (EMS) since 1996 up to 25.25 m in length (by derogation) and 60 t, followed since 2000 by several other countries, such as Denmark, Netherlands, and then Belgium; Germany introduced the EMS up to 40 t for volume demand. Recently Finland and Sweden authorized EMS2 (second generation) up to 33 m in length and 74 t.

Overloads are inducing infrastructure wear, both on pavements and bridges, reduce their lifetimes and safety (3), and even in the worst cases may lead to bridge collapses (Figure 1). Overloads also affect the road safety while increasing the truck instability and the consequences in case of an accident. Finally, overloads deeply affect the fair competition between transport companies and modes. Heavier the weight limits, more aggressive the overloads for a given percentage of overloading. Therefore, the revised European Directive 2015/719 (4) on heavy vehicle weights and dimensions introduced a new article requiring the Member States to perform overweight controls by WIM and to report to the European Commission (EC). Because of the high heavy traffic volume on the main European corridors (TEN-T: Trans-European Transport Network), the lack of staff (police, weighing and traffic officers) and road safety reasons, some Member States decided investigating, or even implementing, direct enforcement by WIM. It increases the frequency and efficiency of weight controls, and avoids stopping vehicles along the roads. Czech Republic and Hungary (5) implemented direct enforcement by WIM in 2011-2018, while Belgium (6), France (7) and Germany are on the way.



Figure 1 Collapse of Annone bridge in Italy under a 108 t truck in October 2016 (legal limit: 44 t)

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However, using WIM for direct enforcement requires a type-approval (certification), initial and periodic verifications of WIM systems by the Legal Metrology. Statistical approaches such as proposed in most of the WIM standards, ASTM1318 (8) or COST323 (9, 10), cannot be used for such legal applications, and the maximum permissible errors (MPE) should be used as stated in the OIML International Recommendation R-134 (11).

The French Ministry of Transport committed IFSTTAR (now University Gustave Eiffel) and the Cerema in 2014 to carry out a R&D project (12) to prove the feasibility of using existing WIM systems for direct enforcement, and to develop specifications to certify them. The first phase of this project, completed in 2018, showed, by testing two marketed WIM systems over 3 years on a motorway (A4), that it was

1 possible to meet the required accuracy classes, OIML 5 or 10 depending on the categories of heavy
2 vehicles. The second phase of the project ran in 2019-2021 developing the specifications and qualifying a
3 test site to certify WIM systems for direct enforcement. Field tests also continued on the A4 motorway,
4 above all with vans (3.5 t commercial vehicles). This paper summarizes the proposed specifications,
5 reports the main results of the field test on motorway over 2015-2019, and presents the procedure and
6 measurements to qualify a certification test site in France (Transpolis).

8 **SPECIFICATIONS TO CERTIFY A WIM SYSTEM FOR DIRECT ENFORCEMENT**

9 **Frame**

10 The certification of an instrument such as a WIM system, for use in a legal metrology frame,
11 includes:

- 12 (1) a type-approval procedure, applied once to a model of the instrument and valid for all the copies
13 manufactured without any hardware or software modification,
- 14 (2) an initial verification performed on each new copy of the instrument after its installation or adjustment,
- 15 (3) periodical or in-service verifications, commonly performed once a year, to check that the required
16 accuracy is still valid.

17 The OIML R-134 (11) specifies the accuracy classes of WIM instruments, which are defined by
18 the MPE on gross vehicle mass (GVM), e.g. classes 1, 2, 5, 10. The R-134 also specifies MPEs for the
19 axle loads. The recommendation also describes a procedure and test plan to assess the accuracy of any
20 WIM system by testing, within its range of operation. This recommendation was developed in the early
21 2000s and first published in 2002, but only for low-speed WIM systems operated on dedicated weighing
22 area and relevant apron. In 2006, its scope was extended for use on road and in traffic lanes, at current
23 speed. However, most of the clauses and provisions were not adapted, which causes some discrepancies
24 and difficulties to implement. In 2018-19, several stakeholders required a new revision to better account
25 for high-speed WIM, and above all for direct enforcement in the traffic flow. This revision is still in
26 progress in the OIML committee TC9/SC2/p11.

27 In each country, the Legal Metrology Organization (LMO) is in charge of approving the
28 specifications and procedure for the certification of WIM systems operated in a legal frame. LMOs mostly
29 apply the R-134, but sometime with national adaptations or derogations, taking into account the end users'
30 or clients' requirements. Therefore, in France IFSTTAR was committed to develop, jointly with the
31 Cerema, specifications meeting the requirements expressed by the Ministry of Transport for direct
32 enforcement of overloads. The SPW (Public Service of Wallonia, Belgium) is doing the same to certify a
33 WIM system for direct enforcement with a slightly different approach (6).

35 **French requirements and specifications for type-approval of WIM systems for direct enforcement**

36 The proposed specifications are based on the R-134 (11). They apply to high-speed WIM systems
37 using road sensors installed on open highways and motorways, operated in the traffic flow. The eligible
38 OIML classes for the GVM are 2, 5, 10, with two additional classes proposed if needed, 15 and 20, not yet
39 in the R-134 but proposed in the revision. The classes for axles loads are D, E, F and an additional
40 proposed class G, with MPEs of 4, 8, 16 and 32% (in-service, but for a 2-axle rigid lorry with half of these
41 MPEs). The proposed multiplicative coefficient applied to the MPE for type-approval test and initial
42 verification is 0.8 instead of 0.5. Various categories of heavy vehicles may be weighed in different
43 accuracy classes (**Table 1**). While the aim is enforcing overloaded vehicles, only fully loaded vehicles, at
44 or above the maximum permitted weight, are recommended for the test (**Table 1**). The French LMO
45 should still approve these clauses. The tandem axles will not be enforced, at least in a first step, because
46 their maximum authorized weight depends on the axle spacing, which is not a certified quantity. **Table 1**
47 also indicates the lower and targeted accuracy classes for each quantity, as expressed by the Ministry of
48 Transport. However, the final accepted class will meet the performances of the submitted WIM systems.
49 The class 5 corresponds to the current tolerance given in static controls by the driving law, i.e. 5%. The
50 aim is not to increase this tolerance to avoid any increase of the overloads. However, for the vans and may
51 be the 2-axle (or 3-axle) trucks, the accuracy of WIM systems may be lower than for heavier trucks and a

1 higher tolerance (e.g. 10%) corresponds to a limited extra amount of goods and of aggressiveness on road
 2 infrastructure.

3
 4 **TABLE 1 Categories of vehicle to be enforced, maximum permitted weight, test range and targeted**
 5 **accuracy classes**

Category of vehicles	Max permitted GVM	Test range	Lower/targeted accuracy class
Van	3,500 kg	≥ 3,500 kg	20/10
2-axle rigid*	19,000 kg*	≥ legal limit	10
3-axle	28,000 kg	≥ 28,000 kg	10/5
4-axle rigid	32,000 kg	≥ 32,000 kg	5
4-axle articulated	38,000 kg	≥ 38,000 kg	5
5 and more axles	40,000 or 44,000 kg	≥ 40,000 kg	5
Axles	Max permitted load	Test range	Lower/ targeted accuracy class
Single axle	13,000 kg	10,000-25,000 kg	F/E
Tridem axle	27,000 kg	≥ 24,000 kg	F/E

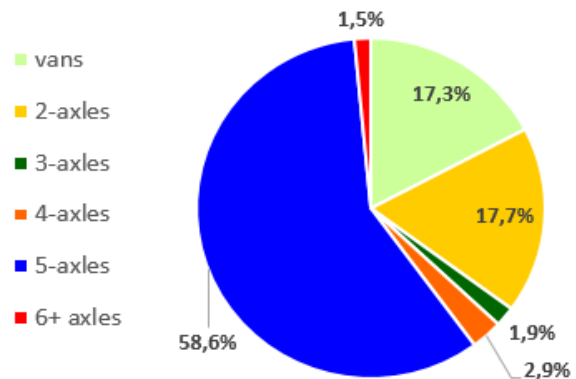
6 * There are several legal limits in this category

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 8 **ASSESSED ACCURACY OF WIM SYSTEMS ON A MOTORWAY**

9 **Objectives and methodology**

10 Two commercial WIM systems (Kapsch and Sterela) are installed and tested since 2015, by the
 11 Cerema (East unit in Metz), on the A4 motorway (Paris to Strasbourg) in Saint-Avold, eastern France
 12 (**Figure 2**). The test site meets the requirements of a class 2 (good) WIM site according to the COST323
 13 specifications. This site is also used for pre-selection of overloads. A control area is located 7 km
 14 downstream, right after a main tollgate, equipped with an approved in OIML class 5 static axle scale for
 15 enforcement. During the control periods, the static weighs are used as references to assess the accuracy of
 16 WIM data. The vehicles from the traffic flow are weighed once in static.

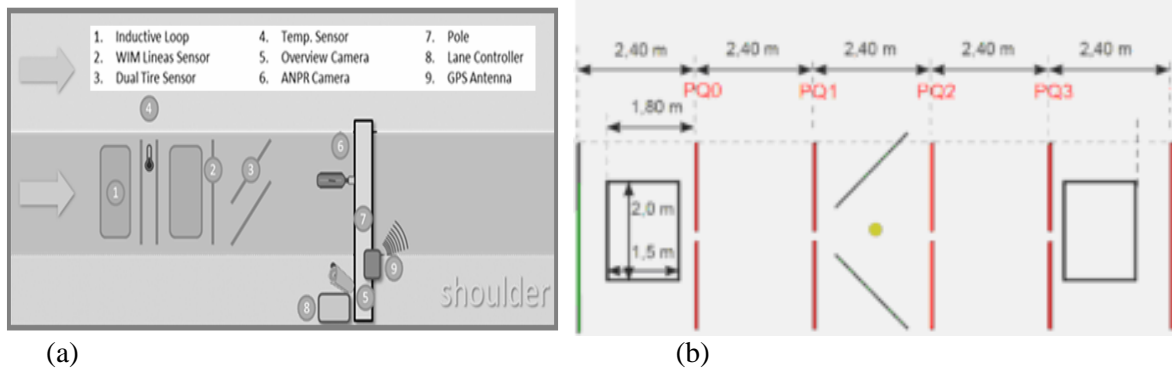
17 Both WIM systems use piezo-quartz Lineas sensors by Kistler with the layout shown in **Figure 3**.
 18 Kapsch uses 3 rows of WIM sensors, and two slantwise sensors for dual wheels detection and wheel
 19 location. Sterela uses 4 rows of WIM sensors, and a V-shaped set of sensors.



20
Figure 2 Test site on the motorway A4 in Saint-Avold (SANEF), and population of reference vehicles from the traffic flow

21 From November 2015 until August 2019, 1,253 trucks and 332 vans from the traffic flow were
 22 weighed in static over 36 days of measurements, forming the reference vehicle set for accuracy
 23 assessment (**Figure 2**). These vehicles were mainly fully loaded or slightly overloaded, and pre-selected
 24 by a third WIM system. The accuracy of the WIM systems and their capability to perform direct
 25 enforcement are assessed by evaluating the statistical accuracy according to the COST323, which is
 26

1 acceptable in this study phase, and in full reproducibility conditions (using vehicles from the traffic flow).
 2 However, the errors exceeding the MPEs of the OIML classes are also noted, in accordance with the
 3 criterion fixed for direct enforcement.
 4



5
 6 (a) (b)
 7 **Figure 3 Layout of (a) Kapsch system, (b) Sterela system**
 8

9 **Results and conclusions**

10 Over the whole test period, the Kapsch system delivered measurements over 19 days, providing
 11 validated data for 559 trucks among 561 measured, 1,098 single axles among 1,103, 553 groups of axles
 12 among 555 and 182 vans among 186, i.e. 99.5% of validated measurements. The Sterela system delivered
 13 data over 36 days, for 1,042 trucks among 1,253 measured, 2,035 single axles among 2,449, 1,045 groups
 14 of axles among 1,260 and 307 vans among 332, i.e. above 83% of validated measurements. Doubtful
 15 measurements are eliminated by these systems and built-in algorithms, and thus neither accounted for in
 16 the statistics or MPE assessment, nor leading to any wrong penalizing. Because of some technical issues,
 17 the Kapsch system only worked over a bit more than a half of the period.
 18

19 **TABLE 2 Numbers of functioning days and measurements and accuracy of both WIM systems**
 20 **according to the COST323, conditions R4-III for each WIM system.**

KAPSCH	Number	Mean (%)	Std deviat (%)	π_o	Class	δ	δ_{min}	π
gross weight	559	1.68	1.96	91.7	A(5)	5	4.6	94.6
group of axles	553	2.42	2.45	91.7	A(5)	7	6.0	96.7
single axle	1098	0.83	2.87	92.1	A(5)	8	5.4	99.1
Vans	182	1.18	3.99	90.5	B(10)	10	7.6	97.5
STERELA	Number	Mean (%)	Std deviat (%)	π_o	Class	δ	δ_{min}	π
gross weight	1042	1.42	2.02	92.1	A(5)	5	4.4	95.5
group of axles	1045	2.35	2.73	92.1	A(5)	7	6.4	95.4
single axle	2035	0.37	3.51	92.4	A(5)	8	6.4	97.4
Vans	307	3.22	2.70	91.2	B(10)	10	7.6	98.4

	KAPSCH				STERELA			
	GVM	GoA	SA	Vans	GVM	GoA	SA	Vans
Period 1	4.3 A(5)	6.0 A(5)	5.0 A(5)	5.7 B+(7)	4.6 A(5)	6.5 A(5)	6.4 A(5)	7.6 B(10)
Period 2	5.2 B+(7)	6.4 A(5)	6.2 A(5)	7.4 B(10)	3.7 A(5)	5.8 A(5)	6.4 A(5)	8.3 B(10)
Period 3	5.1 B+(7)	4.8 A(5)	8.7 B+(7)	9.0 B(10)	4.1 A(5)	7.0 A(5)	7.4 A(5)	7.2 B(10)
Total	4.6 A(5)	6.0 A(5)	5.4 A(5)	7.6 B(10)	4.4 A(5)	6.4 A(5)	6.4 A(5)	7.6 B(10)

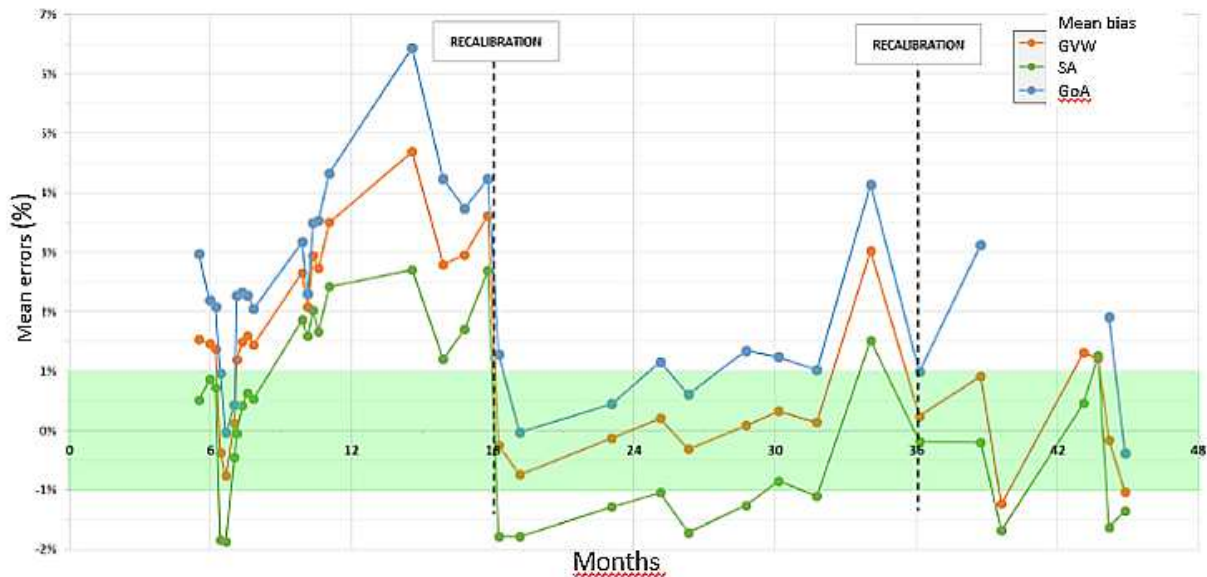
Lower part: each cell contains the δ_{min} and the accuracy class.

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1 **Table 2** gives the accuracy of each system according to the COST323, over the whole period,
 2 from 9/6/2016 until 8/28/2019 for Kapsch, and from 11/9/2015 until 8/6/2019 for Sterela. This provides
 3 fruitful information on the performances of the systems, prior to a future type-approval to be done with
 4 respect to the OIML recommendation. The means and standard deviations are those of the relative errors
 5 of the WIM data vs the static weights measured on the approved axle scale (the gross vehicle weight and
 6 group of axle loads are obtained by summing up the individual axle loads). The test conditions are R4, full
 7 reproducibility, as all the vehicles are taken in the traffic flow and weighed once, and III, i.e. full
 8 environment reproducibility (more than a year of testing). π_0 is the minimum confidence level required for
 9 each entity (gross vehicle mass – GVM, single axle – SA and group of axles – GoA loads), which depends
 10 on the sample size (statistical uncertainty), on the test conditions (repeatability/reproducibility) and on the
 11 entity. δ_{min} is the lowest tolerance (half of the confidence interval width) which exactly matches the
 12 confidence level π_0 . δ is the tolerance of the accepted accuracy class for each entity, and is greater or
 13 equal to δ_{min} . π is the confidence level of the interval $[-\delta;\delta]$, and is greater or equal to π_0 (11).

14 The accuracies of both WIM systems are very similar, in class A(5) for all entities of the trucks,
 15 and in class B(10) for the vans. The analysis, also done for 3 sub-periods between the systems adjustment
 16 (recalibration), is reported in the lower part of **Table 2**. The Kapsch system was adjusted late March 2018
 17 and mid-June 2019, while the Sterela system was adjusted mid-May 2017 and in October 2018. The
 18 accuracies of each system in each sub-period (periods 1 to 3) are very close to the accuracy over the whole
 19 period. A more detailed analysis day by day was done, showing a slight drift and bias increase which led
 20 to annual recalibration (**Figure 4**).

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Figure 4 Evolution of the mean bias along the time and adjustments (recalibrations) – Sterela system

26 These results are encouraging and in agreement with the requirements expressed by the Ministry
 27 of Transport. However, the metrological requirements are more demanding than the COST323, because
 28 all the errors should be lower than the MPE of the retained accuracy class, to guarantee that no vehicle
 29 could be wrongly penalized (false detection). **Table 3** shows the numbers and proportions of
 30 measurements, by entity and systems, which exceeded the MPEs of the OIML classes 5 and 10, over the
 31 whole period. The MPEs are 5 and 10% for GVM and 8 and 16% for axles and groups of axles in classes
 32 5 and 10 respectively, for in-service verification. For trucks, the class 10 is almost met, all along the 3
 33 years (Kapsch) or 4 years (Sterela), with only 1 to 4 measurements out of the tolerances (less than 0.2%).

1 This is fully satisfactory on a class 2 site. The MPEs of the class 5 are only exceeded by less than 3.5% of
 2 the trucks, mostly at the end of each period between recalibration. It means that the class 5 is achievable,
 3 either by a more frequent recalibration or by improving the sorting process implemented in each system,
 4 which eliminate the doubtful measurements. Reducing by 5 or 10% the rate of validated measurements
 5 would not significantly affect the efficiency of direct enforcement, but would reduce the tolerances and
 6 thus the overloads. For the GVM of vans, the class 10 is almost met by the Kapsch system and not far for
 7 Sterela, and again would be achievable by slightly decreasing the validation rate. On a class 1 site it was
 8 shown that the classes 5 and 10 are met by trucks and vans respectively.
 9

10 **TABLE 3 Numbers and proportion of measurements exceeding the MPEs for OIML classes 5 and**
 11 **10**

OIML	KAPSCH				STERELA			
	GVM	GoA	SA	Vans	GVM	GoA	SA	Vans
class 5	20 3,6%	5 0,9%	17 1,6%	42 23,1%	36 3,5%	27 2,6%	50 2,5%	74 24,1%
class 10	0	0	2 0,2%	1 0,6%	0	2 0,2%	4 0,2%	9 2,9%

12 All these results led to the feasibility of using high-speed WIM for direct enforcement, without
 13 increasing too much the tolerances. However, the manufactured WIM systems remain to be type-approved
 14 by the LMO.
 15

16 **QUALIFICATION OF A CLOSED TEST SITE FOR TYPE-APPROVAL**

17 **Interest to do the type-approval tests on a closed site**

18 At this stage, it is proposed to carry out the type-approval tests on a closed test site for the
 19 following reasons:

- 20 - it is much safer to perform such tests outside of the traffic flow, above all for the lowest speeds or for
- 21 runs which may not be centred in the traffic lane,
- 22 - it will not be allowed to run overloaded vehicles on an open road,
- 23 - the runs on open road, and above all on motorways and highways, generally are much longer (loops
- 24 between two exit/entrance), and require much more time and fuel (thus CO2) than on a closed site,
- 25 - most of the required tests may easily be done on a closed site; if a few complementary tests require the
- 26 traffic flow, they will be done on an open road.
 27

28 Moreover, if the test site is slightly better than some operational WIM sites, it is not an issue
 29 because the type-approval test determines the best accuracy class in which an instrument may be used. On
 30 each operational site, each copy of the WIM system will pass an initial verification and may be declared
 31 and operated in a lower accuracy class, according to the site characteristics.

32 This section presents a proposed closed test site, for French or European certification of WIM
 33 systems for direct enforcement, which may be open to the interested countries.

34 However, the SPW in Wallonia (Belgium) preferred to carry the type-approval tests on open road,
 35 after rebuilding the pavement on the site.
 36

37 **Presentation of the Transpolis test site and objectives of the trial**

38 The site of Transpolis is proposed. This site was developed to carry road and street tests of
 39 solutions and equipments for new mobilities, incl. autonomous vehicles, both in urban or interurban area.
 40 The test site is located 30 km northeast of Lyon (France), on a former military ammunition storage camp
 41 of 80 ha. The area with the former storage buildings, whose facades are modelling houses and buildings,
 42 represents a “city” (Figures 5 and 8). Streets were built in this area, which is surrounded by a circular
 43 boulevard. The WIM test zone is located on a straight main boulevard (6 lanes) crossing this area and is
 44 1 km in length. There are more roads and portions of motorways outside the “urban area”. The site is fully
 45 equipped with energy and telecommunication facilities, incl. 4G and Wifi. An axle scale is available in a
 46 garage located near the site entrance where the test vehicles are prepared.

1 Before proposing this site for type-approval tests, the aim was to qualify it for this purpose. First it
2 was required to find a location where all categories of trucks could run at current speeds (up to 90 km/h),
3 even fully loaded, and in safe conditions. This was achievable on the main boulevard because of the road
4 coming from the site entrance almost aligned with it (**Figure 5**). The braking distance after the section
5 planned for WIM installation is long enough (400 m) to reduce the speed and take the turn on the circular
6 boulevard. Using the other roads of the site, the truck can achieve a loop in 2-3 min.
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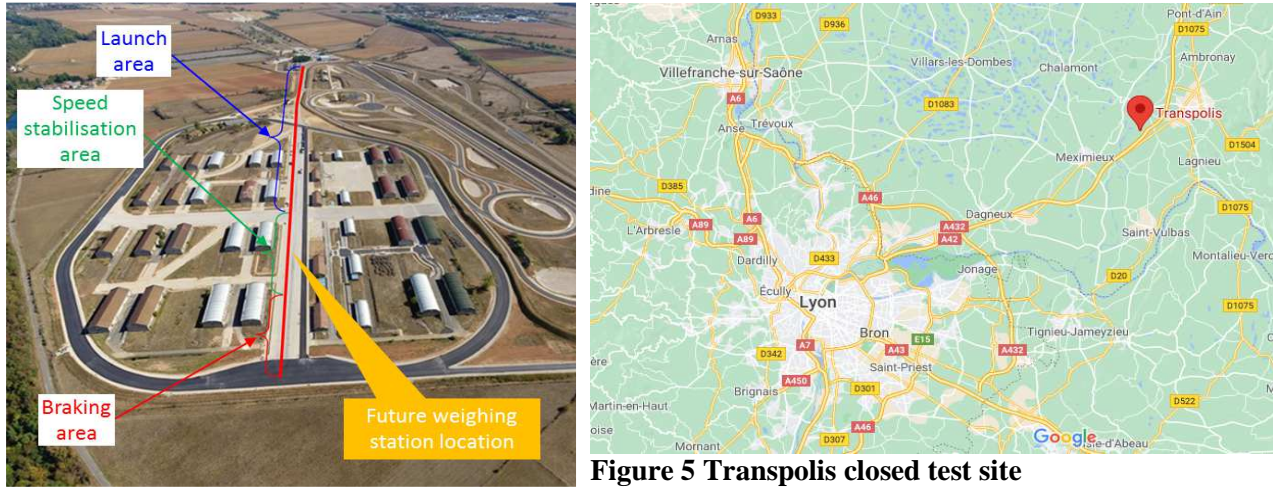


Figure 5 Transpolis closed test site

8
9 The most important question was to verify that the pavement on the test location is representative
10 of a common/good motorway or highway pavement. A test site should have a good evenness in order to
11 avoid too much dynamic effects, which may refrain a WIM system to meet the expected accuracy class.
12 Reversely, the LMO requires that the test site is not much better than the sites on open road where the
13 WIM systems will operate after approval. Therefore, two vehicles were instrumented as described in the
14 next sub-section, a 5-axle articulated truck and a light commercial vehicle (van), to perform measurements
15 in Transpolis and on the site of Saint-Avold on the motorway A4, where the tests with vehicles from the
16 traffic flow were already conducted.

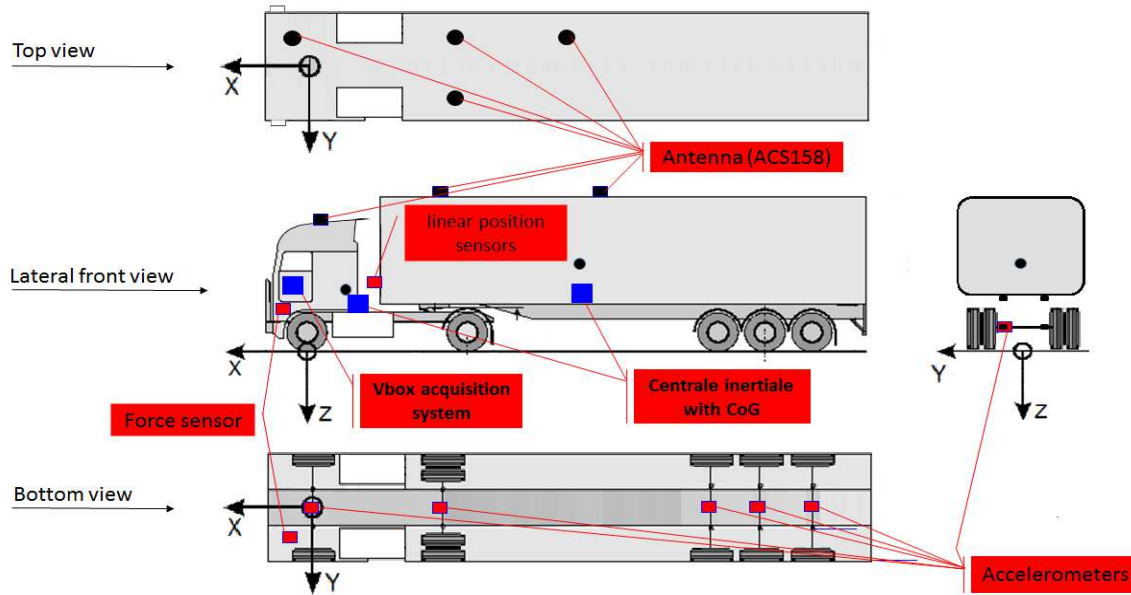
17 In the current version of the R-134, a half tolerance applies for the MPEs of type-approval tests
18 and initial verification, i.e. 2.5 and 5% respectively for the GVM in classes 5 and 10. This is very
19 demanding, and therefore some members of the OIML committee TC9/SC2p11 proposed to take the full
20 tolerances for all tests, while some other members (incl. France) proposed to apply a reduction coefficient
21 0.8 instead of 0.5. It is mandatory to check that the dynamic variations of the axle loads do not exceed too
22 much these reduced tolerances on the test site, otherwise the type-approval test may reject the targeted
23 accuracy classes. On some operational WIM site with lower characteristics, a WIM systems type-
24 approved in a given accuracy class may fail the requirements during the initial verification. In this case, it
25 may be used in a lower accuracy class (with higher tolerances). However, the opposite is not possible. A
26 WIM system type-approved in a given class can never be accepted in a better class, whatever the initial
27 verification. Therefore, it is safer, both for the vendors and for end users, to carry the type-approval tests
28 on a good site, representative of the best highways where weighing should be performed. The trials aimed
29 to compare:

- 30 (1) the variations of axle loads and gross vehicle weight of fully loaded instrumented vehicles, at
31 speed in Transpolis, with the required tolerances;
32 (2) these variations of axle loads and gross vehicle weight with those of the same truck (T2S3)
33 operated on the motorway A4, in Saint-Avold.
34

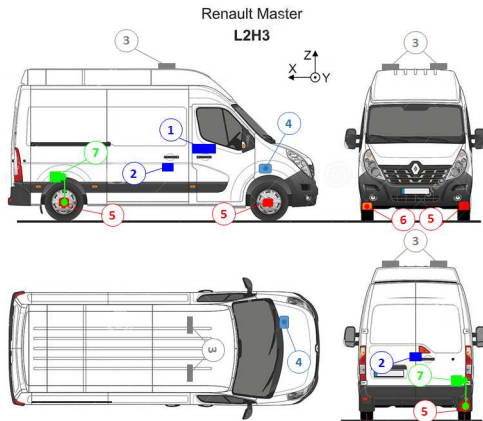
35 Vehicle instrumentation and assessment of the axle impact forces

36 Accelerometers and inertial measurement units (IMUs) were mounted by the Cerema (Centre-East
37 unit in Lyon) on the tractor, the semi-trailer bodies and axles of the articulated truck T2S3 (**Figure 6**), and

1 on the body and axles of the van (**Figure 7**), to measure the vertical accelerations of suspended and
 2 unsprung masses.
 3



4 **Figure 6 Sensors location on the 5-axle articulated truck T2S3**
 5
 6



7 **Figure 7 Sensors location on the van**

The axles of the T2S3 are instrumented with accelerometers (in red), as the front suspension arms and the rear axle of the van. The IMUs are mounted on the tractor and on the semi-trailer of the T2S3 (in blue), and on the body of the van (in green). The data sampling was done at 100 Hz.

A filtering of the recorded accelerations by frequency ranges allows distinguishing those of the suspended masses (tractor, semi-trailer and van bodies), in the range of 1 – 2.5 Hz, and those of unsprung masses (wheels, axles and suspension arms), in the range of 10 – 18 Hz. A third range of eigenfrequencies 5 – 9 Hz corresponds to the wheel imbalance of the truck.

8 Impact forces can be derived from the masses and accelerations. For a rigid body with a mass M
 9 and a single support point, the impact force at t can be expressed as: $F = M(g+\gamma(t))$, where g is the gravity
 10 intensity ($g = 9.81 \text{ m/s}^2$) and $\gamma(t)$ is the vertical acceleration of the body in motion at t . For a suspended
 11 mass moving on a not even pavement, $\gamma(t)$ varies around 0, with a maximum amplitude γ_{\max} (assuming that
 12 the variations are symmetrical between $-\gamma_{\max}$ and $+\gamma_{\max}$). The dynamic amplification factor (DAF) may be
 13 expressed as $D = \gamma_{\max}/g$.

14 For a 2-axle rigid vehicle, the model is a bit more complex. Three masses are involved: M_1 , M_2
 15 and M , the unsprung mass of the first axle, the unsprung mass of the second axle and the suspended mass
 16 of the body. If these masses are affected only by vertical accelerations, g , γ_1 , γ_2 and γ , the impact forces on
 17 each axle i are given by: $F_i = a_i M(g+\gamma) + M_i(g+\gamma_i)$, where a_i is the proportion of the body mass M carried
 18 by the axle i . The DAF of the axle i is given by: $D_i = (a_i M \gamma + M_i \gamma_i) / (a_i M + M_i) g$. If the vehicle is affected

1 not only by bounce motion, but also by pitch motion, i.e. a rotation around a horizontal axle perpendicular
 2 to the vehicle, the impact forces are modified; the coefficients a_i become time functions.

3 For a 5-axle articulated truck, the model becomes even more complex. There are 7 masses
 4 involved, M_1 to M_5 , M_i and M_s , the unsprung masses of each axle, the mass of the tractor and the mass of
 5 the semi-trailer. In addition to the vertical accelerations of each mass, more accelerations are generated by
 6 the pitch motion of the tractor, of the semi-trailer, and some load transfer from the semi-trailer to the
 7 tractor via the fifth-wheel coupling. The wheel imbalance effect must be considered. Roughly speaking,
 8 the unsprung masses are generally around 1/10 of the suspended masses.

9 Using the on-board measurements provided by the instrumented vehicles, and with a few
 10 simplification assumptions (e.g. pitch motion is neglected), the proposed estimate of axle i impact force is
 11 given by **Equation (1)**:

$$F_i = (W_i - M_i) \gamma_{sm\ i} + M_i \gamma_{um\ i} + M'_i \gamma_{wu\ i} \quad (1)$$

13 where W_i is the static load of axle i - the truck being weighed axle by axle on a horizontal area - including
 14 M_i the unsprung mass of the axle i (sum of the mass of the wheels on axle i and the axle itself mass) and
 15 the proportion of the suspended masses supported by the axle i . $\gamma_{sm\ i}$ is the component of the vertical
 16 accelerations of the suspended masses supported by the axle i , $\gamma_{um\ i}$ is the acceleration of the unsprung
 17 masses of the axle i and $\gamma_{wu\ i}$ is the acceleration due to the imbalance of the wheels of axle i . M'_i is the
 18 mass of the wheels on axle i . Some of these values were provided by the truck manufacturer MAN. The
 19 last term of **Equation (1)** summarizes the forces induced by the wheel imbalance on the axle i , but should
 20 be split wheel by wheel.

21 The dynamic amplification factor related to the axle i is estimated by: $D_i = F_i/gW_i - 1$

22 and for the whole vehicle (GVM): $D = \sum_i(F_i)/Mg - 1$ where $M = \sum_i(W_i)$.

24 Measurements and results

25 The first measurements were done in Transpolis in April 2019, with the T2S3 (**Figure 8**). Only
 26 the tractor was instrumented. The truck was loaded at 40 t, with 7 t on the steer axle, 11 t on the drive axle
 27 and 22 t on the tridem (semi-trailer). It did a few series of 6 runs at 90, 70 and 50 km/h, on a dedicated
 28 lane, and a few more runs on adjacent lanes to compare the effect of the evenness. The estimate of the
 29 dynamic amplification factor for the steer axle was around 4.3% and for the drive axle it reached 5.5%.
 30 The values are less than the MPE of axle load in the OIML class 5 (8%), and even less than 0.8*MPE
 31 (6.4%). Therefore it was decided to continue the investigation and qualification of the Transpolis site.

32 In July 2019, the same T2S3 was driven to Saint-Avoid on the A4 motorway, fully instrumented
 33 on all axles, both tractor and semi-trailer. The static axle loads were 7 t (steer axle), 11.3 t (drive axle), and
 34 22.7 t on the tridem, for a GVM of 41 t. The unsprung masses of each axle provided by MAN were:
 35 535 kg, 1,090 kg, and 3*375 kg. The truck did 21 runs on the site where the two WIM systems (Kapsch
 36 and Sterela) are installed. Each loop took app. 20 min (a bit more than 30 km). The speed range was 68.5
 37 to 89 km/h, with 13 runs above 87 km/h. A half of the runs were done with the truck centred in traffic lane
 38 equipped with the WIM sensors. 4 to 5 runs were done with the truck on the left and right part of the
 39 traffic lane. The dynamic impact factors of the tractor axles (steer and drive axles) varied from 2 to 7%.
 40 For the axles of the tridem these factors did not exceed 4%. These values are slightly higher for the tractor
 41 than those gathered in Transpolis, because of the pavement evenness (site in class 2 according to the
 42 COST323, vs class 1 for Transpolis). However, these values remain lower than the MPE in class 5
 43 (OIML), and moreover, each WIM system uses at least 3 rows of WIM sensors, averaging the impact
 44 forces. The maximum error on axle load with the Kapsch system (3 sensor rows) was 5.3%, while with the
 45 Sterela system (4 sensor rows) the maximum error was 4%. Roughly speaking, and if the sensors spacing
 46 is well designed, the dynamic factors may be reduced up to 40% ($1/\sqrt{3}$). The maximum errors of each
 47 WIM system are slightly above these reduced values, but in the same order of magnitude. They are
 48 compatible with the tolerance of the class OIML 5 for axle loads, even with a 0.5 or 0.8 factor for initial
 49 verification.

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Figure 8 Trial in Transpolis on the main boulevard in the “urban area”

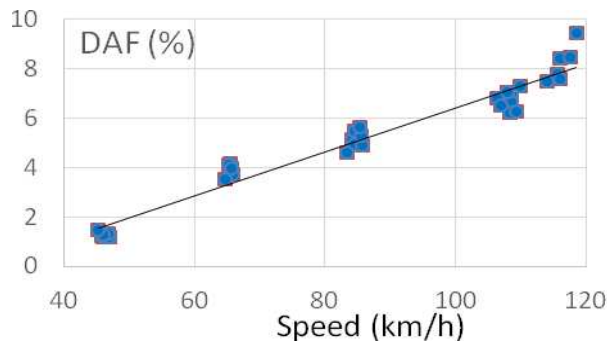


Figure 9 Dynamic amplification factor (DAF) of the van depending on the speed (Transpolis, July 2020)

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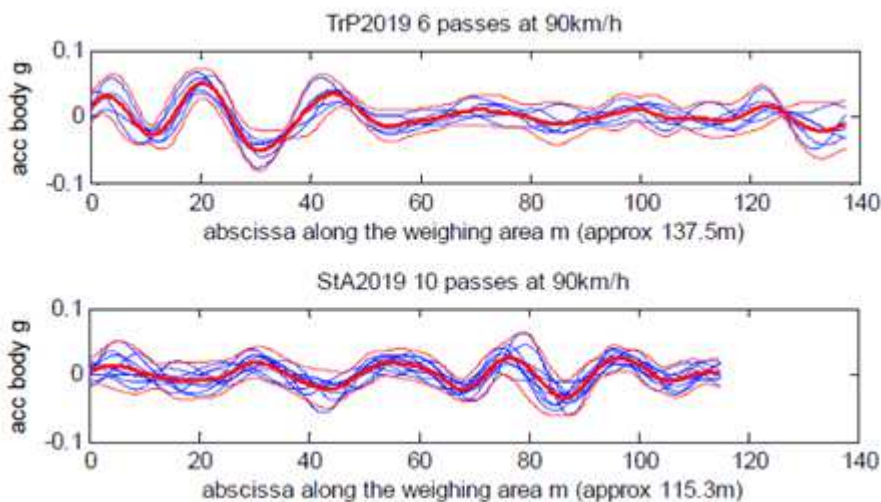


Figure 10 Measured vertical accelerations of the tractor (T2S3), in Transpolis (top) and Saint-Avoid (bottom)

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Finally, a last series of measurements were done in Transpolis in July 2020 with the two instrumented vehicles, T2S3 and van. The T2S3 did 39 runs at speeds from 50 to 90 km/h. The van did 37 runs at speeds from 50 to 120 km/h. The T2S3 was loaded as in 2019 (40 t) and the van at 3.5 t. **Figure 9** shows the increase of the DAF for the van (gross vehicle weight) with the speed. The mean DAFs at 50, 65, 85, 110 and 120 km/h are respectively: 1.3%, 3.9%, 5.1%, 6.7% and 8.2%. They are all compatible with the MPEs of the OIML class 10 for in-service verification, and of the class 15 for type-approval and initial verification.

1 **Figure 10** compares vertical accelerations of the tractor (T2S3) for runs at 90 km/h in Transpolis
2 and Saint-Avoid in 2019. In Transpolis, the accelerations are quite high, up to 0.8 g along the 50 m zone
3 from the beginning of the test zone. After that (50 to 130 m), the vertical accelerations are much lower,
4 less than 0.5 g given the excellent pavement evenness. This difference is explained by a rough pavement
5 joint at a crossing 50 m before the test zone. The bounce oscillations initiated when the vehicle passes on
6 the joint are decreasing and are damped after 5 to 6 wavelengths. If type-approval tests are carried out on
7 this site, the joint will be planed. However, with this unevenness, the test site may represent different real
8 pavement surfaces.

9 These trials fully qualify the site of Transpolis to carry out type-approval tests of WIM systems
10 for direct enforcement. The safety and facilities on this site are fully satisfactory, the test runs can be done
11 in 2-3 min on a loop of app. 2 km, which may save a lot of time and fuel compared to a motorway site.
12 Each category of vehicle (van to 40 t truck) may reach its maximum allowed speed even fully loaded.
13 With 6 traffic lanes is it possible to install and test several WIM systems without any interference. The
14 pavement conditions are representative of those of most of the highways and motorways in Europe, with a
15 good evenness (class 1 WIM site according to the COST323). Moreover, as it is a closed site, it is possible
16 to operate overloaded vehicles to check the systems in most of the operational range of weights. Only axle
17 loads cannot exceed a safety limit for the pavement integrity, but for a few runs in a trial, this limit is
18 higher than the 13 t authorized on the French roads. And last but not least, the expected lifetime of the
19 pavement on such a closed test site is much longer than on a trafficked motorway. Thus, the sensors of the
20 WIM systems installed for type-approval tests could survive for many years and be reused at any time if
21 the manufacturer want to improve its certificate after an evolution of its hardware or software.

22 The dynamic amplification factors observed in Transpolis are slightly less than in Saint-Avoid and
23 compatible with the requirements of the target accuracy classes. They even do not exceed the half-
24 tolerance (MPE) of the target classes.

25 26 **CONCLUSIONS**

27 The project on direct enforcement of overloads by WIM results was a great challenge pioneering a
28 very demanding new application of high-speed WIM in a legal metrology frame. The needs for more
29 efficient enforcement of overloads are great, both to ensure a fair competition between transport modes
30 and companies, to extend the lifetimes of road assets, and to increase road safety. Direct enforcement is
31 the future in a world of automated and connected vehicles, and the only solution to face the increasing
32 flow of heavy commercial vehicles. However, it was mandatory to prove the feasibility of using marketed
33 WIM systems for direct enforcement, within the tolerances fixed by the end-users and the legal metrology
34 organization (OIML).

35 A large scale test was organized over 4 years, on a concessionary motorway (A4, SANEF) in
36 Eastern France, involving two volunteer WIM manufacturers, Kapsch and Sterela. Two WIM systems,
37 predesigned for future direct enforcement, using respectively 3 and 4 rows of piezo-quartz WIM sensors,
38 were successfully tested with more than 1,800 trucks and vans of the traffic flow, weighed in static on an
39 approved axle scale. Their accuracies were assessed both by a statistical approach described in the
40 COST323 (European specifications/pre-standard for WIM), and by a metrological approach (MPE)
41 following the R-134 International Recommendation. It was shown that both WIM systems were very close
42 to meet the requirements of the OIML class 5 for fully loaded trucks, and class 10 for fully loaded vans.
43 With periodical adjustment (recalibration) and an appropriate sorting algorithm to eliminate the doubtful
44 measurements, the WIM systems could deliver reliable measures of overloaded vehicles with a high rate
45 of success.

46 Specifications were developed to submit a type-approval procedure, following the R-134 and
47 slightly adapted to the end-user's requirements. This procedure is now under investigation by the French
48 Legal Metrology Organization and its National Testing Laboratory (LNE), which must approve it before
49 implementing it. A closed test site was also found (Transpolis), where the type-approval tests specified by
50 the R-134 could easily be performed. Trials and measurements were done with two instrumented vehicles,
51 a 40 t tractor with semi-trailer and a 3.5 t van. The results demonstrated that the pavement and road profile

1 on this site were both representative of most existing highways and motorways, and that the dynamic
2 variations of axle loads and gross vehicle weight induced by the pavement profile remain compatible with
3 the reduced tolerances of the type-approval tests.

4 However, the implementation of direct enforcement is now under the control of the competent
5 authorities, Ministries of Transport, of Interior, of Justice, the French Legal Metrology Organization for
6 the certification, and a few other organizations involved in road traffic enforcement.

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8

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20 **AUTHOR CONTRIBUTIONS**

21 The authors confirm contribution to the paper as follows: study conception and design, interpretation of
22 results: D. Betaille and B. Jacob, data collection and analysis: Cerema teams, D. Betaille; draft manuscript
23 preparation: D. Betaille and B. Jacob. All authors reviewed the results and approved the final version of
24 the manuscript.

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