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Investigation of Truck Weights and Dimensions using WIM Data

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Abstract

This paper presents a study carried out with extensive weigh-in-motion (WIM) data collected on the French main road network, involving 3 millions of trucks. The data were collected by three WIM stations located on highly trafficked highways and motorways, continuously over a whole year. The data were analyzed using statistical software developed by the US National Science Foundation.

The trucks of the traffic flow were classified into almost 20 categories, depending on the silhouette, number and spacing of axles, body configuration (trailer/semi-trailer), type of axles (steering, driving or standard axle) and wheel or tire (single, twin, wide). The data were analyzed by category.

The location of the centre of gravity of the payload was calculated and the variability of its abscissa along the vehicle was analyzed in each category. The loading patterns and behavior were analyzed and the results reported here for 5-axle articulated trucks and 2-axle rigid truck with 2-axle trailer.

Then, the axle load distributions were analyzed by axle rank and truck category, and modeled with multimodal Gaussian probability distribution functions. The modes have been determined using a maximum of likelihood method. These modes are useful to design endurance tests of truck tires.

These investigations provide a better knowledge about truck loading, overloads and truck aggressiveness on infrastructure, and may lead to optimization policies. In this case, the results are used directly in the domain of tyre optimization.

Keywords: Trucks; weight; gross weight; load; axle; dimension; weigh in motion (WIM); operation; tire; infrastructure.

Nomenclature

AVI	automatic vehicle identification
CoG	centre of gravity
GHG	greenhouse gas
GWV	gross vehicle weight (equal to the sum of all the axle or wheel loads)
HCV	heavy commercial vehicle (permitted gross weight above 3.5 t)
OCR	optical character recognition
OEM	Original Equipment Manufacturer
PDF	probability density function
WIM	weigh-in-motion

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1. Context and Objectives

1.1. Tire Manufacturer's Perspective

The HCVs' loading conditions, and above all the load distribution on each wheel/tire govern the tire design and sizing, and therefore the tire cost and performance trade-off. Oversized tire manufacturing requires more raw materials and leads to a higher rolling resistance and a higher cost, what directly impacts on fleets efficiency and GHG emissions. On the other hand, an undersized tire may not meet the stability requirements for the truck configuration and use considered. To properly design a tire for the targeted use, it is necessary to know the load to be carried and the axle and wheel load distribution.

With an accurate knowledge of the HCVs' axle configuration and load balance, the tire manufacturers can propose a better technical and commercial offer for each business case, optimizing the truck efficiency and ensuring good safety conditions. Thus, the tire tests should be adapted to fit the design with the real use and not only prescriptive load limits per axle.

1.2. Infrastructure and other Concerns

There is also a need for a better knowledge of real HCVs' weights and dimensions to properly assess their impacts on infrastructure, e.g. pavements and bridges deterioration and fatigue damages, size compliance with the road and parking lot geometry, efficiency of safety equipments such as safety barriers, etc. An accurate knowledge of HCVs' weights and dimensions is also a tool to implement fair road charging and tolling policy, and to optimize the logistics. Last but not least, it is necessary to monitor and enforce overloaded and oversized HCVs to ensure a fair completion between transport companies and modes, which is a requirement of the revised Directive 96/53EC of the European Commission (1996) on HCV's weights and dimensions.

Indeed, the HCVs' dimensions are described in the manufacturers' catalogues, but they do not provide any information on the real loading conditions in operation on the roads. However, it is not easy to know the true loading of HGVs while in operation. Only WIM systems and networks, which are now installed in many countries, can provide reliable data on a large scale, allowing to perform statistical analysis and to better understand the real use of HGVs.

1.3. Paper Overview

Section 2 introduces the WIM data used in this study. Section 3 explains the developed methodology and the HCV's classification used. Sections 4 and 5 present the results on the longitudinal load distribution, the payload CoG location, and the axle load distribution. Conclusions are given in Section 6.

2. Weigh-in-motion systems

2.1. WIM in France

A network of 29 WIM stations was installed in France from 2008 until 2012 for an accurate pre-selection of overloads, Dolcemascolo et al. (2015). All together, 48 traffic lanes are instrumented with WIM sensors and continuously monitored. The WIM stations have been installed on motorways and highways with more than 1,500 HCVs/day, and spread all around France (fig. 1).

The WIM data are collected 24/24hr and 7/7 days, and two cameras are connected to each station, taking pictures of the license plate and of the whole HCV if an overload, overspeeding or any other violation is suspected. These data and the pictures (with an AVI system by OCR) are automatically transmitted to a National database under the control of the Ministry in charge of Transport and the CNIL (National Commission for Individual Rights). The WIM stations are installed upstream to HCVs' check points, i.e. area equipped with static or low speed approved weighing

scales. During the checking periods, in case of an overload suspicion, the WIM data and HCV's identification are transmitted to the police staff and traffic officers to intercept the suspicious vehicle and double check it; in case of an infringement evidence, the vehicle is fined and if needed immobilized for downloading. Otherwise, outside these checking periods, the data of suspicious HCVs are stored (with the license plate number during a month) and the Ministry of Transport may perform company profiling and issue warning letters; the if needed, in company checks may be carried out..

Along a year, app. 30 millions of HCVs are weighed and recorded by these 29 SIM systems, providing a huge amount of data, which may be analyzed with the permission of the Ministry of Transport. The recorded parameters are:

- hourly flow of all vehicles, of HCVs and of overloaded HCVs, all calculated every 6 minutes and then averaged over longer time periods;
- individual HCVs' data: timestamp, velocity, distances between axles, distance between bumper and first axle, axle loads, GVW. Two pictures are taken if there is a suspicion of infringement;
- aggregated data on flow, velocity, length and loads.



Fig. 1. Standard WIM station in France: (a) WIM sensors in the pavement; (b) cameras in the road side cabinet.

The WIM systems are automatically self-calibrated (by fixing the load on the first axle) and mostly meet the following accuracy for app. 95% of the measurements (the contractual requirement was the accuracy class C(15)):

- accuracy class B(10) according to the COST323 European Specifications of WIM, Jacob et al. (2002): GVW: $\pm 10\%$, single axle load: $\pm 15\%$,
- velocity: $\pm 1\%$,
- total vehicle length (bumper to bumper): $\pm 10\%$,
- axle spacing: $\pm 1\%$,
- license plate number recognition rate: 80%.

The total vehicle length is less accurate than the axle spacing because it is measured by magnetic loops instead of WIM sensors.

2.2. WIM Data analyzed

The presented investigation has been carried out with extensive WIM data collected on several French highways and motorways. One full year of traffic data (September 2013 - August 2014) on three different locations were analyzed, on a heavy trafficked motorway with dense international HCV traffic, on a less trafficked motorway, and on a National road. A total of 2,933,331 HCVs were recorded on these 3 sites.

3. Methodology

3.1. HCV Classification

For the required investigation on the real use of HCVs and tires, Michelin proposed a rather detailed HCV classification by silhouettes, number of axles, but also axle configuration (tandem and tridem) and wheel configuration (twin, wide and standard). Steer, drive and other axles were also distinguished.

The classification criteria are based on the number of axles, the axle spacing, and the number and location of drive axles. The two first parameters are directly given in the WIM data files. The drive axle identification is mainly based on the presence of twin tires, above all on the tractors of the articulated HCVs, but the detection of twin vs single tire is rather inaccurate with the current WIM sensors. Therefore, other criteria were developed to identify the drive axles, based on axle spacing and load ratio analysis among HCVs with the same number of axles.

For example, to distinguish the three-axle trucks with a drive axle either on the second or the third axle, the ratio of the second axle load to the third axle load has been studied (fig. 2).

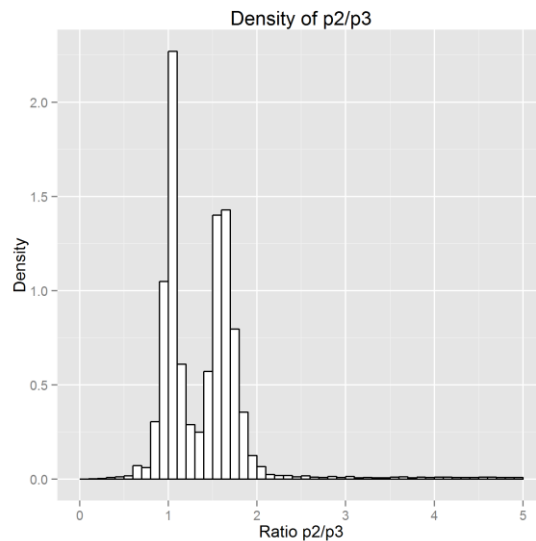


Fig. 2. PDF of the ratio: p_2/p_3 , p_2 = second axle load, p_3 = third axle load, for three-axle trucks.

The PDF shown in fig. 2 is clearly bimodal, indicating two sub-populations. If the ratio p_2/p_3 is lower than 1.3 the third axle is the drive axle, while if the ratio is greater than 1.3 the second axle is the drive axle.

Such types of criteria were found to classify the HCVs into 19 categories, combining silhouette shape and drive axle rank. It was then checked that the categories do neither overlap nor miss too many HCVs. The share of the whole HCV population by category and the characteristics of each sub-population were compared from one site to another, to check if there are criteria to classify the traffic conditions/type, e.g. on motorways, highways, or International vs National itineraries. Some differences were found which may be accounted for in the market approach for a tire manufacturer.

Moreover, the size of each sub-population has been checked to ensure that it is large enough from a statistical point of view. For example, only a few hundreds or thousands of 6-axle HCVs are recorded in our large samples, leading to consider the related results with caution.

3.2. Statistical Analysis of the HCV Load Distribution

The data were picked out in the National WIM database owned by the Ministry of Transport, and transferred in another MySQL database for the study purpose. The statistical analysis, both to classify the HCVs and to calculate the CoG location (section 4) has been carried out with the software “R” (<https://www.r-project.org>), connected to the database with the library “dbconnect” (<https://cran.r-project.org/web/packages/dbConnect/dbConnect.pdf>). For the determination of the axle load modes (section 5), the Mixtools software of the National Science Foundation has been used (Benaglia et al., 2009). This software performs parametric bootstrap for sequentially testing the number of components in various mixture models. A collection of R functions are used for analyzing finite mixture models. The likelihood ratio statistic is used for testing the null hypothesis of a k-component fit versus the alternative hypothesis of a (k+1)-component fit to various mixture models. This is performed for up to a specified number of maximum components. A p-value is calculated for each test and once the p-value is above a specified significance level, the testing terminates.

For all the 19 HCV categories, the payload CoG longitudinal location and the axle load PDF have been analyzed.

4. Payload Distribution and CoG location

4.1. Method of Calculation

The WIM sensors measure the impact forces applied by each axle (axle load) on the road while the HCV is traveling at speed. The GVW is obtained by summing all the axle loads, and is an estimate of the empty vehicle weight plus its payload. The tire manufacturer was interested in the payload longitudinal distribution, e.g. the payload CoG location, to better understand the loading conditions of the HCVs. Therefore, the following procedure has been applied by steps for each HCV category:

- Step 1 - identifying the population of empty HCVs: the 5% lowest fractile of the GVW has been considered in each category,
- Step 2 - axle load distribution of the empty HCVs: the average axle load by axle rank has been calculated in the population of empty HCVs, by category,
- Step 3 - payload distribution on each axle: in each HCV category, the mean loads calculated in the step 2 by axle rank were subtracted to the measured axle loads of the loaded HCVs,
- Step 4 – axle spacing: the average axle spacing by axle rank has been calculated in each HCV category,
- Step 5 – payload CoG location: with the results of steps 3 and 4, the centroid of the payload split by axle has been calculated and the front bumper to the first axle spacing was added to get the abscissa of the payload CoG..

4.2. Payload Distribution

First, the payload histograms for each HCV category were produced and analyzed. One of the questions to be answered is: are the HCVs mainly full in volume or gross weight? Fig. 3 shows the payload PDF for the 2-axle rigid HCVs and for the standard 5-axle articulated (2-axle tractor and 3-axle semi-trailer). The first category has almost a mono-modal PDF (or 2 very close modes) with a long tail on the right. The modes at 2 and 5 t show that the 2-axle rigid HCVs are mostly full in volume before to reach the maximum permitted GVW. The second category has a bimodal PDF with a second mode at 26 t with a very low scattering. As this peak of payload is 26t and the empty truck weights approx. 14t, these vehicles are fully loaded and have a GVW close to the permitted limit. We confirm then that around 20% of vehicles measured are fully loaded.

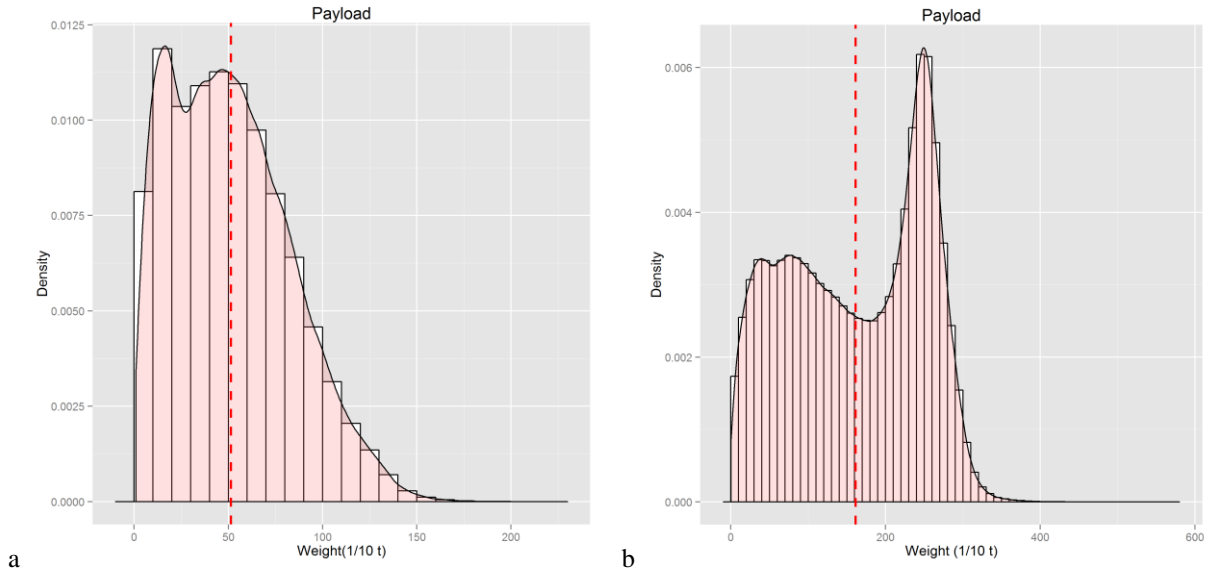


Fig. 3. Payload distribution: (a) 2-axle rigid, (b) 5-axle articulated

4.3. Payload CoG Location

Fig. 4 shows the PDF of the CoG location for two categories of HCVs, but split by payload sub-classes. The loading schemes differ from one category to another. However, in each HCV category when the payload increases, the mean location of the payload CoG is first moved to the rear of the HCV, and finally does not move for the highest loads, while the scattering is reduced. The payload is first installed in front of the semi-trailer (or of the truck or trailer) to save space for additional load close to the back door. Then, if adding more load the whole space is loaded. The most rear mean location of the CoG in a 5-axle articulated is app. 7.2 m, i.e. 1 m in front of the middle of the vehicle length (Fig. 4a). Further increase of the payload is likely made either with denser goods or by adding more goods in height. In both cases the CoG cannot move more to the back.

For the rigid trucks with a trailer, the same trend can be noticed when the payload increases. Nevertheless, the analysis of the CoG location is more complex, because of the two independent bodies loaded either independently or not (Fig. 4b). However, for the fully loaded HCVs in this category, the CoG tends to be concentrated at app. 8 m, which is also 1 m in front of the middle of the vehicle total length.

This statement let us know that the CoG frontward position give the semi-trailer an understeering tendency.

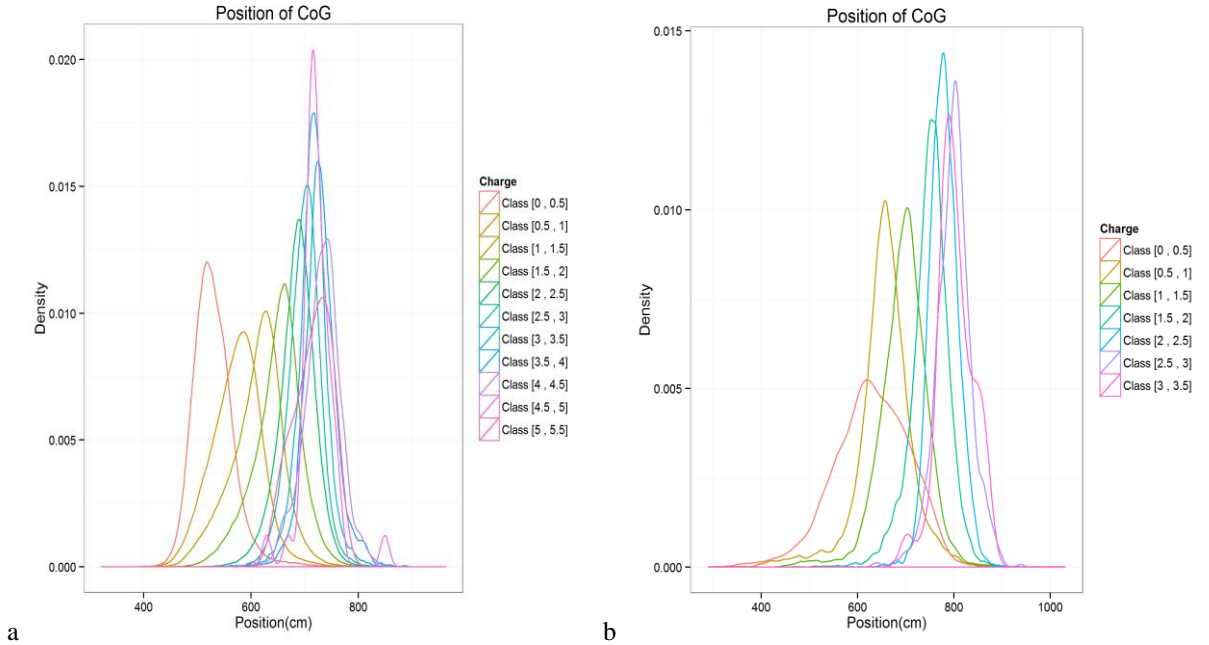


Fig. 4. Location of the payload CoG: (a) 5-axle articulated, (b) 2-axle rigid truck with a 2-axle trailer (on each diagram, the load classes are by 5 t step, e.g. class [0.5,1] contains the payload between 2.5 and 5 t).

5. Axle Load Distribution

5.1. Objective and Principle of Axle Load Distribution Characterization

The tire manufacturer needs to characterize the axle load distribution for each type and rank of axle, in each category of HCV, in order to develop endurance tire tests with calibrated loads corresponding to the real loading modes in operation. Therefore, the next analysis of our WIM data was focused on the axle load distribution and mode identification.

To get these axle load modes, we formulated the problem as the following mathematical optimization: for a given HCV category i , and axle rank j , search the minimal number k of axle load intervals $[0.9P_{ijk} ; 1.1P_{ijk}]$ which contain a given and large enough proportion Π (e.g. 90 or 95%) of the axle loads. The Mixtools software was used for that as explained in the section 3.2 with a maximum of likelihood algorithm. We assumed here that the "DF or each mode were all Gaussian, which mainly fit the real axle load mode distributions. Moreover, the proportion Π was chosen such as $k=1$ or 2 (maximum two modes for each axle load distribution), and it was shown that Π was large enough.

5.2. Modes of the Axle Load PDFs

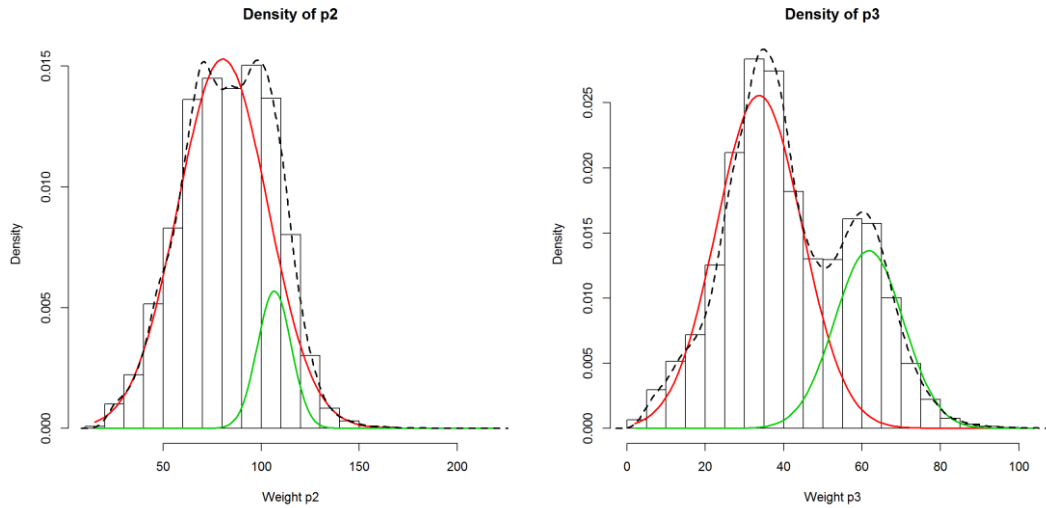


Fig. 5. Axle load PDF and the identified modes for the 2-axle rigid truck with a 2-axle trailer, (a) for the second axle and (b) for the third axle

Fig. 5 gives the axle load PDF and the identified modes for the 2-axle rigid truck with a 2-axle trailer, (a) for the second axle and (b) for the third axle. Both PDF are represented by bimodal Gaussian PDF. The modes for the second axle are located around 8 t and 10.6 t. For the third axle the modes are around 3.3 t and 6.2 t. The fourth axle shows the same PDF and modes than the third axle, because the trailer weight is equally distributed on both axles. A quite small size of the population uses the actual tire load capacity.

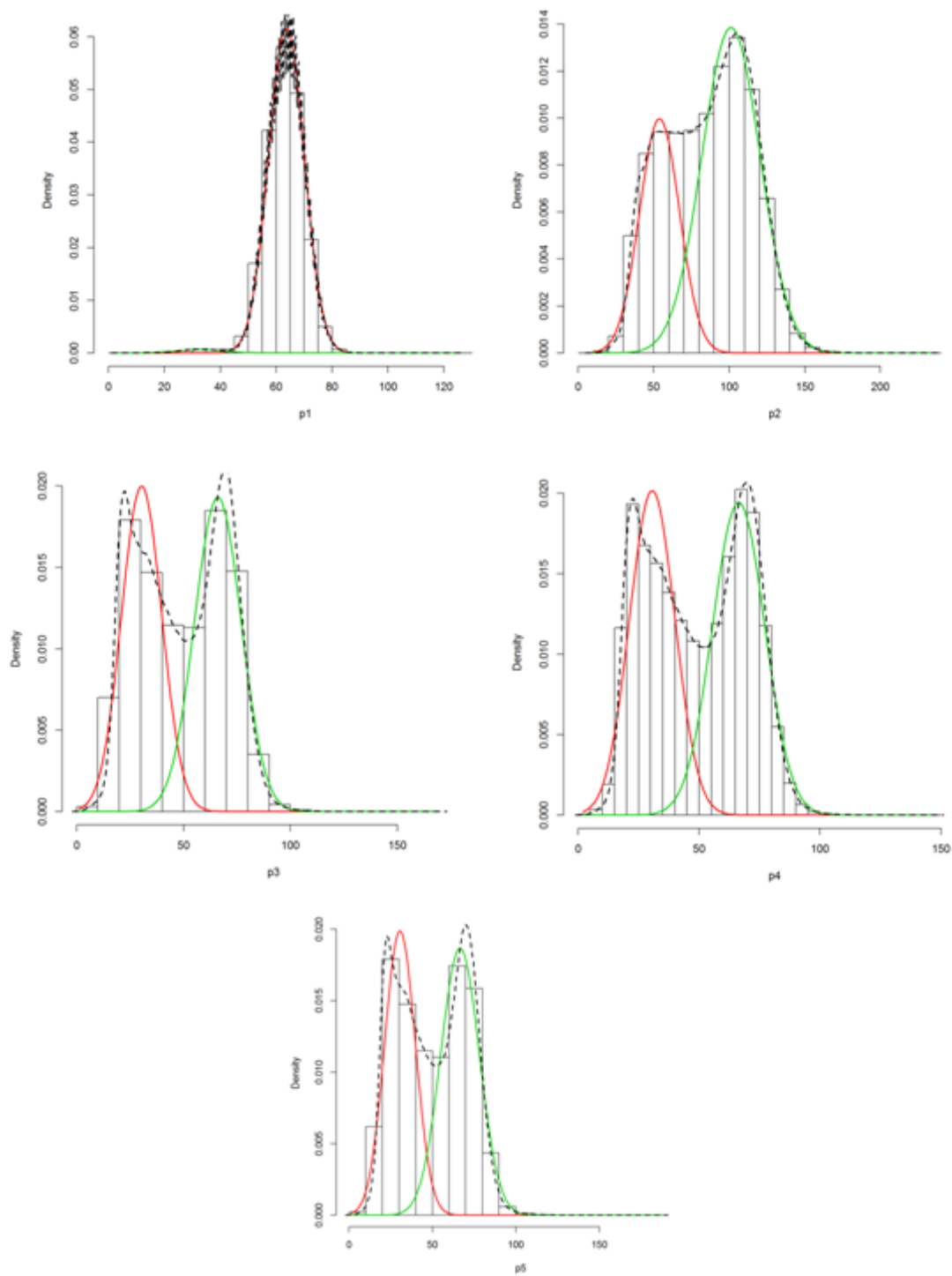


Fig. 6. Axle load PDF and identified modes for all axles of the 2-axle tractor with 3-axle semi-trailer.

Fig 6 gives the axle load PDF and the identified modes for the 2-axle tractor with a 3-axle semi-trailer. From the axle load analysis point of view, it seems that empty convoys as frequent as full loaded convoys, but the trucks with a high load on the drive axle are not the same as those with high loads on the axles of the trailer. A quite small size of the population uses the actual tire load capacity.

We have there a clear statistical demonstration that 2-axle rigid truck with a 2-axle trailer are more dedicated to a volume usage than 2-axle tractor with a 3-axle semi-trailer what offers and is used for a multi-purpose usage.

For the most of the HCVs, the steer axle (front axle) only has one mode, centred around 6 t, what is understandable as the payload don't impact the steer axle load because of the typical axles locations regarding the loading surface.

6. Conclusions

This work reports a study carried out by IFSTTAR about the use of HCVs in France. The large amount of WIM data analyzed, i.e. almost 3 millions of weighed HCVs over a year on 3 sites (2 motorways and one highway) provided interesting results about the payload intensity, its split on the different axles and the longitudinal location of the CoG. Identifying the axle load PDF and modes may be very valuable for the tire manufacturer to design the tire endurance tests.

This study also open the way for further investigations about HCVs loading and use which could be of interest for many professionals, manufacturers, OEMs and transport companies. The investigation will be extended at European level. It also provides tools to monitor overloads and to target the checks for a more efficient enforcement.

By knowing the trucks loading habits, the tire manufacturer can challenge the load capacity usage of the tires and their handling performance regarding their fuel efficiency impact. The performance trade-off could be then explored to propose an adapted offer to different truck configurations, optimizing their fuel consumption and their safety performance. The last but not least issue to deal with is the multi-purpose aspect of the use of the various vehicle configurations.

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