# DETECTION OF LIFTED AXLES OF HEAVY VEHICLES. STATISTICAL APPROACHES BASED ON WIM DATA.




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**Abstract**

A large proportion of in-land freight movements are made on road by heavy good vehicles (HGVs). A major challenge is ensuring compliance with weight and dimension regulations for infrastructure, road safety and fair competition purposes. The SETO project (Smart Enforcement of Transport Operations), an EU-funded collaborative project, focuses on the development of methods for detecting lifted axles using weigh-in-motion (WIM) systems. Our work falls within this framework. It uses WIM data from the French A63 motorway. We deal with the case of the ultra-majority category of trucks with lift axles. We successfully apply two supervised classification methods, namely logistic regression and Random Forest. In particular, the random forest method enables more than 90% of the axles lifted to be correctly identified. This work offers a wide range of perspectives both in terms of methodology and applications.

**Keywords:** Heavy Vehicles, WIM, Detection of lifted axles, Data Mining, Machine learning

## 1. Problem statement and challenges

### 1.1 Interest in detecting lifted truck axles

The aim According to Eurostat, in 2023, around 70% of the distances travelled by heavy goods vehicles in Europe are covered by tractor with semi-trailers. These vehicles comply with the European Council (Directive 96/53/EC), with a total length of 16.50 metres, and 4 to 6 axles. The 4-axle combination (T2S2) comprises a 2-axle tractor and a semi-trailer with a tandem axle, with a maximum authorised gross weight of 38 tonnes. The 5-axle combination (T2S3), which is the most common in the EU and above all in France (75% of the trucks), comprises a 2-axle tractor and a semi-trailer with a tridem axle, with a maximum authorised gross weight of 40 tonnes for international traffic, and 44 tonnes in most of the Member States, incl. France. Direct enforcement of overloads by WIM is a major challenge in many regions around the World. In the EU, the Directive 96/53EC revised by 2015/719, includes an article 10d stating: "*By 27 May 2021, Member States shall take specific measures to identify vehicles ... that are likely to have exceeded the maximum authorised weight and that should therefore be checked by their competent authorities in order to ensure compliance with the requirements of this Directive. Those measures may be taken with the aid of automatic systems set up on the road infrastructure, or by means of on-board weighing equipment installed in vehicles...*". The maximum authorised weight depends mainly on the number of axles of the vehicle or combination of vehicles. Therefore, it is necessary for any automatic (WIM) system, to identify this number of axles.  However, with the development of lifetable axles a significant proportion of vehicles (estimated from 15 to 25%) circulates with lifted axle(s). These axles are not detected by WIM systems with sensors mounted in the road or in bridges. Therefore it becomes essential to develop a new feature making WIM systems able to detect lifted axles. If the axles are lifted incorrectly, the overload can cause damage to infrastructure and engineering structures. Preserving infrastructure is therefore one of the main challenges of this detection.

### 1.2 Positioning of this work in relation to the state of the art

Two main approaches may be used to deal with this issue. Road side cameras taking photos perpendicular to the traffic direction may provide images analysed by dedicated softwares and IA to identify lifted axles (Tchana Tankeu et al., 2025). Another approach consists of analysing the silhouettes of the heavy vehicles and compare them with some references in databases. Using classification statistical methods as k-means (Stocchetti et al., 2020; Quoy & Jacob, 2021) it is possible to identify with a high reliability some lifted axles, which are likely missing at a given location of the vehicle. This paper goes further in this approach using random forest methods.

Combining both approaches may provide a low-cost methodology to enhance the feature of existing WIM systems and detect lifted axles with a high level of confidence, in order to implement direct enforcement of overloads with respect to the current driving laws.

### 1.3 Towards a machine learning approach for detecting lifted axles

This paper mainly focuses on the detection of lifted axles on T2S3, which may lead to a confusion with a T2S2 as the lifted axle is in the tridem. Note that a T2S2 and a T2S3R carrying the same load are very similar, but in the event of overloading, the penalties are not necessarily the same. Therefore, among the T2S2 identified by a common WIM system, counting the axles on the road, there are 3 populations: (1) the T2S2, called “native”, with only 4 axles, referred as T2S2N, (2) the T2S2 car transporters, with only 4 axles referred as T2S2PC and (3) the T2S3 with one lifted axle in the tridem, referred as T2S3R.

For the car transporters (T2S2PC), generally fitted with sliding devices on the trailer. This increases their carrying capacity by several centimetres. These devices make it possible to increase the average length of the vehicles transported. In the traffic observed on the motorway A63, Bordeaux to Bayonne in south west of France, operated by Atlandes, the total length of car transporters often exceeds 16.80 m. T2S2Ns account for more than 85% of all T2S2 on the A63. The silhouettes of the T2S3 are very homogeneous. Most T2S3 are today equipped with one or two liftable axle. According to the technical specifications of OEMs, the most commonly liftable axle is the first axle of the tridem (90%). Lifted axles when the vehicle is not fully loaded, i.e. not at the maximum weight, allow reducing the fuel/energy consumption (less tire friction), the tire wear, and slightly improves the manoeuvrability.

When the first axle of a T2S3's tridem is lifted, its geometric characteristics are a priori similar to those of a T2S2. It is therefore essential to distinguish between these 2 categories.

For this reason, in this paper we propose solutions for the detection of lifted axles in heavy goods vehicle passage databases from WIM (Weigh In Motion) stations. The proposed methods, which mainly use the distances between the axles, require very little computing time. They can therefore be used for real-time detection of axles measured after passing a WIM station.

The rest of the article is organized as follows:

Firstly, we will present the database we have been working with. We will then compare the performance of two supervised classification methods in detecting detected axles. Finally, we will propose some perspectives for this work.

## 2. HGV traffic data available (Sterela – Atlandes)

The section of the French A63 motorway managed by Atlandes runs from Salles to Saint Geours de Maremne in the Nouvelle Aquitaine region. HGVs travel on this stretch of motorway and Atlandes has weighing stations in operation for them. Several measurements are taken as the HGVs pass through the WIM stations. Magnetic loops in the carriageway are used to measure magnetic silhouettes (e.g. total length), while pressure measurements are used to detect vehicle axles and axle weights. Cameras are also used to classify heavy goods vehicles into around sixty possible profiles. However, the system's interpretation is not always accurate. In particular, the cameras do not detect any lifted axles. Figure 1 is an illustration of a WIM station from Sterela. It is this company that equips the A63 motorway with WIM stations.

The data used in this work were collected on the A63 motorway during the week of 2 to 6 september 2024 between 7h and 21h (UTC+1). We focused on HGVs detected as T2S2 by the WIM system. Indeed, due to the limitations of the WIM system, among these T2S2s there is an unknown number of T2S3s with the 1st axle lifted. It should be remembered here that lifted axles are never detected by the WIM system.

For each HGV passing, the main variables collected are: the time of passage, the number of axles detected on the ground, the total length of the vehicle, the distances between successive axles and the weights carried by each axle. Table 1 illustrates these variables. Figure 2 shows the T2S2N, T2S2PC and T2S3R silhouettes and the distances between axles. We have

deliberately chosen to retain only HGVs between 16 m and 16.8 m in length. This choice is justified by the fact that the vehicles all comply with standard 96/53/EC. It also means that most T2S2PCs can be eliminated from the database. There are no axle detection issues for this category.
It is well known that T2 tractors can tow either S2 or S3 trailers. In other words, the technical characteristics of T2 tractors do not depend on the trailers they tow. The variables d1 and d2 will therefore not be discriminating with regard to the identification of T2S3Rs. The same applies to the variables w1 and w2.


**Figure 1 – WIM station by Sterela**

| **Name of the variable** | **Description** |
|---|---|
| Time stamping | UTC when the vehicle passed |
| Length | total vehicle length (cm) |
| d1 | distance between bumper and 1st axle (cm) |
| d2 | distance between 1st and 2nd axle (cm) |
| d3 | distance between 2nd and 3rd axle (cm) |
| d4 | distance between 3rd and 4th axle (cm) |
| w1 | weight on 1st axle (kg) |
| w2 | Weight on 2nd axle (kg) |

| | |
|---|---|
| w3 | Weight on 3rd axle (kg) |
| w4 | Weight on 4th axle (kg) |

**Table 1 - Main variables measured by the WIM system**

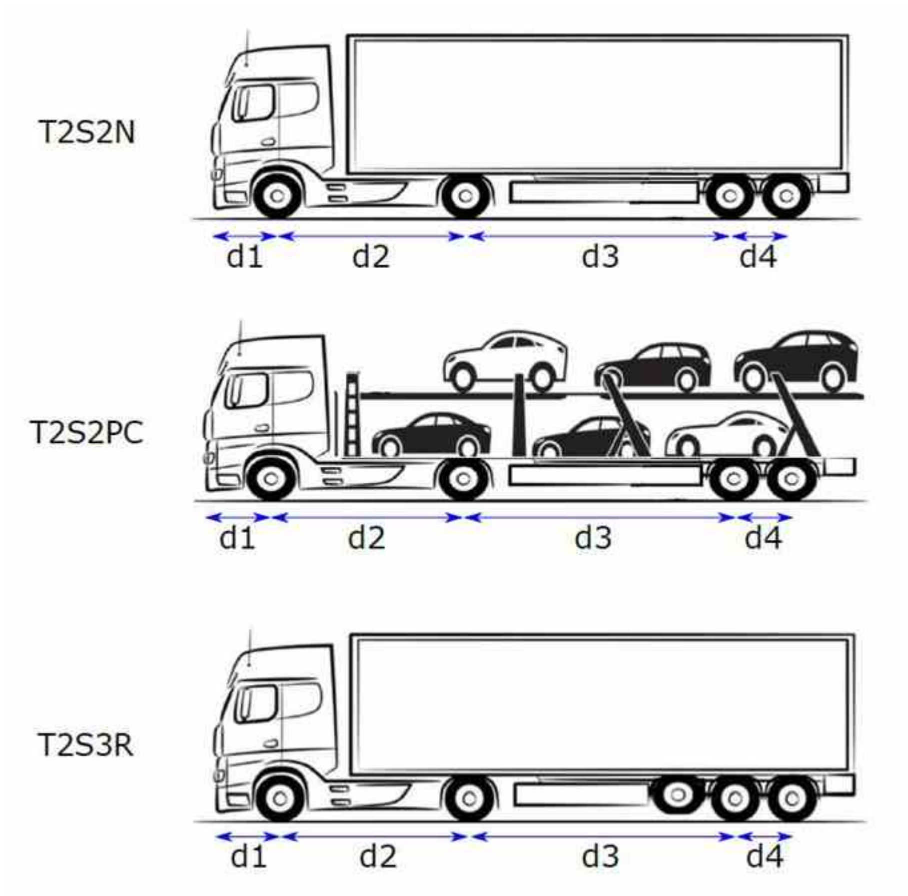



**Figure 2 – T2S2N, T2S2PC and T2S3R silhouettes**

## 3. Data labelling improvement

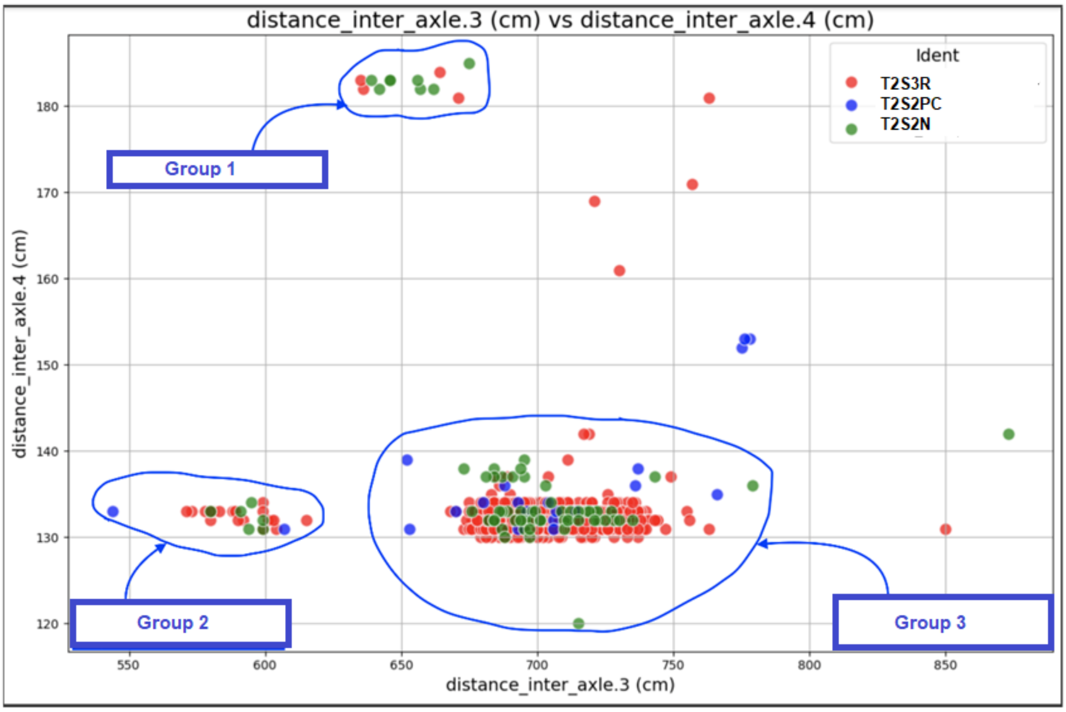
As explained in the previous section, the WIM system does not provide a totally reliable classification. It can only count axles in contact with the ground. For example, it cannot distinguish between T2S2s and T2S3Rs. This is clearly a weakness of this type of system.

Our aim is to better identify T2S3Rs using supervised classification methods. In this context, it is important to have more reliable information on class labels. This will be used to train the models to recognize T2S3Rs among all the trucks considered.
Atlandes, which operates the A63 motorway, has traffic surveillance cameras near the WIM station. Thanks to these videos, it is possible to identify the number of axles in around 90% of cases during the diurnal period. However, the quality of the images makes it impossible to identify the location of the lifted axles. In the remaining 10% of cases, identification is impossible. This is due to the position of the camera, which is not designed to make such detailed observations. Figure 3 shows the image of a truck obtained with this device. Atlandes provided the Gustave Eiffel University with video data for the period from 2 to 6 September 2024. The data described in paragraph 3 was the subject of additional labelling work. This work was carried out at the Université Gustave Eiffel as part of the SETO project. It identified with certainty 2071 T2S3R silhouettes, 135 T2S2N silhouettes and 251 T2S2PC silhouettes.

**Figure 3 – Image of trucks passing near a WIM station**

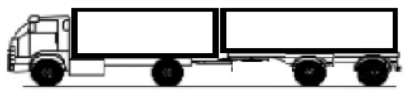
## 4. Brief analysis of data collected

We will now briefly present an initial analysis of these data. As previously mentioned, the d3 and d4 variables are of prime importance in attempting to discriminate T2S3Rs from other T2S2 silhouettes. In order to visualize the data in the enhanced database, we projected the data set onto the (d3, d4) plane. Figure 4 shows the resulting point cloud. We can see that 3 distinct groupings appear. Group 1 is made up of 4-axle trucks with a d4 value close to 180 cm. According to information from the main manufacturers, these d4 values correspond to trucks that are not semitrailers. It is highly possible that these trucks are C2R2. They also have 4 axles, but with different d4 distances to the T2S2s. They are much less present in traffic. The WIM system and the human eye may mistake them for T2S2s. We have therefore decided to exclude them from this study. Group 2 consists of vehicles with a d4 value close to 130 cm. The d3 values vary between 525 cm and 625 cm. According to manufacturer information, these profiles correspond either to T2S2Ns or T2S3Rs when the first axle of the tridem is on the ground. Finally, Group 3 comprises T2S2N, T2S2PC and T2S3R vehicles. For T2S3Rs, the value of d4 suggests that the first axle of the tridem is very possibly lifted.




**Interpretation of groups :**

Group 1 : C2R2



Group 2 : mixture of T2S2N and T2S3R with first axle of the tridem on the ground
T2S2PC (outliers)

Group 3 : mixture of T2S2N, T2S2PC and T2S3R with first axle of the tridem lifted

**Figure 4 – Cloud of silhouettes and interpretation**

## 5. T2S3R recognition

We will now implement two statistical learning methods to detect T2S3Rs in the available database.
The first method applied is logistic regression, a widely used technique in supervised learning designed to determine a linear boundary between classes. Here, it serves as a baseline approach. Further details on this method can be found in Osmer et al. (2013). It is also used in several cases in Tuffery (2011).
The second method used is Random Forest, an approach that combines multiple decision trees. For more details, refer to Breiman (2001)
The methods were applied to normalized explanatory data, and we used approximately 2/3 of the data for training and the remaining 1/3 for performance evaluation.

### 5.1 Detection of T2S3R using a logistic regression method

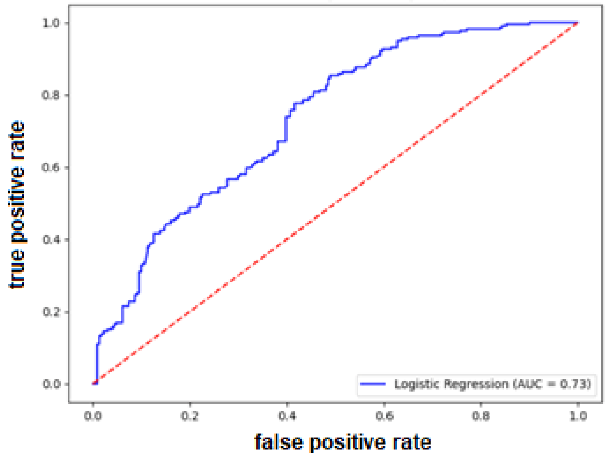
The aim of logistic regression is to build a model that can predict a categorical variable Y from a series of p continuous or categorical explanatory variables $X=(X_1,\ldots,X_p)$.
When the variable Y is binary, i.e. takes 2 values {1,0}, predicting its expectation is equivalent to predicting the probability of the event "1" occurring knowing X. The a posteriori probability is given by the following expression:

$$P(Y = 1/X) = \frac{\exp(\beta_0+\beta_1 X_1+\ldots+\beta_p X_p)}{1+\exp(\beta_0+\beta_1 X_1+\ldots+\beta_p X_p)} \quad (1)$$

where:

- $P(Y=1/X)$ : probability of belonging to the T2S3R class
- $X_i$ : predictors variables which in our case are distances d3 and d4
- $\beta_i$ : coefficient of variable i.

The maximum likelihood method is used to estimate the coefficients $\beta_i$
Figure 5 summarizes the results obtained by applying this method to the available data. It can be seen that the overall performance of the model is 73% (AUC ROC). The model was able to detect 73.36% of the axles actually detected (true positives). Whereas 26.64% of the axles detected were classified as not detected (false negatives). Although this is not our main concern, it is worth noting that almost 67% of the axles not detected were correctly identified by the model. This method therefore gives interesting results, but there is room for improvement. This is not surprising, as this type of method has difficulty in modelling non-linear relationships between the explanatory variables (d3, d4) and the target variable. This is why we are now going to investigate another method.




ROC Curve

| real class \ pretictedclass | T2S3R | T2S2N and T2S2PC |
|---|---|---|
| T2S3R | True positives 73,36% (157) | False negatives 26,64% (57) |
| T2S2N and T2S2PC | False positives 33,05% (78) | True negatives 66,95% (158) |

Confusion matrix

**Figure 5 – Results of logistic regression**

### 5.2 Detection of T2S3R using the Random Forest method

Random Forest is a reference supervised machine learning method based on a large number of decision trees (Breiman, 2001). These trees are constructed randomly and independently of each other. The final prediction is obtained by combining the individual predictions of the trees (majority vote). The process of building a Random Forest is based on two key concepts:

a) Bagging:

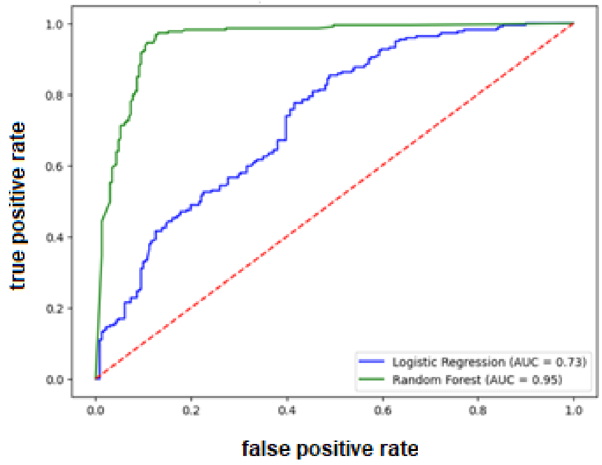
- Decision trees are trained on different subsets of the data. Each subset consists of samples drawn randomly (with replacement) from the original training data.
- This introduces diversity into the trees and reduces the overall variance.

b) Random selection of variables

- At each node of the tree, the algorithm selects a random subset of the explanatory variables from which the best variable is chosen to divide the data.
- This reduces the correlation between the trees and improves the robustness of the model.

In practice, Random Forest requires setting two hyperparameters: the number of decision trees, which we set to 100 by default, and the number of variables used to split a node. Due to the small number of variables, we set this value to 2.
Figure 6 shows the results obtained using this method. It can be seen that the overall performance of the model is 95% (AUC ROC). The model was able to detect 92.5% of the axles actually surveyed (true positives). While 7.5% of the axles detected were classified as not detected (false negatives). Although this is not our main concern, it should be noted that 89.4%

of the axles that were not identified were correctly identified by the model. This method is particularly effective. These methods are capable of capturing complex relationships between variables. In particular, the random forest method is well suited to modelling non-linear relationships.




ROC Curve

| pretícted class / real class | T2S3R | T2S2N and T2S2PC |
|---|---|---|
| T2S3R | True positives 92,5% (198) | False negatives 7,5% (16) |
| T2S2N and T2S2PC | False positives 10,6% (25) | True negatives 89,4% (211) |

Confusion matrix

**Figure 6 – Results of random forest method**

## 6. Conclusion

The detection of lifted axles is an important issue at the moment. Lifted the axles improperly when a truck is loaded is likely to damage road infrastructure. Preserving road infrastructure is therefore one of the main challenges of this detection. Another challenge is to gain a better understanding of HGV traffic. Finally, another longer-term issue is to have the tools to detect any fraud involving wrongful lifting.

The work presented in this paper partly meets these ambitious objectives. This work is based on WIM data from the A63 motorway (France). They were obtained as part of the SETO project under the Horizon Europe program.

We have successfully implemented two supervised classification methods using available data. In particular, the Random Forest method gives very good results in detecting T2S3R silhouettes. This work represents a significant advance on the subject. Until now, existing work on the subject had not been able to detect silhouettes.

This work opens the way to new possibilities. For example, a number of methods likely to yield interesting results remain to be investigated. In particular, we could focus on methods designed for non-linear class boundaries (K-NN, neural networks, etc.). We could also investigate other machine learning approaches such as expert mixtures (MoE).

The methodology developed in this paper could also be extended to other truck silhouettes.

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