Differences in the operation of heavy towing vehicles – features affecting mechanical degradation.

Author, co-author
Affiliation

Abstract

This paper examines differences in the operation of 181 heavy towing vehicles in order to identify features that can explain the level of mechanical degradation. First, it discusses how the allocation of maintenance resources could be optimized by estimating the roadworthiness and the rate of deterioration. Second, it analyzes the data collected from the trailer CAN and describes the distributions of the various features. We identified two groups of trailers in the data, belonging to the same vehicle class but with distinct usage patterns. Trailers from one cluster drove 253 kilometers and braked 33 times per day while trailers from the other cluster drove only 137 kilometers per day but brake 153 times per day.

Introduction

Currently, all trailers are more or less treated equally. Maintenance is either reactive, thus upon failure, or planned. If planned then maintenance is performed on a time basis, distance basis or a combination thereof. Individual vehicles however are known to deteriorate at different rates and often in a stepwise fashion as components fail [1].

Roadworthiness testing for heavy commercial vehicles has changed little despite rapid technological advances. Most standards were set some time ago when vehicles were largely mechanical devices. Directive 2014/45/EC fixes minimum standards for periodic roadworthiness tests of motor vehicles in the European Union, including heavy goods vehicles and their trailers. The minimum frequency of testing for commercial vehicles above 3.5 tonnes is once a year but maybe subject to more frequent testing for vehicles with high mileage. The frequency is based on the expected time between failures, also known as the mean time between failures. It assumes a constant failure rate over time for vehicles with low mileage, leaving room but not accounting for the conditions, environment, usage period, or operator behavior.

Previous studies and guidelines suggest that the failure rate of vehicle safety inspections depends on factors such as [2, 3]:

- The age and type of vehicle operated.
- The nature of its load, the equipment and fittings it carries or supports.
- The type and range of operations on which it is likely to be engaged.
- The type of terrain and the nature of the environment in which it operates or is likely to operate.
- The distance and speeds at which it travels and the journey times.

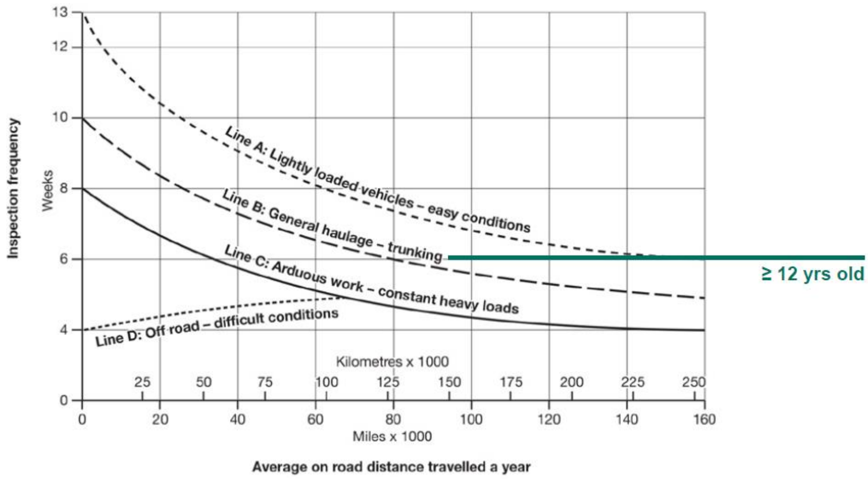

Figure 1. Typical routine maintenance inspection intervals from the British Guide to Maintaining Roadworthiness.

These factors can be used to select an inspection interval, but in practice such factors:

- are ambiguous, e.g. lightly loaded vehicle, rough terrain;
- are often unknown, e.g. load or speed;
- are subject to change, e.g. reassigned tasks or routes;
- can be combined in various ways;
- are subject to fraud, e.g. odometer fraud;
- have an indirect effect on mechanical degradation;
- account for only part of the variation in wear and tear.

Fleet operators sometimes opt to install a hubodometer to record the distance driven by a trailer. The distance driven by a trailer is then recorded via a visual inspection. This is labor intensive and error prone. Others segment by traffic type and select a maintenance schedule accordingly. Different traffic types are known to cause different rates and types of wear and tear. For example, the constant stopping and going in city traffic causes higher abrasion of tires compared to highway traffic. Segmenting by traffic type is perhaps an improvement over time or distance based methods but assumes that trailers operate in a single type of traffic. This assumption is often violated, making this method less suitable for fleets with assets operating under different traffic types or when the type of traffic is unknown, e.g. rental or leasing.

Hence it is important that we identify factors that can help explain the variance in the rate of deterioration between trailers. Such factors are important input for modelling deterioration to identify the different conditions and their effects, and the optimal selection and scheduling of inspections and preventative maintenance actions. The frequency at which inspections are undertaken should be determined by assessing the level of degradation likely to be incurred over a period as a result of the vehicle's usage [4]. Mechanical degradation of the vehicle is the result of forces acting on the vehicle.

Newton's second law tells us that the sum of forces on an object is equal to the mass of an object multiplied by the acceleration of the object, $F=ma$. Such forces are thus at a maximum when the trailer is fully laden and accelerates, brakes, turns or hits a bump.

This article will examine differences in trailer operation, in particular the different forces that cause mechanical degradation, with the exception of shocks.

Theory

The figure below shows the roadworthiness of a vehicle. Periodical inspections are carried out that increase the roadworthiness of the vehicle, as indicated by the vertical lines. The minimum performance and condition required of the vehicle is indicated by the horizontal line. An optimal allocation of maintenance resources minimizes the number of periodical inspections while meeting the required standard. In the example below we can improve the allocation of maintenance resources by:

- Skipping the first two periodical inspections to reduce maintenance costs.
- Carrying out the last two periodic inspections earlier to ensure compliance.

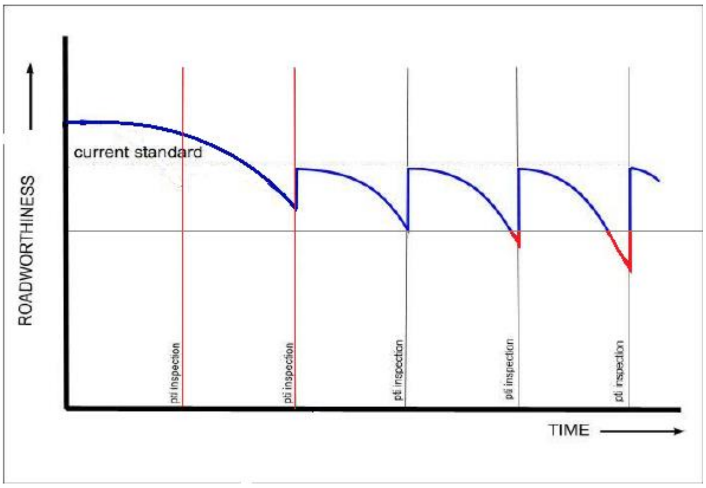

Figure 2. Rate of vehicle deterioration (adapted from Autofore 2017).

In this example, the inspection intervals are fixed and therefore independent of:

- the current roadworthiness of the vehicle,
- the rate of deterioration, and
- the growth rate.

Given the assumption that commercial vehicles owners try to maximize profit, they would wait until the last moment to carry out an inspection, unless the future savings of an inspection are estimated to be higher than the cost of an inspection today. Since estimating the future cost savings is quite complex, additional inspections are hardly performed in practice unless the vehicle is not roadworthy.

Let:

$f(x_t)$ be the roadworthiness of vehicle x at time t,
m be the minimum roadworthiness all vehicles must comply with,
r_{xt} be the rate at which vehicle x deteriorates per unit of time at time t,
g be the growth rate.

The following constraint must then hold:

$f(x) >= m$

If we assume that the deterioration rate of a vehicle is constant over short timeframes, then the maximum amount of time between now and the next inspection interval is then equal to:

$f(x_t) - m / r_{xt}$

A more realistic assumption is that the rate of deterioration grows as the vehicle is used. The rate of deterioration at time t is then given by:

$r_{xt} = r_{x0} (1 + g)^t$

Since time does not necessarily imply usage we should define the rate of deterioration as a function of some other variable, possibly including distance driven, operating time or some combination thereof.

Materials and method

We conducted an observational study of 181 heavy towing vehicles with a mass greater than 3.5 tons. These vehicles were operated across several European countries between 2016-09-19 and 2017-09-19, driving a total of 2.009.853 km. These vehicles were selected from different fleets and fitted with electronic braking systems (EBS) that support the TCAN protocol. The TCAN protocol[1] standardizes the exchange of data between braking

[1] See http://trailercan.org

and auxiliary data collection systems for this class of vehicles. Since most modern trailers are equipped with an EBS system such data is now widely available. The data was collected using a commercially available hardware, capable of processing and storing data and periodically pushing the data to a server [5]. The variables measured for each power cycle include:

Table 1. Data description.

Variable	Description
time_on	Timestamp of power on
time_off	Timestamp of power off
distance	Distance travelled
avg_load	Average load
max_load	Maximum load
num_brake	Number of brake applications for a given pressure range
avg_t	Average duration of a brake application for a given pressure range
avg_p	Average brake pressure applied for a given pressure range
num_vert_acc	Number of accelerations for a given range
max_lat_acc	Maximum lateral acceleration

After analyzing the data, we discarded data from 4 braking systems that did not comply with the TCAN protocol. Next we removed any outliers from the data by discarding any decelerations greater than 4 bar and any accelerations greater than the 95th percentile. These observations are highly unlikely and possibly due to errors in the sensor data or hardware configuration. To avoid division errors we removed any power cycles with a distance of 0. Furthermore we filtered the data by only including power cycles with an average speed greater or equal to 0 km/hour. For each power cycle we calculated the average pressure and duration of a brake application. Last, we transformed the data to be able to compare trailers. This included:

- Scaling the average load to a load ratio by subtracting the minimum load and dividing by the maximum axle capacity.
- Converting binned statistics into magnitudes.
- Weighting averages per power cycle by the total distance driven.
- Secondly, weighting the average pressure and duration of the brake applications per power cycle by the total number of brake applications.
- Calculating the average daily distance between the first and last drive cycle.

When calculating the average daily distance we excluded the first 20 drive cycles to account for new trailers standing still prior to being assigned a task or route. We then removed any trailers from the dataset which had driven less than 5 days or less than 1000 kilometers.

After preprocessing, we obtained the following variables:

Table 2. Preprocessed data description.

Variable	Description
load_ratio	Ratio of the maximum axle capacity which is used (0=unladen, 1=laden)
total_p	Total amount of pressure applied
total_acc	Total amount of acceleration
dec_km	Number of decelerations per kilometer
acc_km	Number of accelerations per kilometer
p_km	Pressure applied per kilometer.
a_km	Acceleration per kilometer
avg_dist	Average distance per day
num_days	Number of days between first power on and last power off event
num_axles	Number of axles

Last, we analyzed the similarity between trailers using k-means clustering. We first removed any variables that are not indicative of average operational usage over time or distance. We then applied principal component analysis (PCA) prior to clustering [6]. PCA reduces the number of observed variables to a smaller number of principal components which account for most of the observed variance of the observed variables. This allows us to analyze variables that strongly differ across trailers and visualize the data to look for any possible clusters. We then ran the k-means clustering algorithm for different numbers of clusters, selected the optimal number of clusters and then predicted the cluster each trailer belongs to.

Results

The key tables and figures can be found below. Table 3 and 4 display the summaries of the statistical analyses per power cycle and per trailer. Figures 3 to 11 show graphical distributions of the data per power cycle. Figures 12 to 20 show graphical distributions for the data per trailer. Figures 21 and 22 display correlation heatmaps of the data at the power cycle and trailer level. Table 5 and 6 show the output of the PCA including the principal components and the explained variance per number of components. Figure 23 visualizes the reduced data. Figure 24 shows the result of k-means clustering. Table 7 shows the cluster averages for the clusters identified.

Key figures and tables

Table 3. Summary of statistics per power cycle

	distance	avgspeed	maxspeed	minload	avgload	maxload	num_axles	load_ratio	maxlatacc	avg_p	avg_t	acc_km	dec_km	a_km	p_km
count	70989	70989	70989	70989	70989	70989	66384	66362	70989	70989	70989	70989	70989	70989	70989
mean	28.69	39.64	68.82	7880.92	8762.41	9893.40	2.04	0.22	2319.25	1.47	1.81	11.22	10233.51	28.69	39.64
std	53.16	21.92	23.00	5332.56	5728.69	6296.72	0.95	0.20	638.74	4.12	1.76	31.55	10200.85	53.16	21.92
min	1	1	1	606	2664	3760	1	0	178	0	0	0.00	0	1	1
25%	2	22	51	4680	5146	5850	1	0.08	1926	0.00	0.37	0.00	2070.59	2	22
50%	5	36	80	5432	6032	6854	2	0.16	2333	0.26	1.30	1.93	7472.73	5	36
75%	28	57	87	8460	9544	11000	3	0.28	2699	1.09	3	8.29	15500	28	57
max	851	243	124	28820	32336	38136	3	0.97	8366	111	15	832.50	214200	851	243

Table 4. Summary of statistics per trailer

	avg_dist	num_days	num_axles	avgspeed	avgload	load_ratio	num_acc	num_brake	a_km	p_km	avg_p	avg_t
count	177	177	166	177	177	165	177	177	177	177	177	177
mean	163.52	93.97	2.65	52.52	9763.92	0.24	0.36	0.38	2.73	2248.98	911.52	6.42
std	82.41	64.07	0.68	10.13	4065.24	0.12	0.18	0.31	1.39	1836.28	136.14	0.90
min	9.72	6.02	1.00	19.83	1788.80	0.01	0.04	0.02	0.28	140.01	497.75	4.46
25%	104.69	40.68	3.00	46.53	5687.48	0.15	0.23	0.23	1.72	1316.50	806.56	5.75
50%	154.06	82.65	3.00	52.97	10100.93	0.25	0.34	0.27	2.54	1611.71	901.48	6.42

75%	209.72	141.79	3.00	60.19	12809.63	0.34	0.46	0.33	3.51	2143.25	1014.34	7.00
max	466.58	293.02	3.00	72.55	19291.18	0.52	1.27	1.74	9.70	9093.45	1304.72	9.64

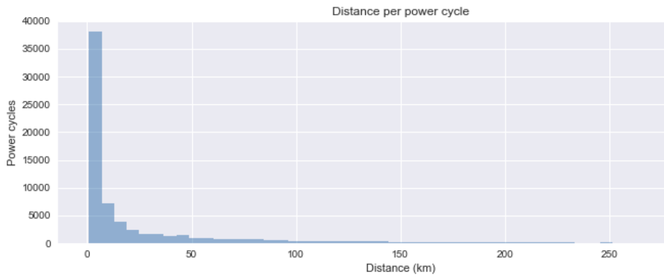

Figure 3. Distance per power cycle.

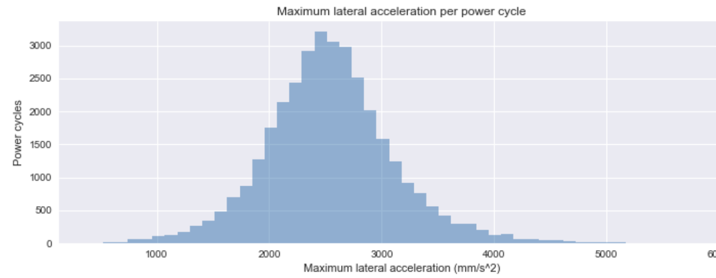

Figure 7. Maximum lateral acceleration per power cycle.

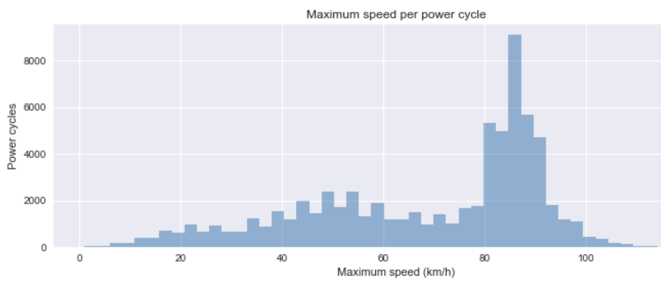

Figure 4. Maximum speed per power cycle.

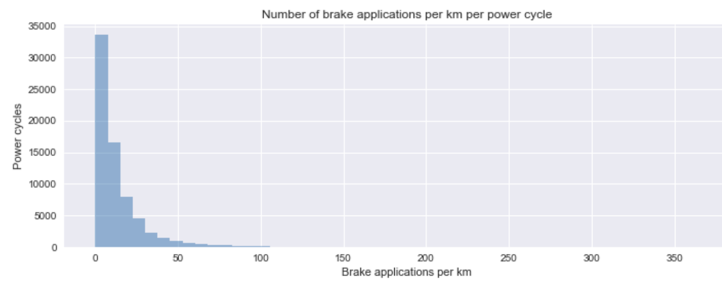

Figure 8. Number of brake applications per kilometer per power cycle.

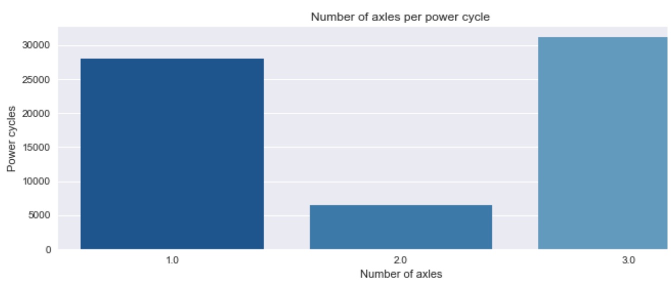

Figure 5. Number of axles per power cycle.

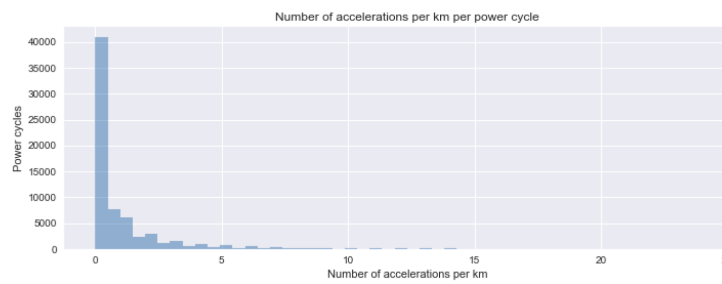

Figure 9. Number of accelerations per kilometer per power cycle.

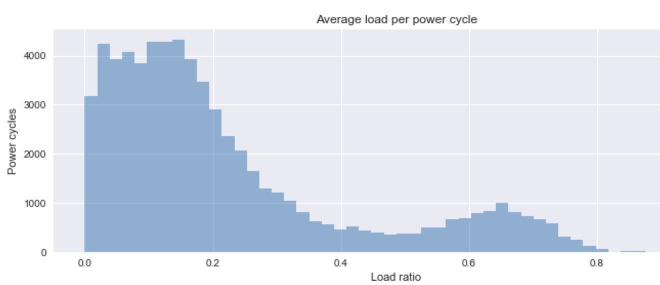

Figure 6. Load ratio per power cycle.

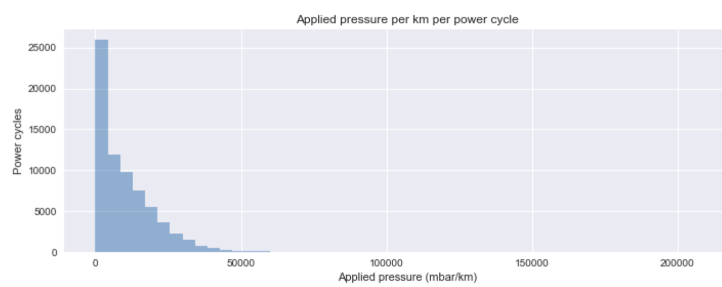

Figure 10. Applied pressure per kilometer per power cycle.

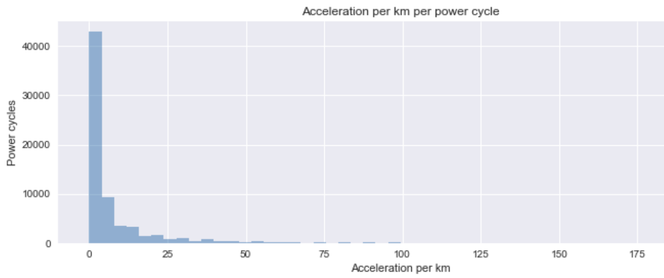

Figure 11. Acceleration per kilometer per power cycle.

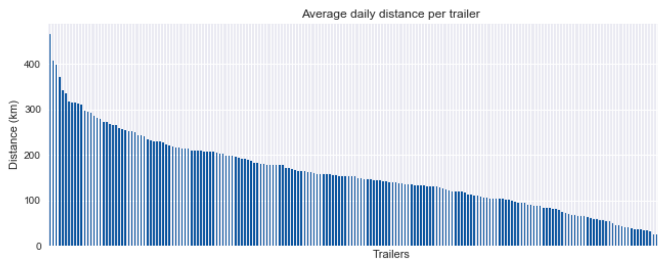

Figure 12. Daily distance per trailer.

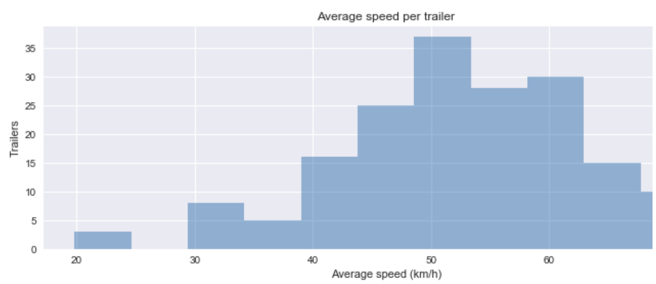

Figure 13. Average speed per trailer.

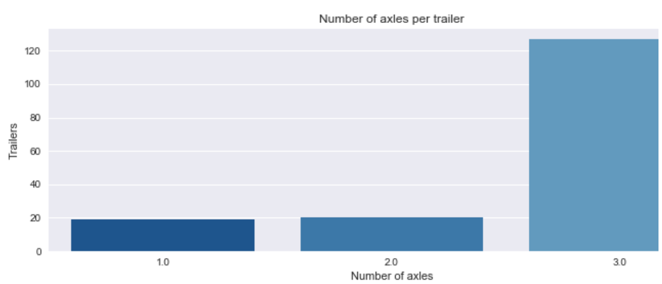

Figure 14. Number of axles per trailer.

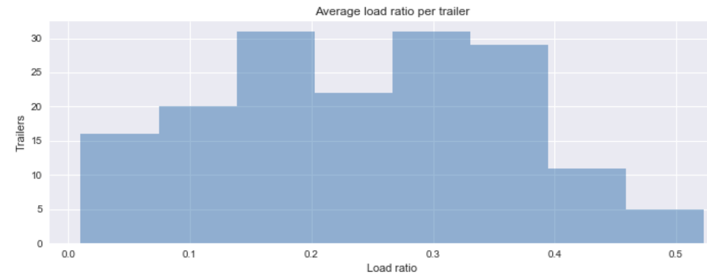

Figure 15. Load ratio per trailer.

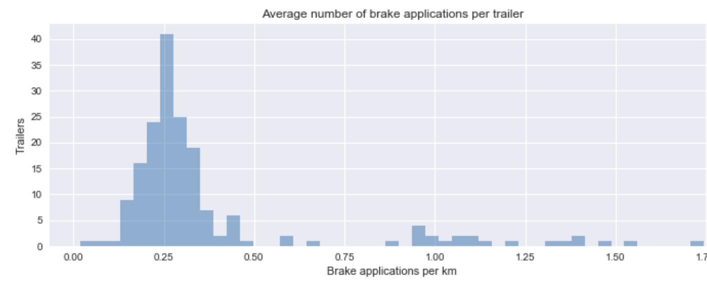

Figure 17. Number of brake applications per kilometer per trailer.

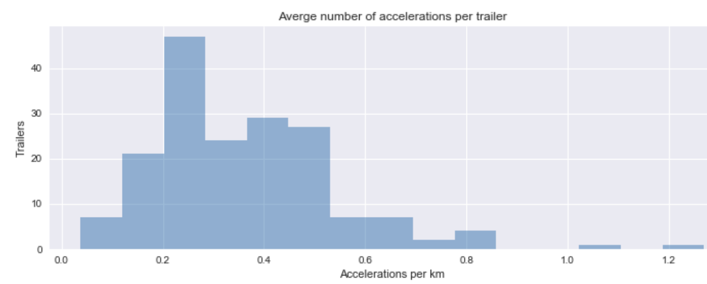

Figure 18. Number of accelerations per kilometer per trailer.

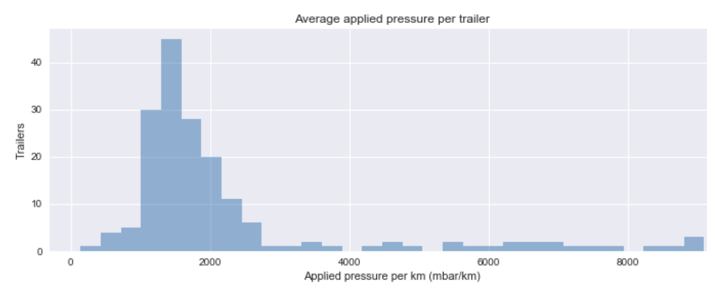

Figure 19. Applied pressure per kilometer per trailer.

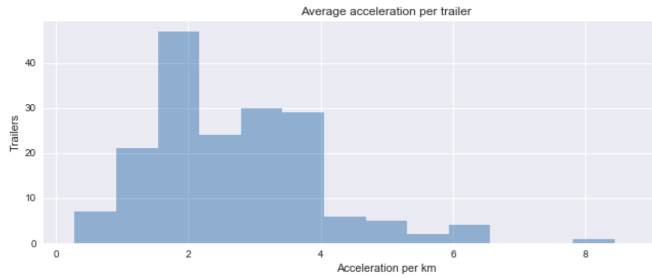

Figure 20. Acceleration per kilometer per trailer.

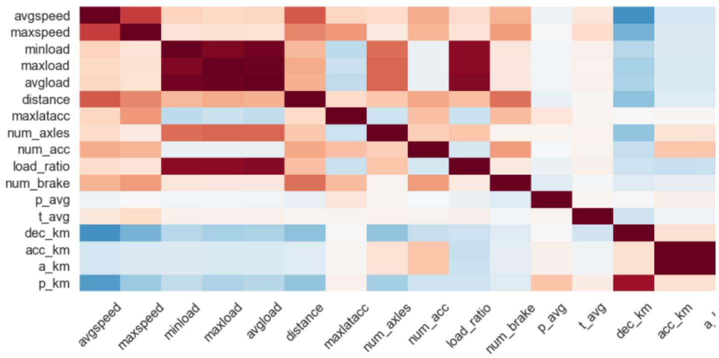

Fig 21. Correlation heatmap of the data per power cycle.

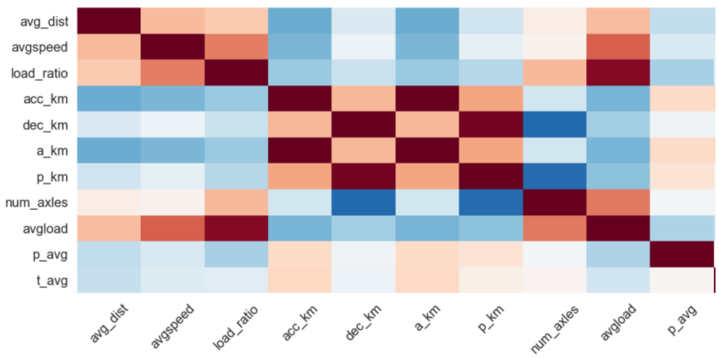

Fig 22. Correlation heatmap of the data per trailer.

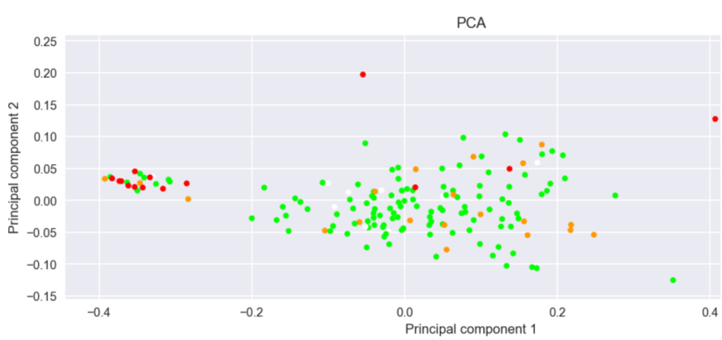

Fig 23. PCA (red: 1 axle, orange: 2axles, green: 3 axles, white: NA)

Table 5. The percentage of variance explained by successive principal components.

Number of components	Cumulative sum of the explained variance
1	0.90755154
2	0.97729851
3	0.99896386
4	0.99998514
5	0.99999572
6	0.9999999
7	0.9999999
8	1.0
9	1.0

Table 6. The principal components.

Variable	1st component	2nd component
avgspeed	4.71487996e-02	5.88893612e-02
loadratio	2.10027954e-04	4.15291057e-04
acc_km	1.25166252e-04	-5.58204121e-04
dec_km	-6.42435378e-05	2.50641878e-04
a_km	9.49312139e-04	-4.23952150e-03
p_km	**-4.72833728e-01**	-1.60563563e-01
p_avg	**8.49332072e-01**	-3.42610944e-01
t_avg	4.94502894e-03	4.15892594e-04
avg_dist	**2.29814858e-01**	9.23769686e-01

Table 7. Cluster averages (from left to right)

cluster	avgdist	avgspeed	load_ratio	acc_km	dec_km	a_km	p_km	avg_p	avg_t
3	**252.86**	52.24	0.16	0.20	0.13	1.51	**695**	**966**	5.47
1	**137.21**	50.11	0.16	0.52	1.12	3.95	**6555**	**914**	6.34
2	179.70	53.06	0.27	0.29	0.23	2.17	1326	916	6.09
4	139.05	52.08	0.25	0.40	0.31	3.05	1924	902	6.76

Key findings

Distance over time

Over a period of 360 days we collected on average 94 days of operational data per trailer. The average distance driven per day was 164 km with a standard deviation of 82 km. Some trailers drove more than 350 km per day. See figure 12.

Maximum speed

The maximum speed per power cycle has three maxima. There is a clear distinction between power cycles with an average maximum speed of 50 versus 90 km. The prior is most likely urban and regional traffic, whereas the latter speed can only be achieved on the highway. See figure 4.

Number of axles

The majority of the trailers have 3 axles but the number of power cycles with 1 versus 3 axles is almost the same. Single axle trailers either generated more power cycles or offloaded more frequently.

Maximum lateral acceleration

The maximum lateral acceleration per power cycle follows an approximately normal distribution. It is more or less random. See figure 7.

Load ratio

Approximately a quarter of the axle capacity is used on average. Some trailers consistently carry higher loads and use half of the axle capacity on average. See figures 5, 6, 14 and 15.

Brake applications and accelerations per power cycle

The number of accelerations and brake applications per kilometer as well as the amount of pressure applied and the amount of acceleration per kilometer follow an approximately half-normal distribution. See figures 8, 9, 10 and 11.

Brake applications per trailer

The distribution of the number of brake applications per kilometer per trailer is skewed. These probably coincide with different traffic types. Some trailers brake as frequent as every 250 meters while some only brake once per kilometer or less. See figure 14.

Correlations

We found a strong negative correlation between the number of axles and the number of decelerations per kilometer. As expected there is a negative correlation between the average speed of a trailer and the number of decelerations/accelerations per kilometer. The average speed of a trailer however was positively correlated with the load ratio. Furthermore, we found a somewhat negative correlation at the power cycle level between the load ratio and maximum lateral acceleration as well as between the load ratio and the number of accelerations and decelerations. To summarize, trailers with a higher average speed, use more axle capacity but brake and accelerate less. See figures 21 and 22.

Principal component analysis

A single component is able to explain 90% of the variance. The average distance, applied pressure per kilometer and average pressure per brake application are most strongly correlated with the component, e.g. they have the largest magnitude. See tables 5 and 6.

K-means clustering

Reducing the data to two dimensions and visualizing the reduced data in a scatter plot reveals three or more clusters. See figure 23. Selecting 4 clusters and running the k-means clustering algorithm produced the best fit. See figure 4. Clusters 3 and 1 stand out in particular. Trailers belonging to cluster 3 drive 253 kilometers per day, brake 33 times per day and apply an average pressure of 966 mbar per brake application. Trailers belonging to cluster 3 on the other hand drive only 137 kilometers per day, but brake 153 times per day and apply an average pressure of 914 mbar per brake application. See table 7.

Discussion

Since the mass and acceleration of a trailer determine the sum of the forces acting on the trailer, trips with higher loads, frequent or harsh accelerating, braking or cornering must have higher wear and tear. Clearly not all trips are equal. Better yet, there is a big difference between trailers with regards to their operation and therefore the forces they are exposed to. Regardless of whether these differences are caused by road conditions or driver behavior, they have an impact on the rate of degradation. More work is needed to understand how these factors affect the rate of degradation and the growth rate, both at the component level and the trailer as a whole.

Two of the main reasons for failing the periodic inspection are worn, faulty or damaged brakes or tires. Since both brakes and tires inhibit motion by absorbing energy, both the rate at which brakes and tires fail and the type of failure must be dependent on the how often the brakes were used and how the brakes were applied. Therefore we would expect to find different rates of wear and tear and different types of wear patterns after similar time intervals for trailers belonging to different clusters, example given the brake lining or tire tread.

How much distance is traveled and how the brakes were applied differs strongly between trailers. Unlike currently used factors, such features can be obtained in a reliable, verifiable and objective manner. This makes them suitable candidates to implement condition-based monitoring.

We collected 94 days of operational data per trailer over a period of 360 days. This discrepancy is due to several reasons. First, the hardware installation did not necessarily coincide with the start of the study. Second, trailers are often sitting before being assigned a task or route. Third, data was offloaded periodically which causes some latency. We excluded power cycles having a distance of 0. Most likely such power cycles occur during stops, loading, unloading and/or shunting. Despite the short distance, such power cycles could have an effect on the wear due to the high frequency with which they occur.

Electronic systems have the potential to improve safety and compliance in areas that previously could not be covered by traditional mechanical safety devices, including periodic inspections. The development of sensors and computing techniques together with a reduction in price has led to the situation where much more information is available than has been the case previously. This in turn will create great challenges. Not only to automate the diagnosis based on this data but also to develop strategies and regulations for improving safety and compliance that allow for a decrease in the frequency of periodic inspections for individual trailers based on the roadworthiness of the vehicle and the rate of deterioration.

References

1. Driver & Vehicle Standards Agency. Guide to maintaining roadworthiness. Commercial goods and passenger carrying vehicles. (Revised 2014)

2. International Motor Vehicle Inspection Committee. (2007). Autofore Report. Study on the Future Options for Roadworthiness Enforcement in the European Union.

3. Jantunen, Erkki & Arnaiz, Aitor & Baglee, David & Fumagalli, Luca. (2014). Identification of wear statistics to determine the need for a new approach to maintenance.

4. Jolliffe, I.T., 2002. Principal Component Analysis, second edition, New York: Springer-Verlag New York, Inc.

5. Peck, Dana & Scott Matthews, H. & Fischbeck, Paul & Hendrickson, Chris T., 2015. "Failure rates and data driven policies for vehicle safety inspections in Pennsylvania," Transportation Research Part A: Policy and Practice, Elsevier, vol. 78(C), pages 252-265.