The Time-Precise Evaluation of Tachograph Charts

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Abstract

If an HGV is involved in an accident, its motion can be deduced from the tachograph recording. This evaluation is performed by the use of mechanical devices. This paper analyses the errors produced by the evaluation process. Theoretical deductions are followed by actual measurements. The circumstances under which the results of the evaluation may be trusted are thus determined.

Introduction

When considering accident reconstruction, one of the major tasks is reconstructing how the vehicles actually approached the point of collision. As the driving speed of a commercial vehicle is recorded by the tachograph, it is certainly desirable to make use of this recording for reconstruction purposes. When reconstructing the approach of a vehicle we need to know the driving speed versus time – as precisely as possible. Therefore, it does not suffice to simply read the speed from the tachograph chart, we also have to assign a certain time to each speed value read from the chart.

With regards to this task we should refer to this as a time-precise evaluation of tachograph charts instead of using the more common term 'microscopic' evaluation, which denotes only one of the possible means of doing so. Of course, temporal precision can only be achieved relative to the start of the time interval in focus. Absolute times cannot be read from the tachograph chart, because the absolute time indicated by the tachograph is adjusted manually.

Though tachographs were not originally intended for this use, time-precise evaluation has been common in Germany since the early 50's when Kienzle started to develop mechanical devices required for such evaluation. Since then, more than a hundred thousand tachograph chart evaluations have been conducted by Kienzle [1]. If a commercial vehicle is involved in an accident, it is quite common in Germany to delegate the task of reconstructing the motion of that vehicle to Kienzle or VDO.

Despite the prevalence of this procedure, its accuracy had never been scrutinised up until 1993 when Kienzle assigned the task of a thorough investigation of it to myself. This paper is an updated version of my original report [2].

The Apparatus

The speed is recorded in a polar co-ordinate system on the tachograph disk. The radius corresponds to the driving speed and the turning angle corresponds to the time elapsed. The mechanical device used for the evaluation process consists of an incident light microscope with a modified object stage, depicted in **fig.** 1. The tachograph disk is placed

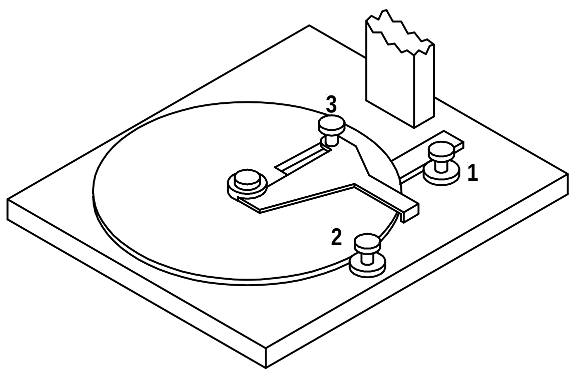

Fig. 1: Modified Object Stage of the Incident Light Microscope

on a turntable that may (of course) be turned and also be shifted horizontally. Thus the modes of liberty of the turntable correspond to the polar co-ordinates used in the recording.

A hairline within the eyepiece indicates the perpendicular of the turntable radius. By shifting the turntable such that this hairline intersects the tachograph chart at a given point, the speed at that point may be calculated based on the requisite shift ①.

On top of the turntable there is a slide with a hairline etched into the back of it, indicating the (approximately) radial direction. (We shall come back to this point later in greater detail.) The angle of rotation ② needed to get this hairline to intersect the tachograph chart at a given point is equivalent to the time elapsed. The direction of the hairline with respect to the exact radial direction may be adjusted by the mechanism ③. Of course, **fig.** 1 is a simplified version of the original apparatus.

Nowadays the adjusting wheels are equipped with pulse-sending units so that the turn count can be read into a data logger. The evaluation procedure itself remains however mechanical in nature. One of the main disadvantages of the mechanical apparatus is the play between its component parts. Once the evaluation process has started, you may turn the table in one direction only or you will have to restart the whole evaluation procedure from the beginning. One of the main advantages however is that the measurement takes place 'in situ', so distortions due to magnification do not affect the measurement.

Today, one may think of applying computer technology to the problem, tracing the image of the tachograph chart (semi-) automatically. The main problem in doing so is the distortion produced by the magnification. This magnification is inevitable because a time interval of 1 s corresponds to a mere 3.4 μm on the 40 km/h circumference. This means that at least 7500 dpi are needed to yield a 1 s resolution. Such a resolution can only be achieved by a magnification applied prior to digitisation – using hardware commonly in use.

The Speed Threshold

All tachographs have a speed threshold. If the driving speed stays below this threshold, the recording stylus remains at the *circle of rest*. The exact value of the speed threshold depends on the recording range that the tachograph has been designed for. The diameter of the circle of rest has a given standard value and as such should touch the time scale markings. Within the circular recording area, the deflection of the stylus is linearly proportional to speed. The tachograph disk is divided up into concentric circles of 20 km/h distances. The difference in diameter between the circle of rest and the circle representing 20 km/h is less than that between the other circles. This difference corresponds precisely to the value of the speed threshold.

If the table of a tachograph chart evaluation indicates standstill, these values and their corresponding time values are based on an extrapolation of the recording. The time value gained by this extrapolation is rounded off to whole seconds. Neither the table nor the graphical illustration reflects the original evaluation point, i.e. the entrance point into the circle of rest.

When looking at the speed recording, driving manoeuvres of (maximum) speeds that remain below the threshold (*creeping drives*) are indistinguishable from a standstill position. Under certain conditions, more lengthy creeping drives can be detected by having a close look at the distance recording. The circular recording area for distance has a width of 5 mm, so that 1 m driving distance corresponds to 1 μm within the recording. A driving distance of 40 m then corresponds to the width of the recording line. If the creeping drive is bracketed by longer standstills, we may observe a minute difference in the radii of the recorded circles.

The Divergent Scales

When deriving speed versus time functional dependency from the tachograph chart, the main problem stems from the fact that the scales of the two recorded variables differ so greatly. A change of 1 km/h corresponds to a change of 165 µm in radius whereas a time interval of 1 s corresponds to only 3.4 µm on the 40 km/h circumference. If we consider a change of 10 km/h per second (=2.8 m/s²) as typical for driving manoeuvres, the corresponding slope of the recording line would be 1:500 (the 'typical slope').

The width of the recording line is about 55 µm. According to the temporal scale this corresponds to 16 s. We shall denote the time increment corresponding to the width of the recording line as the *line time* in the following. On the other hand, the width of the recording line corresponds to only 0.3 km/h on the speed scale.

Using the mechanical-optical evaluation device, time values may be taken in intervals of about 0.5 s. During the evaluation process the original recording is approximated by a polyline. The choice of vertices is up to the evaluator. In general, the time values derived from the recording are rounded off to whole seconds to avoid the impression of higher accuracy than is justified.

The *Guiding Line*

So far we have described the recording process in terms of a polar co-ordinate system. Considering the practical implementation in a mechanical device, it is obvious that the guide rail of the recording stylus cannot be mounted precisely radial. When mounting the assembly, production tolerances have to be taken into account. This means that even if one were able to stop the tachograph disk from turning and could simply alter the speed, the recording line would not be precisely radial.

In order to represent the direction that corresponds to an infinite acceleration on the tachograph disk (when mounted on the turntable), the concept of the guiding line was developed. The orientation of the guiding line must be fixed prior to evaluating the segment of interest. Let me point out at this juncture that the guiding line is a purely theoretical concept. Its orientation cannot be precisely derived from any characteristic properties of the tachograph recording.

When using the mechanical device, the guiding line is represented by a hairline etched into the back of a slide. This hairline has a width of about 3 µm, corresponding to about 1 s on the 40 km/h circumference. The angle between the hairline and the exact radial direction may be altered via mechanical adjustment. Before the segment of interest (shortly before collision) can be evaluated, the angle between the hairline and the radial direction must be fixed. This is done by evaluating acceleration and deceleration manoeuvres prior to the segment of interest.

At the start of the recording, the mechanism of the tachograph has to 'settle' such that its play is eliminated. Thus it takes some time for the direction of the guiding line to stabilise. Removing the disk from the tachograph will destroy the current guiding line. Nonetheless even obvious violations of this code of conduct do not necessarily inhibit evaluation [3].

Furthermore, the locus of the pivot of the disk will change when transferring it from the tachograph to the evaluation device. Thus, even if the guide rail of the stylus were mounted completely radial with respect to the pivot (in the tachograph), this direction would not coincide with the radial direction in the evaluation device. The offset between the two pivots is commonly denoted as *eccentricity* and the error resulting from this as the *eccentricity error*.

The Flank Method

The remarks referring to the width of the recording line show that the recording on the tachograph disk cannot be considered as a conventional plot of a function in a (modified) polar co-ordinate system. Normally, we consider the plot of a function as an acceptable

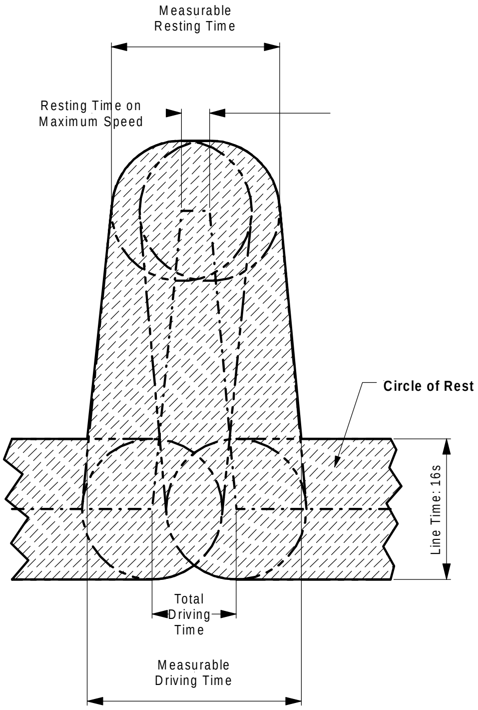

Fig 2: Single Overlap Recording

approach to the mathematical concept of a curve that represents a precise correspondence between the two co-ordinates. If we take a given curve that is 16 times wider than one of the co-ordinate units, we have to apply special procedures in order to obtain a definite assignment between the two co-ordinates.

We are thus forced to find an improved representation of the mathematical concept of the curve as it occurs in the tachograph recording. Basically, there are two possible solutions to this problem, the most common of which is the tracing of the edge of the recording line. One may deliberately take the ‘left’ or the ‘right’ edge. If the recorded acceleration changes sign, the recording may consist of overlapping parts. This occurs if the time interval in which the speed remains at its local maximum (or minimum) is shorter than the line time.

In the recording **fig.** 2 the ‘right’ edge of the rising line segment and the ‘left’ edge of the falling line segment cannot be seen. So the side referred to has to be switched at the apex. Because the evaluation is based on the visible flanks of the peak, I shall refer to this procedure as the *flank method* in the following. The interval that the speed remains at its maximum (minimum) may be evaluated by subtracting the line time from the width of the summit.

The Trough Method

If the acceleration changes sign more than once during the line time, we encounter multiple overlaps in the recording. In the case depicted in **fig.** 3, both edges of the rising curve segment are invisible. In such cases the recording is illuminated directly from the top via a prism. As the recording line is ‘scratched’ into the recording layer, it will have the shape of a three-dimensional trough. When lighted from the very top, the specular reflection into the eye of the observer originates primarily from the bottom of this trough, i.e. the centre of the line. The centre of the recording line thus stands out by its lighter colour.

Using the trough method we link the evaluation to the centre of the recording line. When switching between the flank and the trough method we have to account for the time shift of half of the line time (8 s).

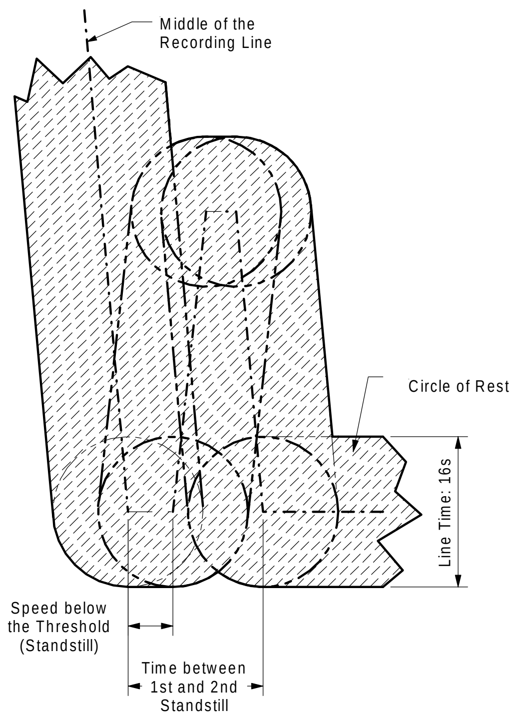

Fig. 3: Twofold Overlap Recording

Errors Affecting the Speed Coordinate

EU regulations differentiate between three conditions with reference to permissible errors for recorded speed [4]:

- errors produced by the tachograph itself prior to fitting it into the vehicle
- errors subsequent to fitting the tachograph into the vehicle
- maximum error occurring between recalibrations

This categorization corresponds to the different sources of error:

- incorrect recording by the tachograph itself
- errors produced by imperfect adjustment between the rpm's of the drive shaft and the ration (i.e. pulse count) that the tachograph is based on (*ration correction*)
- change in wheel diameter or scrub radius

For modern electronic tachographs we may expect that the deflection of the stylus (produced by a step motor) is linearly proportional to the pulse frequency fed into the device. We have tested the tachograph used for our experiments and found that the recorded speed corresponded exactly to the ration indicated on the calibration sheet. Older tachographs that function mechanically (on the eddy current principle) have a non-linear relationship between the rpm's fed into them and recorded speed. Put succinctly: the first item of the EU regulation mentioned above targeted mechanical devices. This source of error is negligible for modern electronic devices. Incorrect adjustment of the circle of rest can still cause of a constant offset in the recording. Such an offset, however, may be easily accounted for in a thorough evaluation.

In the past, the ration correction was performed by an adapter gearbox. Naturally, the adjustment was limited to preset gear ratios. This is what the second item of the regulation mentioned above was intended for. Nowadays, the electronic tachograph ration may be adjusted precisely to the pulse frequency produced by the electronic pickup at the drive shaft. Consequently, this regulation has in fact also been superseded by evolution in current technology.

The third item of the EU regulation is targeted primarily at the effect of tire wear and the possible ageing of the tachograph. Though a digital device is not affected by ageing, the effect of tire wear does have to be accounted for. The circumference of a worn HGV tire is up to 2% less than that of the new tire. A change in wheel diameter produces a recording error that is linearly proportional to driving speed. The same will hold true if ration correction is incorrect. Thus for electronic tachographs the following relation is yielded

$$\Delta v = c_v \cdot v \qquad (1)$$

For mechanical devices that function on the eddy current principle, we have to account for non-linear errors. Electronic tachographs that have been recently re-calibrated will record driving speed highly accurately.

Errors Affecting the Time Coordinate

Reading Error

Even the hairline itself has a width of 1 s, which means that the intersection point between the hairline and the reference curve (middle or flank of the recording line) is not that precisely defined. The edges of the recording line will also appear somewhat rippled because the recording is produced by a mechanical scraping process, comparable to that used for producing old phonographs. Tachograph disks of inferior quality may even impede a time-precise evaluation as the 'brittle' material of the recording layer breaks at the rims of the trough as the stylus passes through it.

The reading error is stochastic in nature. It may change sign arbitrarily between the vertices of the evaluation. We may assume that there is some correlation between errors affecting consecutive vertices. We are, however not able to predict the degree of this correlation via theoretical considerations. Sections evaluated via trough method tend to be affected by greater reading errors than those sections evaluated by the flank method.

Displacement of the Reference Curve

If a single overlap in the recording forces the evaluator to switch from the left to the right flank of the recording line (or vice versa), the line time (16 s) must be accounted for. This time shift is many times greater than the desired degree of accuracy. Thus low proportional errors between the assumed and actual line time will result in significant time shifts. The corresponding effect appears when switching back and forth from the flank to the trough method. In this case, the time shift corresponds to half of the line time.

Irregularities in the Registration Layer

In an ideal setting, the registration layer of the tachograph disk would have a constant viscosity over its whole area. In the ‘real world’ however, we face local solidification in the registration layer, especially when using low-cost tachograph disks. These may deflect the stylus toward the softer material. Such irregularities may be misinterpreted as either variations in speed or as being the result of impact.

Guiding Line Skew

The ideal guiding line is equal to the imaginary line representing infinitive acceleration. For this reason the orientation of the hair line (as its real-world representation) should correspond to an acceleration which is as high as possible. The quality of the hairline may thus be characterised by the acceleration a_c which it represents. Skew produces an error proportional to driving speed. For the temporal error between two arbitrary vertices - *i*, *j* - we obtain

$$\Delta t = \frac{v_i - v_j}{a_c} \qquad (2)$$

The error in overall driving time is therefore proportional to the speed differential between beginning and end of the entire driving manoeuvre. This means that if the speed at the beginning and end of the evaluated driving manoeuvre is the same (particularly zero), there will be no error in the evaluated driving time due to skew.

The overall distance traversed may be calculated by multiple application of the trapezoid rule

$$s = \tfrac{1}{2}\sum_{k=0}^{n-1}\left(v_k + v_{k+1}\right)\cdot\left(t_{k+1} - t_k\right) \qquad (3)$$

The error will then be

$$\begin{aligned}\Delta s &= \tfrac{1}{2}\sum_{k=0}^{n-1}\left(v_k + v_{k+1}\right)\cdot\left(\Delta t_{k+1} - \Delta t_k\right)\\ &= \frac{1}{2\,a_c}\sum_{k=0}^{n-1}\left(v_k + v_{k+1}\right)\cdot\left(v_{k+1} - v_k\right) \qquad (4)\\ &= \frac{1}{2\,a_c}\sum_{k=0}^{n-1}\left(v_{k+1}^2 - v_k^2\right)\end{aligned}$$

Via the subtraction conducted in the summation term all speeds with exception of the first and last cancel each other out, leaving

$$\Delta s = \frac{v_n^2 - v_0^2}{2\,a_c} \qquad (5)$$

As for the overall driving time there will be no error in the calculated distance if the speeds at the beginning and the end of the driving manoeuvre are the same. Particularly when evaluating driving manoeuvres bracketed by starting and stopping, there will thus be no error resulting from skew.

Eccentricity

The error caused by eccentricity differs somewhat from ‘normal’ skew. Eccentricity will cause the guiding line to alter its direction in the form of a sinusoidal function through a 360° turn [5]. Because the evaluation interval usually consists of only a few seconds, the direction of the guiding line may still be assumed constant within this interval.

We should, however keep in mind that the direction of the guiding line is determined elsewhere on the chart, usually somewhat prior to collision. Because of possible eccentricity, the direction of the guiding line should be determined as closely as possible to the evaluation interval, without actually including it. As the guiding line is determined by comparing the values of start and stop acceleration, this demand may be hard to fulfil in highway accident cases.

Driving Experiments

Experimental Setup

The basic idea was the generation of a reference measurement for comparing evaluation results with afterwards. We thus used a reflection photocell as a contrast taster counting white strips affixed to the tire flank, i.e. we measured the distance traversed by the tire circumference. Our procedure guarantees that deviations between our reference plot and the tachograph chart evaluation can be limited to errors originating from the tachograph itself or from the evaluation process because other sources of error have been excluded.

With the pulses generated by the reflex taster, we decrement an electronic counter, whose counter reading was read by a computer in fixed time intervals. We thus produced a time-distance recording as opposed to the time-speed recording of the tachograph. As our primary interest usually is the time-distance relationship derived from the tachograph recording, this way of proceeding was expedient. On the other hand, we can easily calculate the time-speed relationship by taking the derivative of our recording.

Conception of the Experiment

We conducted two test drives with an overall duration of five minutes each. The evaluator was instructed to evaluate only the visible part of the recording and retrain from the usual extrapolations to standstill. All data thus refers to driving speeds above 7 km/h, which was the speed threshold of this particular tachograph. Consequently, 'stopping times' denote the time interval that the stylus remained on the circle of rest.

- Flank Method
  The stopping time between the single driving manoeuvres mostly exceeded the line time. The moving time of the single driving manoeuvres was generally shorter than the line time. Most of the test driving manoeuvres could thus be evaluated using the flank method.
- Trough Method
  If the stopping interval is shorter than the line time, we have multiple overlaps occurring in the area between the single driving manoeuvres. This effect occurred in a number of twofold driving manoeuvres.
- Creeping drives
  In two instances we randomly introduced creeping drives. They were 30.6 m and 18.05 m in length.

Maximum Speed

Fig. 4 compares the evaluated maximum speed with that taken from our reference plot. The data includes all 16 of the driving manoeuvres, the straight line indicating the linear regression. All errors fall into a ±0.5 km/h range around the general trend. This is the error span we should expect by rounding off the

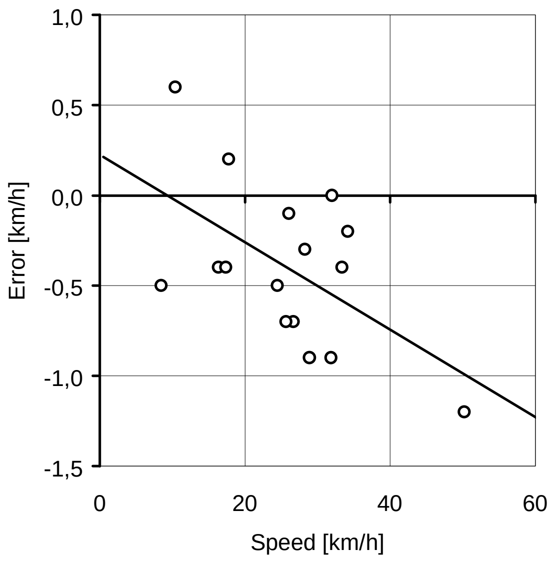

Fig. 4: Evaluation Error: Maximum Speed

speed to integer values. The general trend depicted by the linear regression represents the error produced by the tachograph itself, resulting in a recorded speed that is 2% below the actual speed.

Overall Driving Time

Fig. 5 shows the error in the evaluated overall driving time. Single driving manoeuvres that could be evaluated by the flank method are indicated by blank points. The twofold driving manoeuvres are marked by solid points connected by a line. The numeration indicates the number of the driving manoeuvre.

For those motions that could be evaluated by use of the flank method the errors fall into a range of –1 s to +2 s. The general tendency to overestimate driving time may be due to an underestimation of the line time. The maximum error of – 3.3 s occurred in driving manoeuvre no. 7. In this driving manoeuvre, maximum speed did not exceed 16 km/h and start acceleration as well as stop deceleration were lower than in the other driving manoeuvres. As the speed exceeded the threshold by only about 9 km/h, the slope at the flanks of the driving manoeuvre was hard to estimate. The evaluator may thus have been misled by the other manoeuvres evaluated and rounding off to whole seconds was likely the last straw.

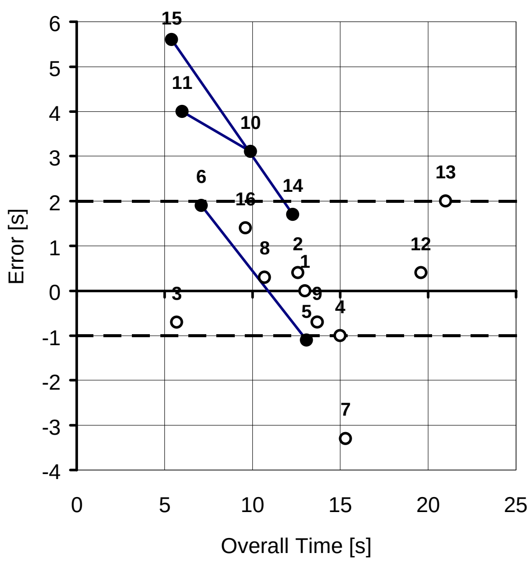

Fig 5: Evaluation Error: Overall Time

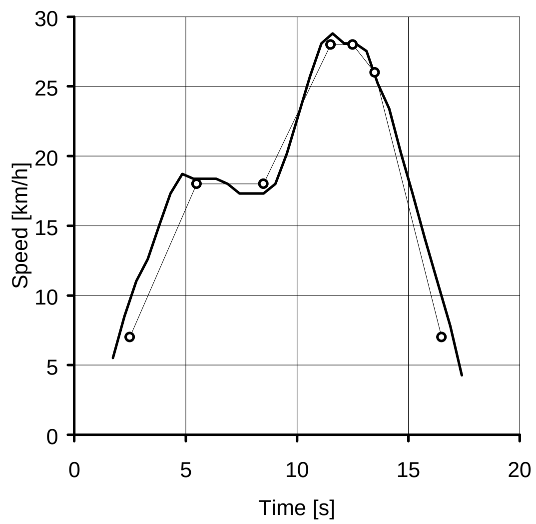

Fig 6: Example of Satisfactory Coincidence

When examining the twofold driving manoeuvres we encounter overall driving times that are considerably longer than in our reference recording. In particular, the evaluator obtained driving times for the second part of the twofold driving manoeuvres that significantly exceeded our recorded times. Unfortunately, the evaluator reset the time origin for each driving manoeuvre. This means that we are not able to judge both parts of the twofold driving manoeuvre in their entirely. Acceleration and deceleration of the visible flanks were evaluated with the same precision as for the single driving manoeuvres. This causes one to speculate that the overall driving time, i.e. the time elapsed during both parts of the driving manoeuvres, including standstill, is generally evaluated with the same precision as for the single driving manoeuvres. It would appear that the evaluated standstill between the two parts is too short. The resulting unaccounted-for time is apparently assigned to the second starting manoeuvre, yielding a start acceleration that is much too low.

Shape

Fig. 6 to 9 compare our reference recording with the evaluation results. Because the time origin of the evaluation was reset for each driving manoeuvre, there is no definitive way to superimpose the evaluation results and our reference recording. Our presentation is such that we achieved maximum coincidence on an overall basis.

Fig. 6 illustrates the high degree of coincidence that may be attained when fate is smiling on you. Start acceleration and stop deceleration show impressive coincidence with our findings. Furthermore, the evaluator noted the discontinuity produced by the gear shift and introduced two additional vertices.

On the other hand, there are driving manoeuvres where the evaluation results show little coincidence with our reference chart, **fig.** 7. Although the evaluator has noted the discontinuity in the acceleration manoeuvre and has introduced a vertex at that point, the evaluated acceleration manoeuvre shows little coincidence with the reference chart.

Even satisfactory coincidence of overall driving time and distance does not guarantee that the shape of the evaluated curve resembles the shape recorded by us, **fig.** 8. But if we shear the evaluated chart by a suitable angle, we may again attain satisfactory coincidence. This is a good example of how skew of the guiding line affects evaluation results. The solid line with blank points indicates the original result. The dashed line with solid points was obtained by shearing the original result by 4 m/s². Similarly low values for the characteristic acceleration were also observed

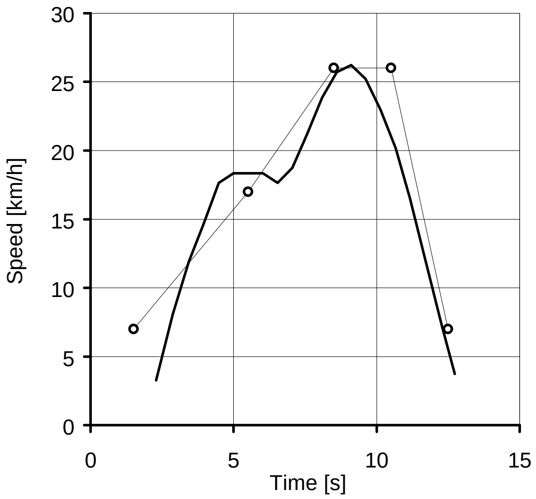

Fig 7: Example of Intermediate Coincidence

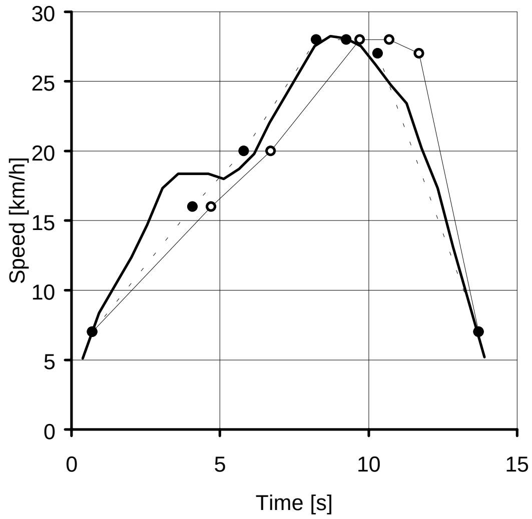

Fig 8: The Effect of Skew

for driving manoeuvres nos. 2 and 13. For all other driving manoeuvres the additional error produced by skew was roughly 1 s per 50 km/h, corresponding to a characteristic acceleration of 15 m/s².

If we compare the evaluation result for the twofold driving manoeuvres with our reference recording, we encounter the same significant deviations as in summary comparison. **Fig.** 9 shows the second part of the twofold driving manoeuvre 14/15 as an example. The deceleration at the end of the driving manoeuvre could be evaluated using the flank method. As expected, we ascertain a reasonable coincidence between evaluated and actual value. At the summit the evaluator was forced to switch to the trough method. The time shift associated with this switching has not been compensated for correctly, however, and approximately 2.5 s of error remain. At the circle of rest, the error in the time co-ordinate has then reached a value of 5.5 s.

Creeping drives

The two driving manoeuvres where the speed did not exceed the threshold were not detected, although the distance traversed was more than 30 m in one case and the evaluator knew about the test situation. This was probably due to the lack of a standstill of greater duration before and after the creeping drives.

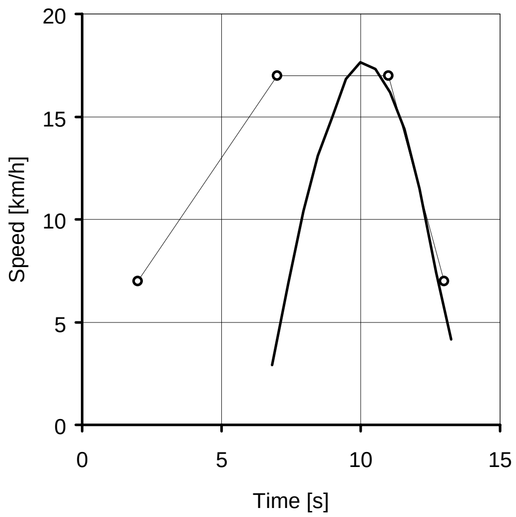

Fig. 9: Unsatisfactory Coincidence when Using the Trough Method

Conclusions

Theoretical considerations as well as the results of the experiment show that the main problem of tachograph chart evaluation lies in the time co-ordinate. In contrast, the errors affecting the speed co-ordinate are much smaller than suggested by the EU regulation. Errors in speed indication by electronic tachographs are linearly proportional to driving speed. A shifting of the circle of rest may easily be accounted for in a thorough evaluation. Therefore, the EU regulation's setting of linear error limitations is misleading with regard to the nature of the error sources.

The evaluation may achieve a high degree of accuracy for those parts evaluated by the flank method. In contrast, the trough method usually yielded poor results only. The reason for this finding is not definitively clear. It may either be that the middle of the trough is not defined with the necessary precision or it may be due to a deflection of the stylus toward the trough as formed by the previous recording. If standstill does not exceed the line time, starting manoeuvres should not be evaluated for reconstruction purposes.

It is astonishing how well the choice of vertices coincides with discontinuities in the recording. The gear shift always induced the insertion of at least one additional vertex.

Skew of the guiding line introduces additional errors into the evaluation process. When adjusting the direction of the guiding line, the evaluator makes implicit assumptions on 'reasonable' start acceleration and stop deceleration. Erroneous assumptions will result in excessive skew. In any case, skew of the guiding line does not have any influence on the calculated overall distance between starting and stopping.

Insufficient driving time prior to the evaluation interval, opening the tachograph or long driving manoeuvres without any stopping hinder the ascertainment of the correct guiding line.

Creeping drives can be detected if they are bracketed by standstills of greater duration. When assuming a creeping drive, one should examine the distance recording closely before leaving the disk to the evaluation process.

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