LOAD SPECTRUM PREDICTION FOR TRANSMISSIONS UNDER REALISTIC USE COMBINING TESTS AND COMPUTER SIMULATIONS

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INTRODUCTION

In order to analyse road performance, fuel consumption and emission as well as fatigue life, it is important to know how the vehicle transmission performs under realistic conditions of use and over longer distances. The ever increasing complexity of transmissions demands extensive testing so that even rare or improbable occurrences can be taken into consideration.

Driving tests with complete measuring equipment for recording the conditions of use are not possible in the construction phase (availability) and are only possible to a limited extent at a later stage because of the time and costs involved.

Ascertaining load spectrums using computer simulation is therefore an important new development to supplement test drives and rig tests. Fuel consumption and emission is also becoming more and more important and this can be analysed with only minimal additional time and expense. The modular system described below is used for developing vehicle drive trains.

The data shown here are the results for a DaimlerChrysler SLK 350 with 7-gear automatic transmission measured over a period of approximately 6 months. It was our aim to obtain load spectrums for the most varied driving conditions and to derive from these collectives which can be conveyed for practical use. To assess the influence of the vehicle engine, we also used two other vehicles, a small car (VW Lupo) and a middle class car (Audi A4 Quattro 2.5 TDI) taking measurements partly on the same routes.

SYSTEM OVERVIEW

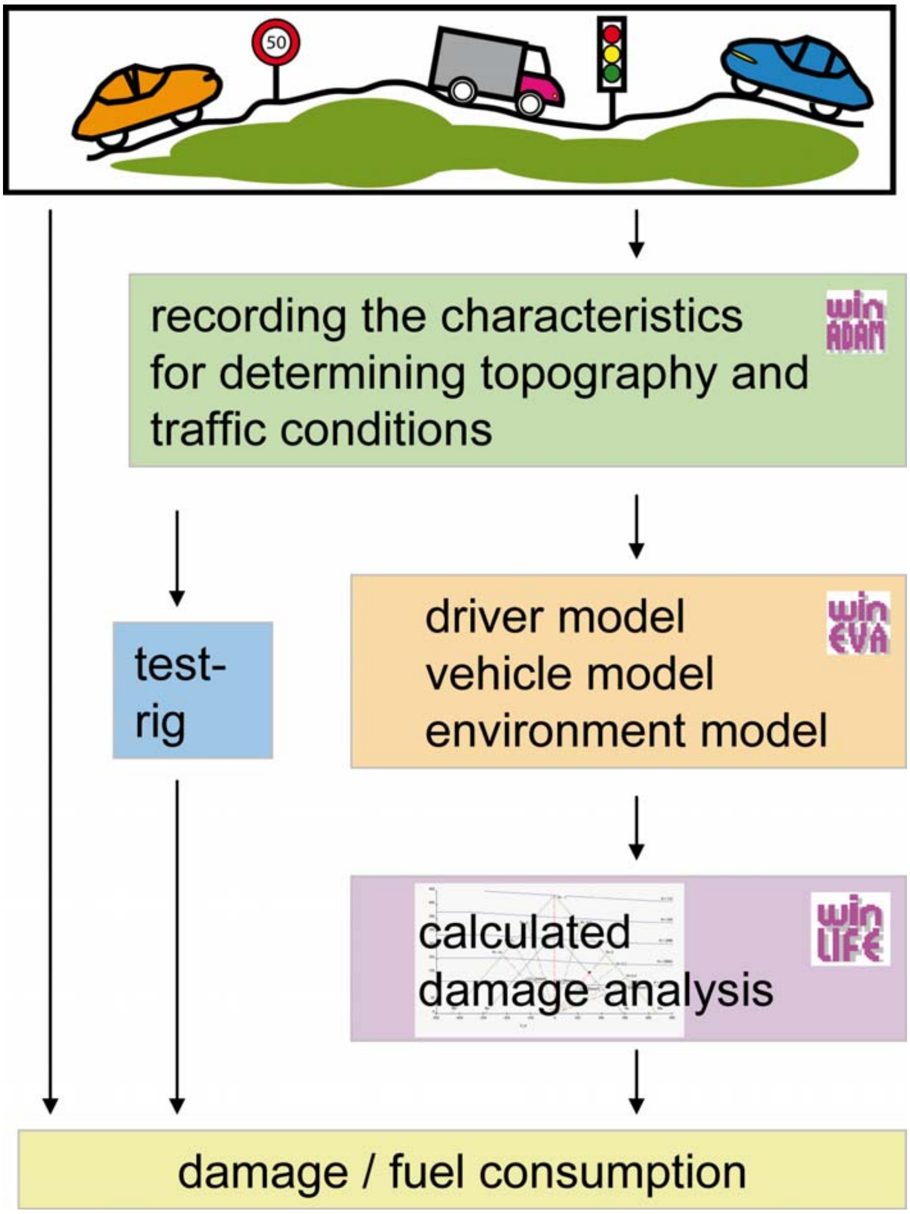

Figure 1 – Prognosis for fuel consumption and fatigue life combination of tests and recording measured data, rig tests and computer simulation

A prognosis for fuel consumption and fatigue life can be made by carrying out tests under realistic conditions. These can be very costly and time consuming and they can only be reproduced up to a limited extent.

If characteristic data for the route and the traffic has been recorded in a test drive then it is possible to re-trace the same conditions on a drive train test rig and achieve similar results for fuel consumption and fatigue life. Rig tests can be reproduced well and the costs are lower and the time needed is less than for a test drive.

A further step towards saving time and money is to replace the test rig with computer simulations. Measured route data has been used here to create a detailed model of the processes occurring in the drive train. The simulation provides the user with sufficiently accurate mechanical quantities and fuel consumption, data which is then used for the fatigue life calculations showing the damage to the components of interest. The computer simulation is extremely quick and cost effective.

The results of the test drive, the rig test and the computer simulation can be amended. You can use a greater proportion of results from the computer simulation and test rig simulation and less data from the test drive and the conclusion will be just as exact.

DRIVER-VEHICLE-ENVIRONMENT SYSTEM / ELEMENTS OF THE SIMULATION SYSTEM

If the simulation is to be realistic, it is necessary for the information on the influence parameters, i.e. on the vehicle and its environment, including traffic and the driver, to be sufficiently exact. The exercise is to describe realistically not only the individual models, but also how they work together so that conclusions can be reached regarding performance, fatigue life and also fuel consumption.

The vehicle which can be described relatively easily using well known formula combinations is steered by a driver who operates the vehicle with actuators (accelerator pedal, brake and steering wheel etc.) The driver decides on the actuators according to environmental information (road curvature, slope, visibility, road surface friction, characteristics of the vehicle, and driver’s state of mind).

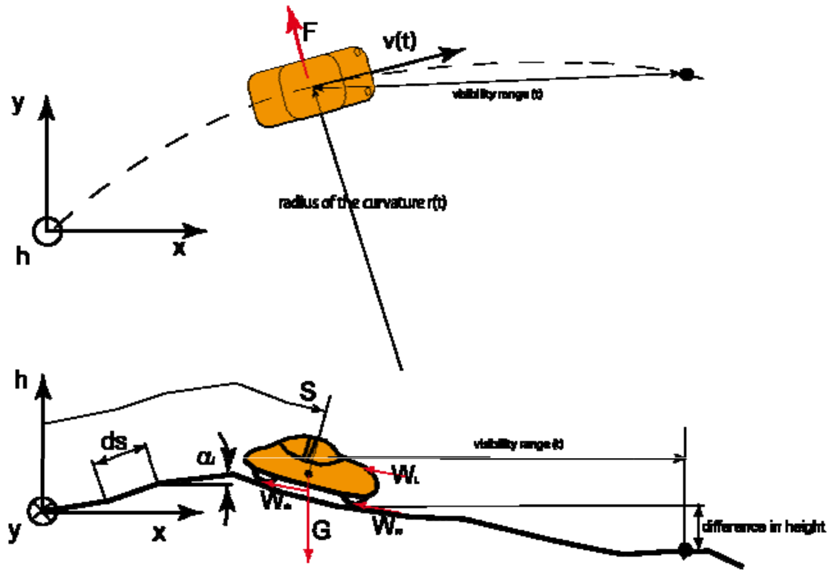

Figure 2 - Data to describe the individual vehicle in the environment

The individual vehicle with the acting driving resistance and centrifugal force is described using well known physical links. Environmental data such as slope, curvature, friction, visibility etc are presumed to be constant for individual route intervals ds. Depending on the task, ds ranges from just a few centimetres to several metres (Figure 2).

The traffic limitations which exist (speed limit) and the interrelation with other drivers also has an influence on the driver's behaviour and the resulting driving cycles. It was our aim to quantify the traffic influence but reduce the amount of data so that no additional measurements were necessary. This aim was achieved by post-processing the video recording and the recorded events and data are shown schematically in Figure 3.

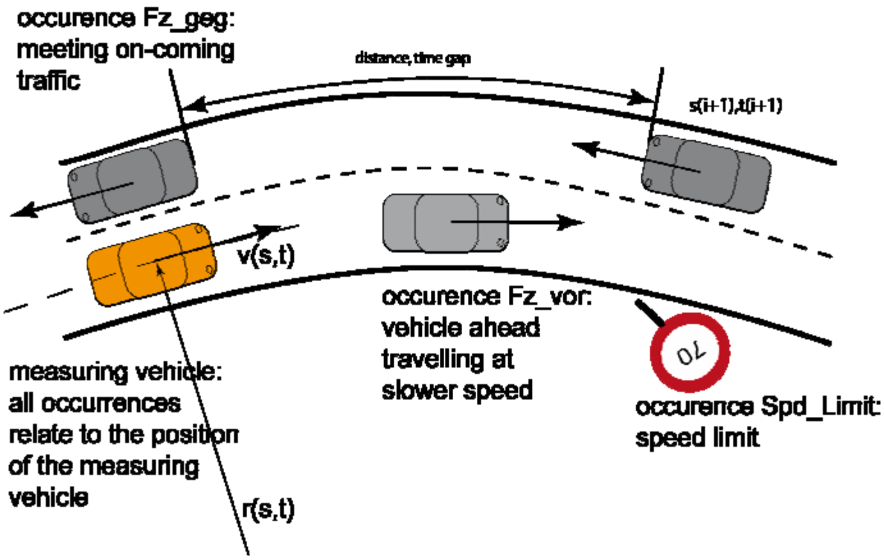

Figure 3 - Circumstances, occurrences and dimensions which arise because of other traffic.

The elements of our simulation system are therefore as follows:

- Measured data recording system winADAM/winMAP to record simply but adequately the exact conditions of use (speed, topography, route, curvature, video recording) (NN, 2004).

- Simulation system winEVA for the vehicle drive train and the driver enabling the user to make a prognosis for vehicle dynamics, fuel consumption and load spectrums based on the measured data. (WILL, 1992) (WILL, 1999) (KLOS, 2004)

- Fatigue life analysis system winLIFE which makes it possible to estimate the fatigue life based on the winEVA simulation results (WILL, 2001) (HAEC, 2002) (KOER, 2002) (KOER, 2002_2) (WILL, 1999_2)

COLLECTING VEHICLE DATA (ROUTE, TOPOGRAPHY, TRAFFIC)

Figure 4 - Measuring System winADAM in the box with all sensors

winADAM is a measuring box (Figure 4) which has all the necessary sensors for measuring the quantities shown in Table 1. Several different measurement quantities are used to record the position xy, the driven route s, speed v, height h, longitudinal slope α. – if possible using several methods to eliminate measuring errors – to obtain a signal which is as exact as possible. A coupled navigation running parallel to the GPS measurement also makes it possible to determine the position with adequate accuracy even when the GPS signal fails. A map can be scanned into the system and shown together with the recorded route.

The measuring box contains all necessary sensors and only needs to be placed horizontally in the vehicle with the GPS aerial on the roof. The system also has a CAN interface and 10 further ports for analogue measurements.

A standard GPS receiver only receives one signal per second. A DGPS receiver will receive 10 signals per second.

The other measurements can be gauged with up to 1 kHz per channel. Because of the amount of data, however, only a maximum of 200 values per second are measured. The video signal generally records 10 pictures per second, enabling the user to make an adequately accurate assessment of the traffic situation and road signs. If measurements are being taken over several days then you can reduce the picture frequency to 1 picture per second to keep the amount of data manageable.

Table 1 - Values recorded in winADAM (values with back-up measurements in bold print).

	Typical Sample rate [Hz]	Measured value	Sensor, Process	**Calculated values Derived values**
Route data	1 (10)	x(t),y(t),z(t)	[D]GPS	S(t),**x(s),y(s),z(s),** K(s)
	50	$a_l(t)$,	Acceleration sensor	**S(t) ;v(t)=** $\int a_l dt$ **; v(s)**
	50	γ(t)	Yaw rate sensor	K(s)**=f(γ(t),v(t),s(t)) ;**
Topography (height profile)	50	p(t)	Pressure sensor	**H(s), α(s)**
	1 (10)	z(t)	[D]GPS	**H(s), α(s)**
Driver's behaviour	1 (10)	V(t)	[D]GPS	**V(s)**
	50	$a_l(t)$,	Acceleration Sensor	**S(t) ;v(t)=** $\int a_l dt$ **; v(s)**
	50	$a_q(t)$	Acceleration Sensor	
	50	γ(t)	Yaw rate sensor	a_q (t)**=f(γ(t),v(t))** **a_q(s)**
Environment /traffic	1 …. 10	Video picture with time and location shown	Video-picture	**s_g , t_g , v_{zul}** **Conditions: subsequent journey, friction classification, visibility obstruction, overtaking**

With:

a_l	[m/s²]	longitudinal acceleration of the vehicle
a_q	m/s²]	transverse acceleration of the vehicle
a_v	m/s²]	vertical acceleration of the vehicle
α	[°]	longitudinal slope
h	[m]	height
K	[1/m]	curvature
p	[mbar]	ambient pressure
x,y,z	m]	coordinates of the road points
γ	[°/s]	yaw rate
v_{zul}	[m/s]	legally permitted speed
s	[m]	Route
s_g	[m]	Distance to oncoming traffic
t_g	[s]	Time lapse to oncoming traffic
t	[s]	time
[D]GPS		(Differential) Global Positioning System

Post-processing the measured data by assessing the video information

The driver's behaviour and the traffic conditions have an important effect on the driving cycles. To objectify this influence and to incorporate it in the simulations, the video information is analysed retrospectively and converted to the numerical values or condition variables shown in Figure 3.

- legally permitted speed
- obstruction by other traffic (whether there is a vehicle ahead)
- time and distance between vehicle and oncoming traffic (overtaking potential)
- active and passive overtaking
- road conditions (dry, wet, etc)
- visibility (good visibility, rain, fog)

Firstly, the volume of traffic can be recorded by counting the vehicles coming towards you. The type of (oncoming) traffic (lorries, cars) can also be seen. The conditions are usually similar in both directions.

If the road is clear and there is no vehicle ahead, then the ratio between the actual driven speed and the legal speed limit – taken over a longer distance – indicates the driver's state of mind. It is also possible to judge the concentration and uniformity of the driving. The number of times the driver overtakes or is overtaken, and the relative gaps with regard to oncoming traffic, give an insight into the driver's motivation. The subsequent analysis of the video recording takes time but provides important additional information.

The results of the data recordings and the post-processing of the video film taken during a measured journey can be seen in Figure 5. Here you can see the above mentioned additional information as well as the details for the route, the height profile and the speed. To make the diagram suit your requirements, you can select sets of information, fade them in/out or superimpose them.

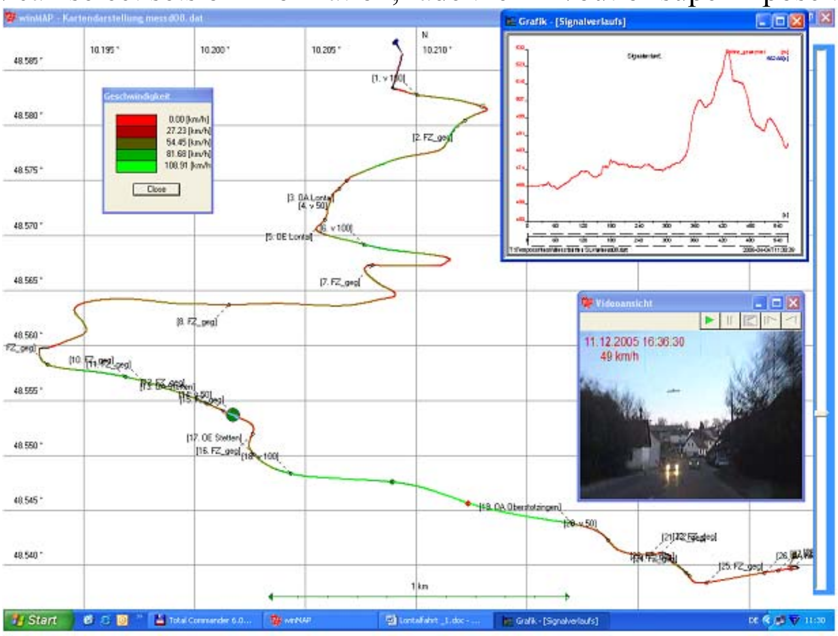

Figure 5 - Driving cycle: Recorded with winADAM and post-processed after analysing the video recording.

Analysing satellite pictures

Driving the required route with the measuring system is simple, but somebody has to do it. In the following case, the test involved the Nürburgring but there was no time to drive round the track. As there are no influential traffic conditions on the Nürburgring, it was sufficient to record the track data only. Based on this information, we wanted to calculate the speed development using a driver-vehicle model. In (HAEC, 2005) we saw that the calculation results achieved using this method are acceptably consistent with actual measurements. We analysed and digitised the satellite pictures available in Google-earth and compared them with the measured route data in (GREI, 2004) and (HAEC, 2005). We proved that for the requirements here, perfectly adequate recordings could be obtained. The only thing we could not measure was the height profile so that we had to measure this from (HAEC, 2005) and transpose it onto the route.

THE SIMULATION SYSTEM FOR DRIVER, VEHICLE AND ENVIRONMENT IN WINEVA

Vehicle simulation model

The drive train of the virtual vehicle is shown in separate components opposed to the real drive train. This is known as modular assembly. The drive train starts at the engine and is completed over the drive train elements through to the wheels. This modular assembly means that it is easy to make alterations to the drive train.

The model is scaleable which means that various model depths can be taken into account. We have been able to integrate a simulation with torsion vibration taking into account complete dynamic occurrences within the gearbox including the gear change procedures according to (KLOS, 2004). If these highly dynamic occurrences are not of interest, then you can work with a much simpler model where the time compression (real time / calculated time > 1000). The user can decide which model refinements he would like to work with.

Extensive comparisons between calculations and measurements have been described in (GREI, 2004): and it can be seen that the results achieved from both methods are very similar both for the time paths and the static frequency of the signals.

Figure 7 shows how we used the drive train of an MB-SLK 350 with W7A700 as an example for this test. The drive train consists of the components engine, converter, automatic transmission, drive shaft, rear axle middle piece, side shaft, brakes, and wheels. The individual drive train elements are described by their specific characteristics as well as the stationary characteristic lines or ranges.

The load spectrums are obtained for a DaimlerChrysler 7-gear with converter and automatic transmission. The design for this type can be seen in Figure 8.

Figure 6 - Measurement car

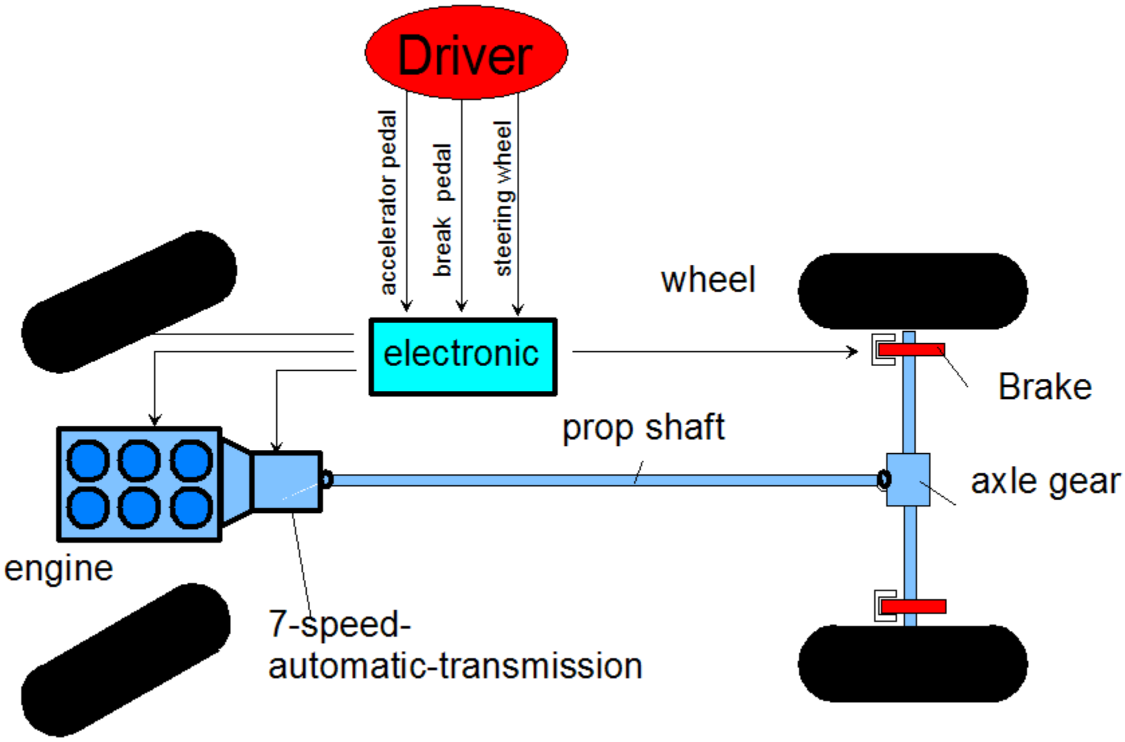

Figure 7 - Car with its drive train (schematic view) and the main elements considered in the simulation model

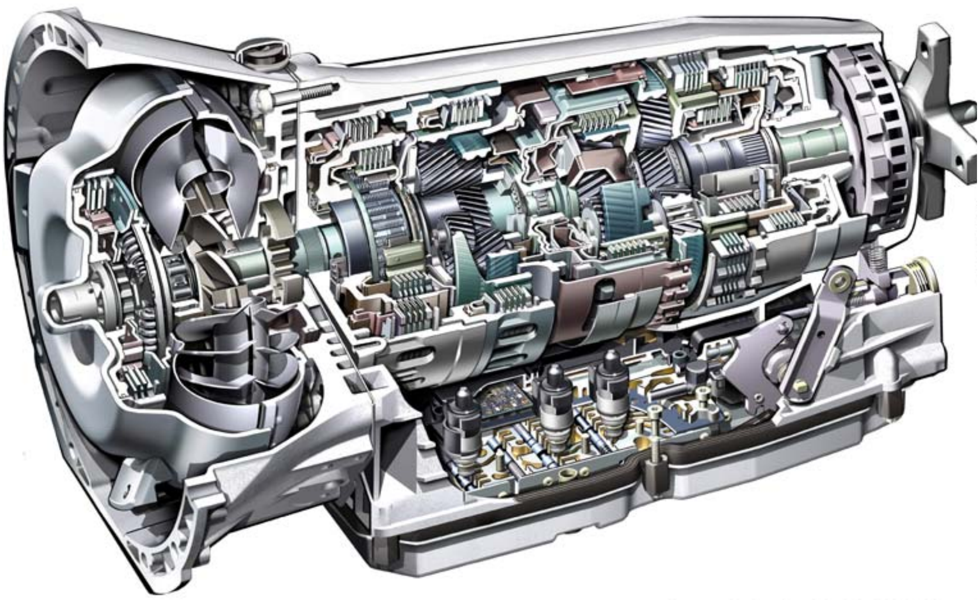

Figure 8 - DaimlerChrysler's 7-gear automatic transmission for which the load spectrums are simulated (source: DaimlerChrysler).

The vehicle data for the SLK 350 were taken from (LUEC, 2004) and the missing values, e.g. transmission switch points obtained by taking our own measurements. By running test-drives and then comparing and adapting the vehicle data we were able to obtain an acceptable picture of the gear changes applied

A race course (Nürburgring) simulation under extreme conditions

The basis for this simulation was just the course but without any speed development path. We used our winEVA driver model which also takes the lateral dynamics into account. We also selected the gear stick position S. The relative gear change programmes had already been ascertained in test drives. The simulation was for an automatic gear box, i.e. the gears were not changed manually. This behaviour is equivalent to a sporty kind of driver. If the car is driven in a racing manner then the driver changes gear manually.

The 20 km virtual trips on the *Nürburgring* demand extreme border line conditions for the drive train and it is interesting to see the difference between these and the "every-day collectives" in view of the time compressed acceleration effects of the Nürburgring collectives.

Simulation results for various conditions in every day use.

As well as identifying the extreme load limits, it was also our aim to see how a DaimlerChrysler 7-gear automatic transmission functions under completely varying conditions. The procedure used here should be used for the whole life cycle of a DC SLK 350 in use by the customer. We also wanted to summarise the collectives for similar routes (motorway, rural roads, and town) in order to give an account as accurate as possible regarding the conditions of use and the fluctuation range. It was necessary to record long stretches because it is only possible to reproduce the measured cycle up to a certain degree. Figure 10 shows the results of several measured journeys taken on the same route. You can see that there are characteristic developments in the speed which are influenced in particular by:

- Legal speed limits
- Traffic lights, crossroads
- Traffic density, (heavy traffic, vehicle ahead, empty road)

These conditions are recorded and documented in detail making it possible for us to make a realistic simulation for all sorts of traffic scenarios.

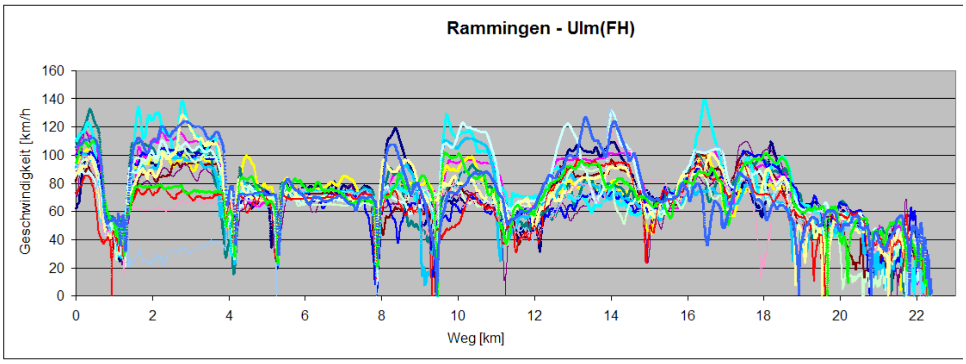

Figure 9 - Driven speed during a number of journeys measured with a DC SLK 350 vehicle with the same driver along the same stretch of road but with varying traffic density

The journeys measured under normal every-day conditions were taken with a vehicle driven by members of our Steinbeis Transfer Centre who keep to all the general traffic regulations on public roads. We refer to these journeys as the STC collectives. This is a completely different situation to the conditions on the Nürburgring where extremely difficult conditions exist which are not representative for normal car use. The STC journeys are much more realistic for other vehicle users but are still not representative for normal vehicle use. They just give us an example of the possibilities within the user spectrum. It must also be noted that the STC collectives are only for a relatively short journey as we were only able to use the vehicle for a few months because the winter of 2005/2006 was so snowy.

The driven routes were divided into the following categories

- cross country (rural roads, through villages)
- - motorway
- - towns

Separate collectives were created for each category.

Transmission load spectrum

The average speed driven on the STC route with the SLK 350 was 49 km/h while an average speed of 122 km/h was reached on the simulated test on the Nürburgring. The mean speed driven in each gear can be seen in Figure 11. It is interesting to see the proportion of the journey driven in each gear (Figure 10): The proportion driven in 4th and 5th gear (middle gears) is much higher on the Nürburgring as on the STC route. On the Nürburgring the 7th gear is hardly used but the 6th gear is used almost equally in both journeys. On the STC route the 7th gear is used for nearly 50% of the journey so that the engine is operating within the revolution speed range resulting in the most favourable rate of consumption for this part of the journey. On the Nürburgring the 5th gear was used most.

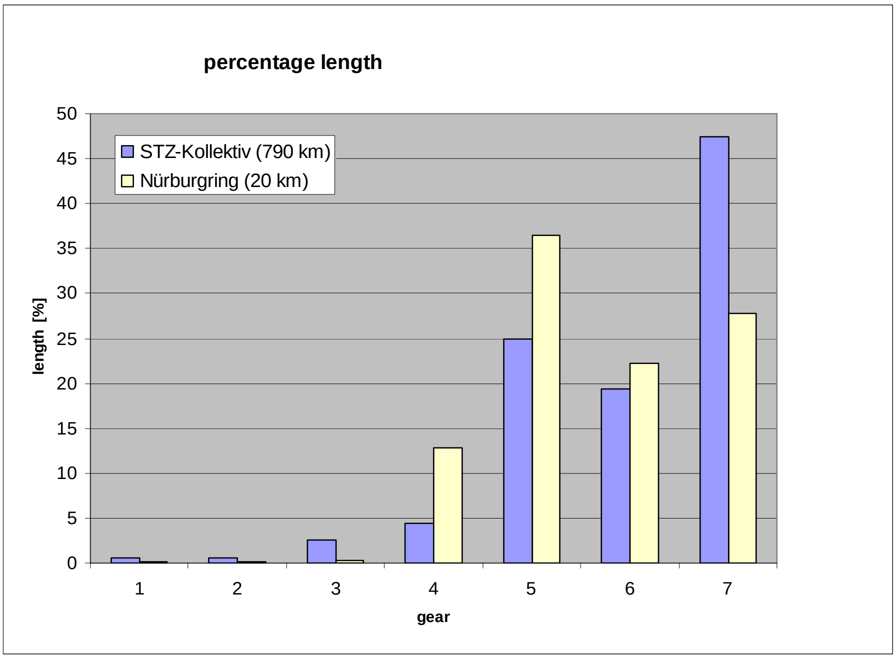

Figure 10 – Distance percentage driven in each individual gear for the STC collective and the Nürburgring

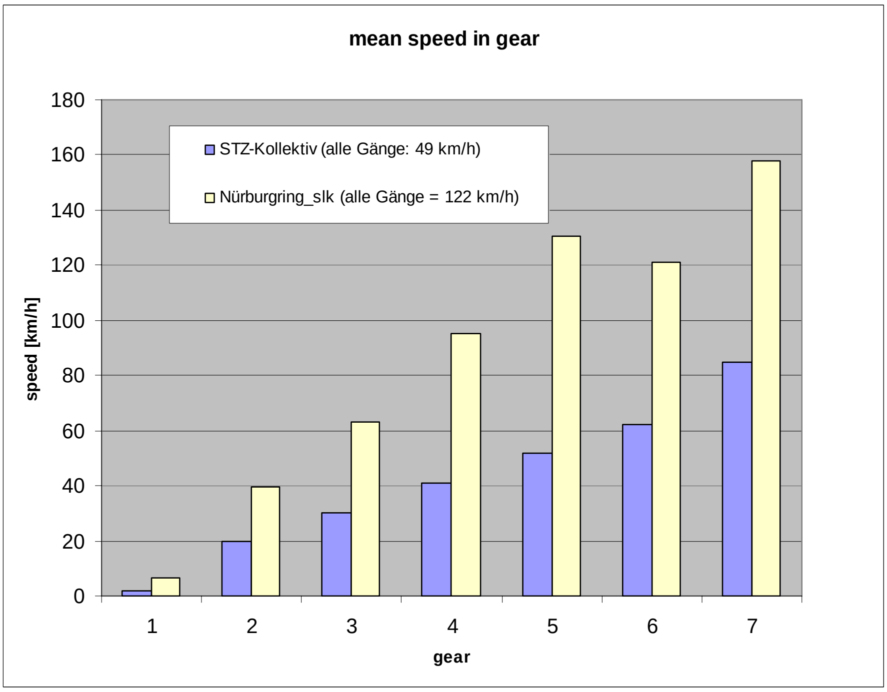

Figure 11 - Average speed in each individual gear for the STC collective and the Nürburgring

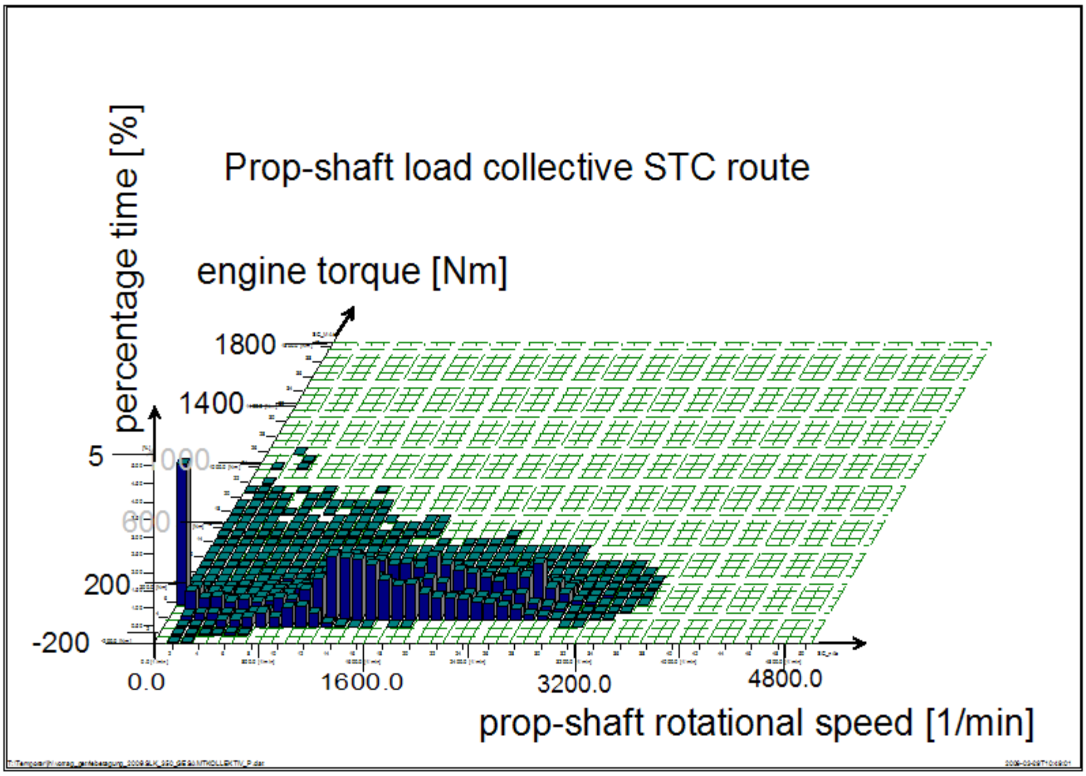

Figure 12 - Time percentage of prop shaft moment and revolutions for the STC route

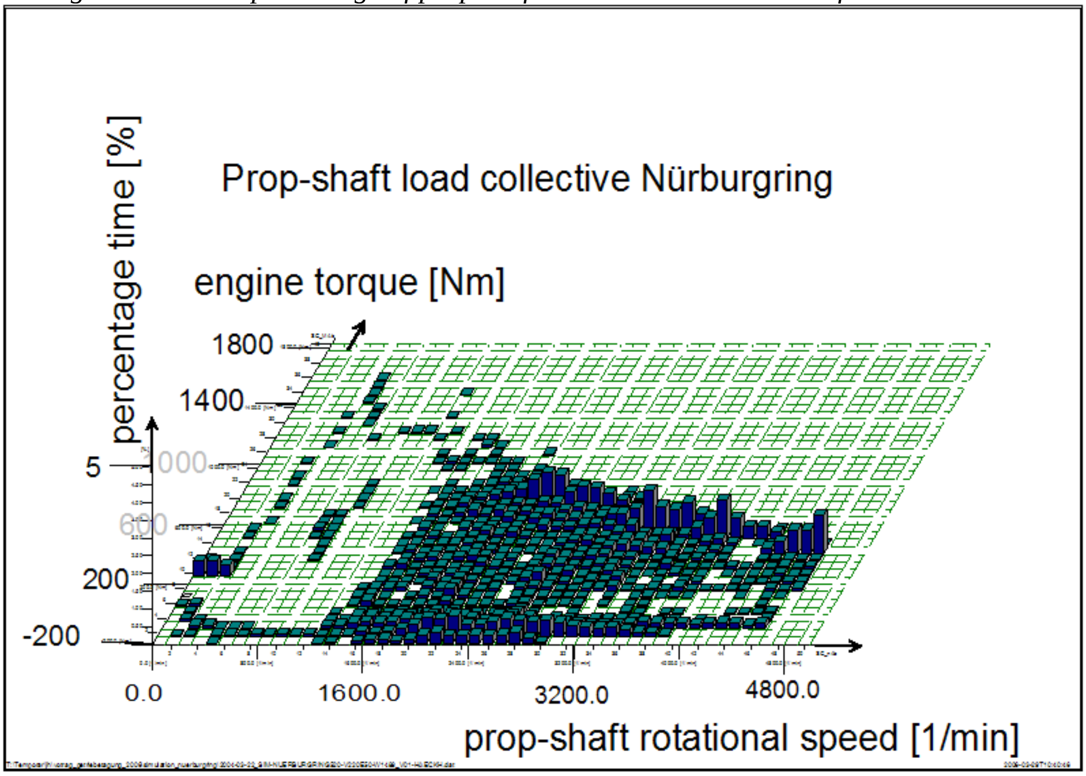

Figure 13 - Time percentage of prop shaft moment and revolutions for the Nürburgring route as in (GREI, 2004) but shown in a different way.

The load spectrums of the transmission – i.e. the prop shaft moment over the number of revolutions are shown in Figures 12 and 13. Die analysis for the STC route is based on a 790 km stretch and the density of the engine operating points is therefore greater than for the 20 km long Nürburgring route. We can see that the operating points in the STC collective are found mainly when the number of revolutions is low and therefore the performance is also comparatively low. The maximum torque is however similarly high. This is explained by the fact that there are some steep hills on the STC route which were taken at a constant low speed.

On the other hand, in the Nürburgring collective many of the engine operating points are where there is a higher number of revolutions at the ideal tensile force hyperbola with maximum engine performance (see engine load spectrum in Figure 14). Compare this with the Figure 15 which shows the engine operating points for the STC route. The number of revolutions is low which has a positive effect on fuel consumption.

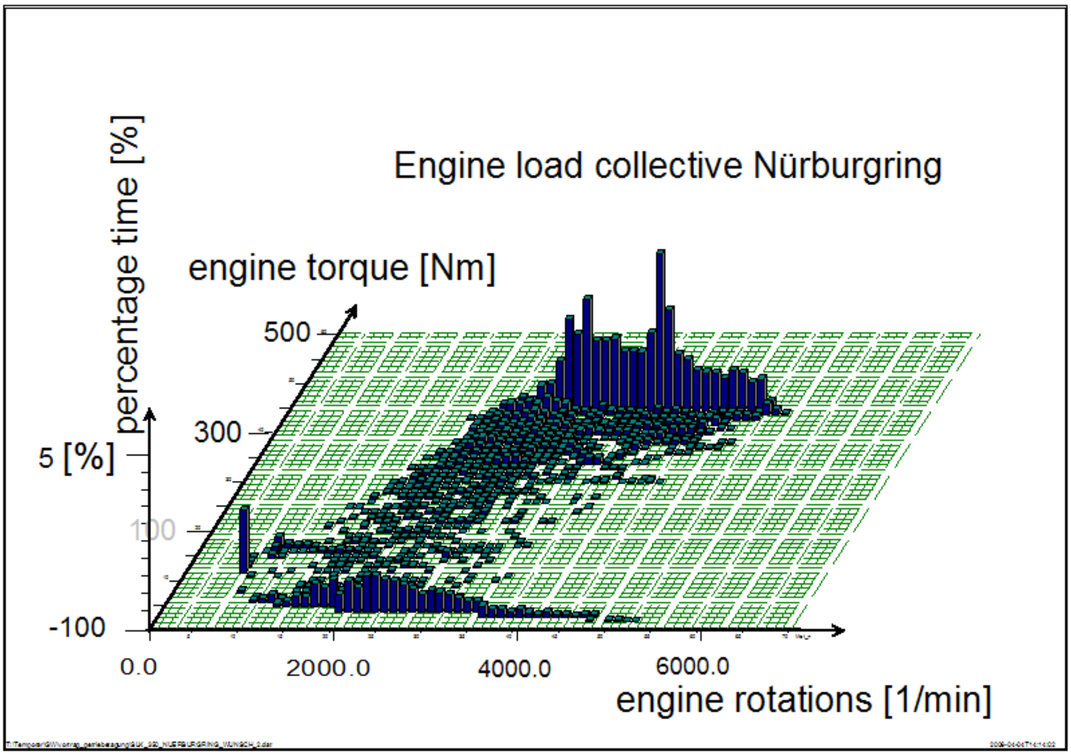

Figure 14 - Time percentage for engine torque and revolutions for the Nürburgring

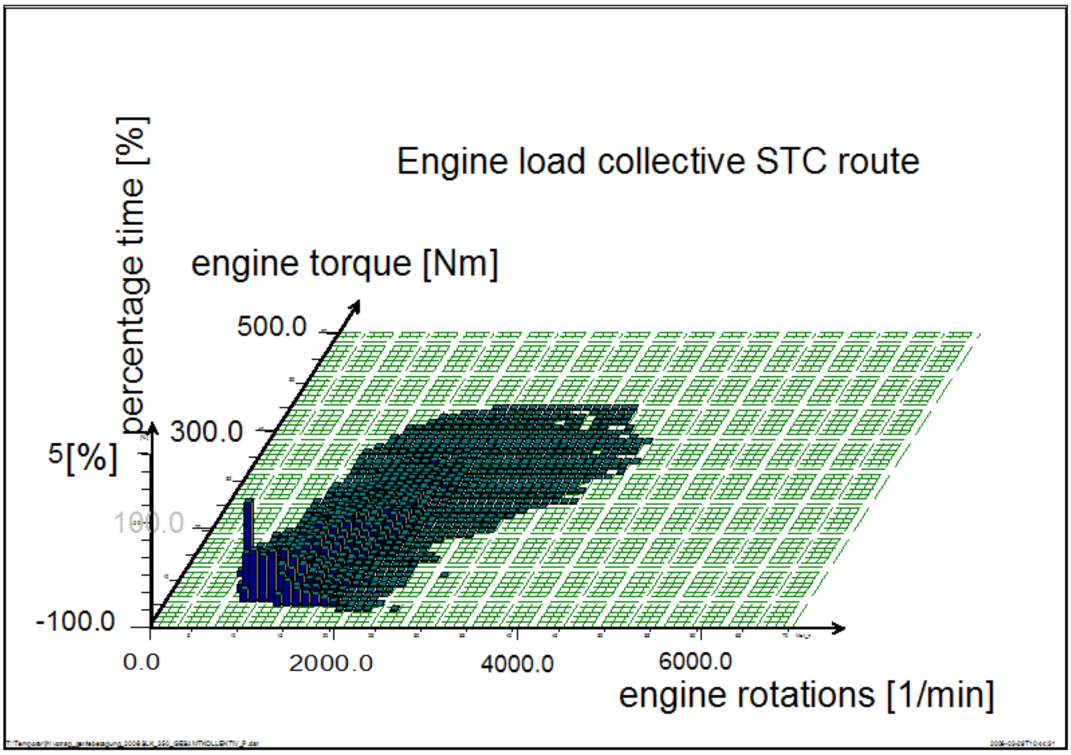

Figure 15 - Time percentage for engine torque and revolutions for the STC route

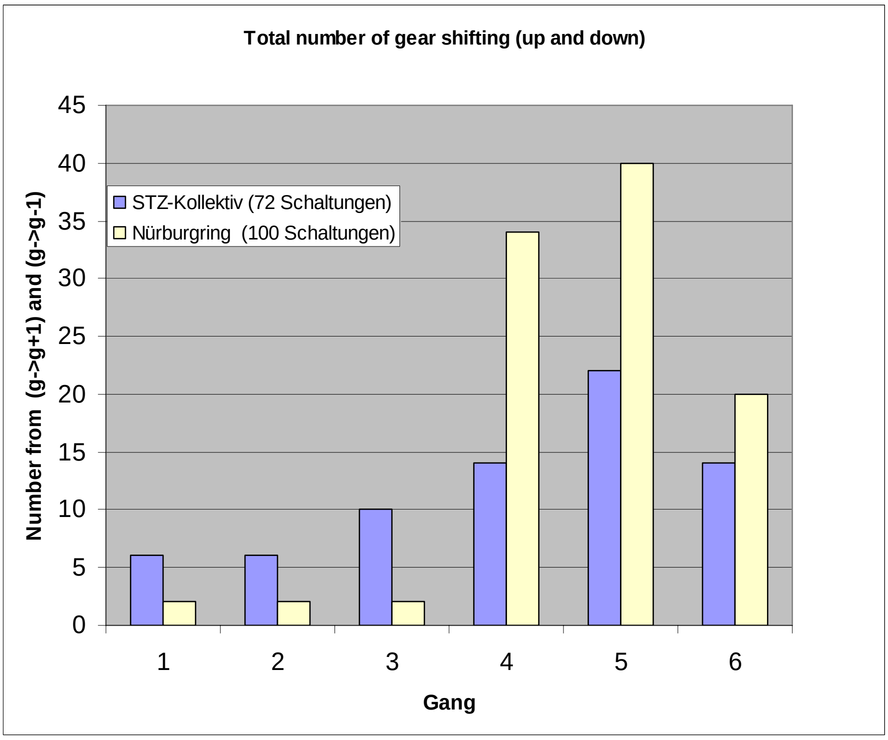

Figure 16 - Total number of gear changes (up and down) over a distance of 20 km

Figure 16 shows the number of gear changes to and from the individual gears over a distance of 20 km. We can see that if the vehicle is driven at high speed there are more changes in the higher gears. On the STC route the speed is lower and there are more gear changes in the lower gears.

So that we could compare the normal range, we took the length of the Nürburgring as our standard enabling us to make a direct comparison of the engine prop shaft moment for the Nürburgring and the STC route (Figure 17). The maximum value and also the curvature of the collective are very different so that there is an obvious time compression in the Nürburgring load spectrum.

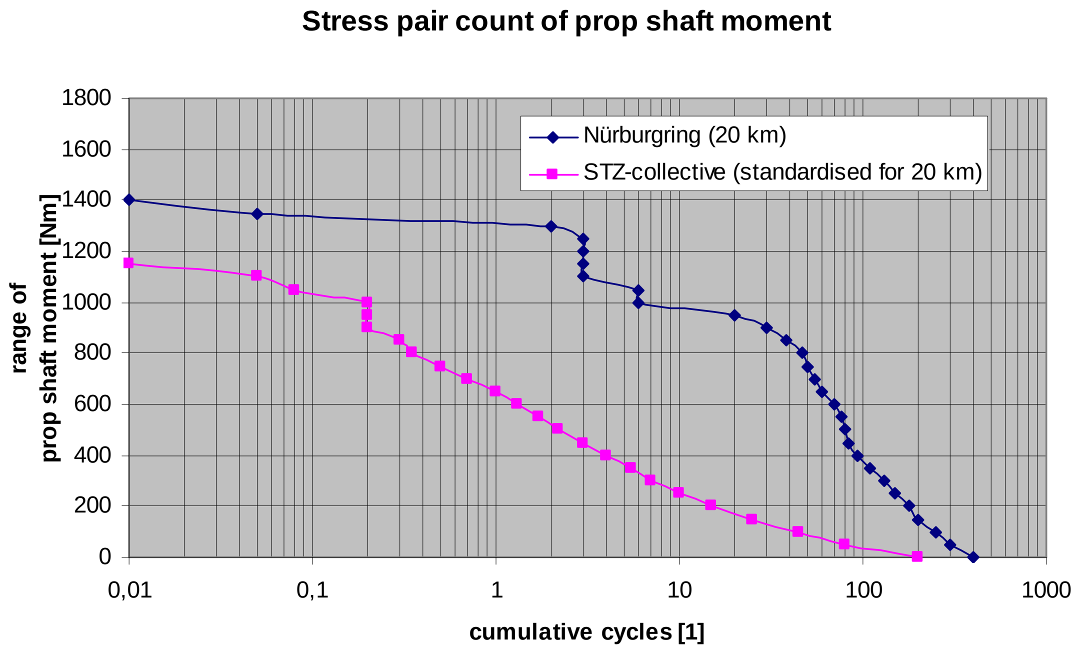

Figure 17 - Stress pair count for the STC route (converted to 20 km) and the Nürburgring (GREI, 2004) (length 20 km).

Figure 18 shows the comparative damage in the individual gears occurring throughout the journey if the equivalent route is driven at full throttle. We call this the equivalent full throttle distance. This is obtained by calculating the prop shaft normal damage against a fictitious S-N curve without fatigue limit. The results were not converted to the same distance, i.e. those shown for the STC route were taken over 790 km and those for the Nürburgring over 20 km.

We can see that the damage occurring in 2nd to 4th gear is more or less the same for the Nürburgring and the STC route although the Nürbugring is 20 times shorter. Gears 1-3 were hardly used on the Nürburgring and the load resulting here is therefore minimal.

It is obvious that the demands of the Nürburgring are extreme but it is also clear that the proportionate use of gears is different from normal driving conditions.

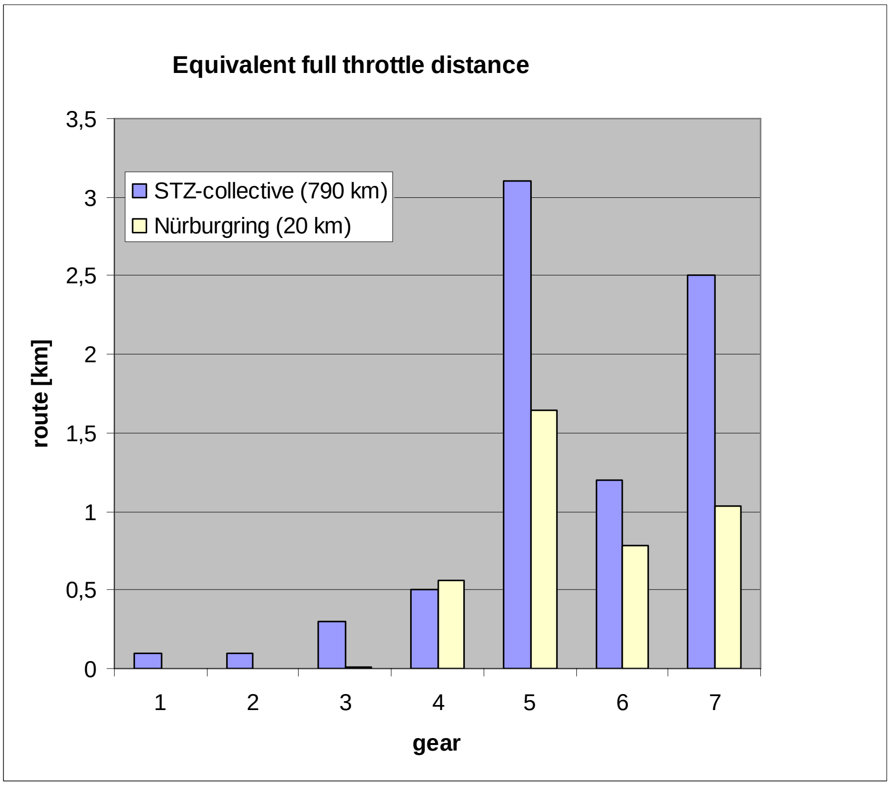

Figure 18 - Comparison of STC route and Nürburgring driven at full throttle

Re-tracing the speed cycles on the test rig

As with the computer simulation, our aim with the test rig is to re-trace the actual conditions of the measured journeys so closely that the results achieved for fatigue life and fuel consumption are the same as in reality. Here again we used our simulation system winEVA and we were able to retrace the actual speed development paths with sufficient accuracy on the test rig. The load spectrum for the gear box output (Figure 19) can be used to analyse the comparisons between the various types of simulations and tests. It can be seen that the load spectrums obtained from the pure computer simulations are very similar to those obtained from the rig tests. The damage to the transmission occurring in both the computer simulations and the rig test is similar.

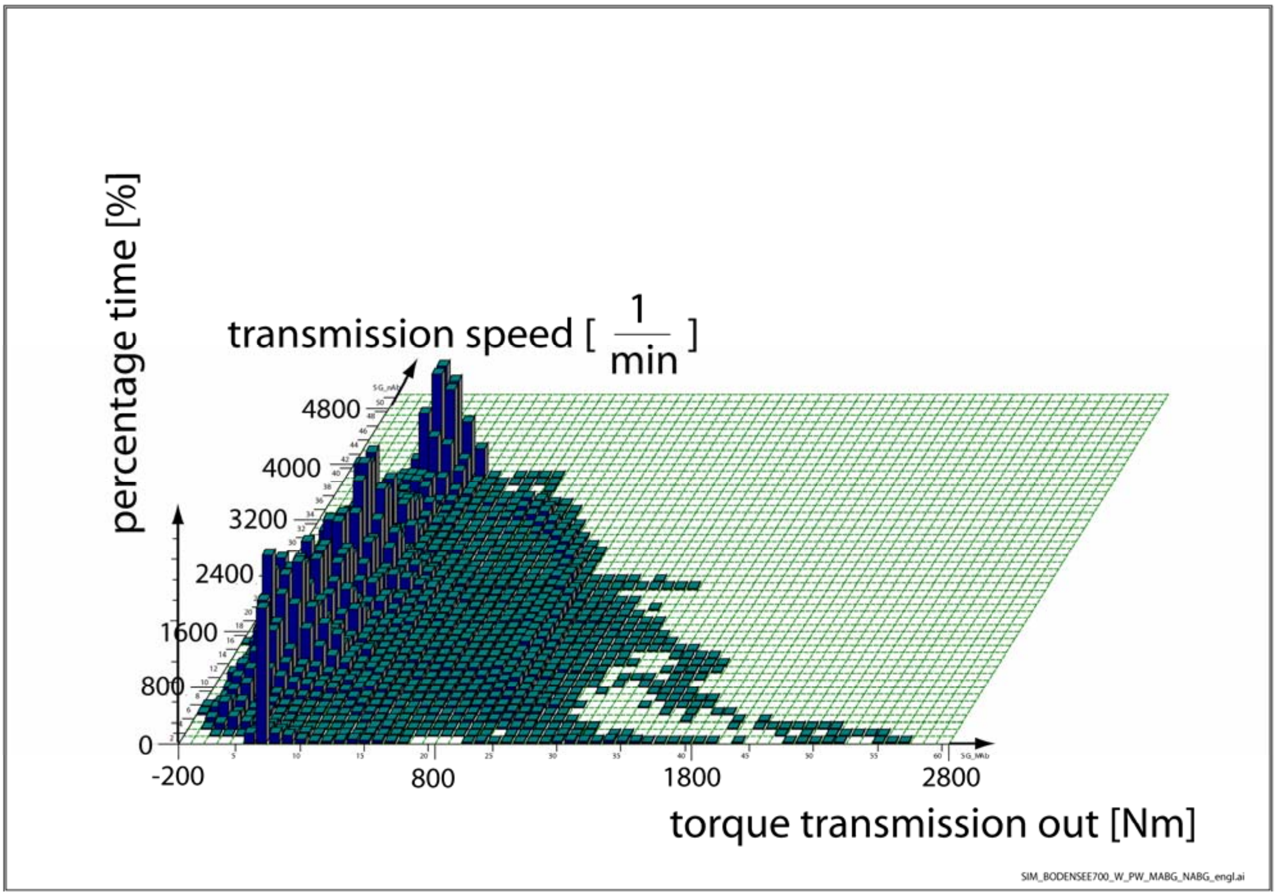

Figure 19 – Load spectrum obtained from a test rig driving real speed cycles with winEVA (source DaimlerChrysler)

CONCLUSIONS

With the measuring system winADAM, which we have described here, it is possible to record test drives with accurate data on the description of the route, the topography, the traffic conditions and other particular occurrences.

This recorded information can be used in computer simulations to calculate realistically accurate load spectrums for drive trains.

The simulation system also makes it possible to re-trace the measured routes on a test rig. The load spectrums obtained in this way match the results from the computer simulation.

By comparing road tests, rig tests and computer simulations, you can find the weak points which have to be eliminated. This method also means that additional road and rig tests can be substituted by computer simulations without any loss in quality of the results.

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