In automotive companies, designing the vehicle dynamics to be customer-oriented with the help of road trials is largely the responsibility of trained professional drivers. A driver model that corresponds to an average – and therefore customer-relevant – driver presents an opportunity to evaluate the vehicle in an objective and reproducible way. This vehicle evaluation was developed at Volkswagen in close cooperation with the Institute for Vehicle Technology at Technical University Braunschweig (Germany).

Reproducible Transverse Dynamics Vehicle Evaluation in the Double Lane Change

1 Current State of Technology

The field of transverse dynamics vehicle evaluation is concerned with vehicle performance in different driving situations and the causes of this performance. To date, road trials have been by far the most common method of assessing the driving dynamics of vehicles in the automotive industry. Outside the open loop tests, reproducible driving performance can be achieved by using driver models – as frequently used in simulations – in combination with real vehicles.

1.1 Evaluation Possibilities in the Road Trial

Road trials have become the established method for designing driving dynamics in the automotive industry. Thanks to frequent practice and their professional qualifications, professional drivers contribute to a high degree of reproducibility and minimal variation when it comes to subjective assessments. Therefore, a professional driver evidently has an advantage when it comes to the combination of driving and assessing a vehicle. Despite the driver's great skill, the driving differs even within one road trial. To objectify vehicle dynamics, the process unavoidably has to be divided into two: measuring and subsequent assessment. As a consequence of this, driving manoeuvres have to be carried out as reproducibly as possible. The demand for reproducibility leads to a separation of the existing driving manoeuvres into open loop and closed loop tests [12, 16]. Primarily for technical reasons, there has only recently been a heightened tendency towards increasing reproducibility in the area of driving dynamics in the closed loop test.

1.2 Evaluation Using Driver Models

Initial approaches to reproducing driving performance use a prediction of the transverse deviation for transverse regulation [10, and elsewhere]. Later approaches attempt to optimise the theoretical system aspects of path guidance [5, 7]. At the same time, a pilot control that works in parallel is introduced [5, 11]. The driver performance changes depending on the driver and driving situation [2, 6, 13]. This especially needs to be taken into account when the model is parameterised. The performance of the overall control loop appears to be constant after the driver has adapted to a driving situation [3]. This approach is used as the basis for deriving an evaluation of the vehicle in a newer work [6] within a simulation using the parameters from the adjusted driver model. In the road trial, driver models are generally present as path following control [8, 12]. The characteristics of these models therefore do not represent a human driver, instead they minimise deviations from the target path. This means that the objective – reproducible assessment using driver models in the road trial – is still unfulfilled.

2 Concept

Certain demands are made of the road trial in the context of objectifying driving characteristics: increased reproducibility vis-à-vis the professional driver, realistic driving manoeuvres and a driver model based on the average driver. The driving manoeuvre fundamentally defines the dynamics and driver's foresight in the driving situation. Since the road trial for a double lane change is clearly designed, the driver will very probably fix the trajectory in his mind in advance. During the trial, the average driver's manner of driving in the linear driving range is mainly marked by controlled performance. This leads to a driver model divided into open-loop and closed-loop control [2, 5, 6, 7]. Since the driver adapts to the vehicle in question in the linear driving range, he will control the vehicle well in this case. This assumes that the driver includes the driving characteristics in his foresight. In the ideal case, an inverse vehicle model is created as pilot control. The closed-loop control compensates for unforeseen disruptions, such as a side wind, and has to be adjusted to the average driver's performance in the linear driving range. Assuming a known, constant driver-vehicle performance, the parameterisation of the driver model can be standardised for a known vehicle performance and be executed objectively for any vehicle. This model of the average driver can be used to reproducibly measure the vehicle right up to its limits and to objectively measure the transverse dynamics.

3 Performance of Average Drivers

It has to be differentiated between the average driver and professional drivers. The following identification of the transverse dynamics transmission performance is based on technical measurements taken to record the driver performance.

3.1 Differentiation from Professional Driver

The term "average driver" refers to vehicle drivers who do not have any lasting experience of the effects typically produced in the transverse dynamic non-linear driving range. Here it has to be assumed that a one-off experience with difficult driving situations does not lead to the driver learning how to handle the vehicle at its limits, due to the driver's state of mind at the time [3]. Professional drivers have two additional performance characteristics that the average driver does not. One is a higher degree of perception as a result of practice and experience, the other is the ability to control the vehicle even in demanding driving situations, thanks to training. In the context of the double lane change, these innate driver characteristics manifest themselves in a stable driver-vehicle control loop. The professional driver stabilises the vehicle by quickly making a steering manoeuvre at an early stage, as soon as excessive oversteering occurs. The average driver, on the other hand, would be overtaxed in the oversteering situation. He is not familiar with this driving state and he is not familiar with the necessary means to control the situa-

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tion. He reacts using the driving skills learnt in the linear driving range, which although tend to be correct, but lag too far behind the vehicle's movement. As a consequence, the driver-vehicle control loop surges and demonstrates unstable performance above a certain speed.

3.2 Piloted Driver Performance

The driver performance is made up of two components: open-loop and closed-loop control. Open-loop control is based on an assumption that the average driver exhibits optimum theoretical transmission performance in the transverse dynamic linear driving range. This is because this type of driver would be completely acquainted with his vehicle (after a becoming familiar with it) [4, 6]. The single track model [15] describes the transverse dynamic transmission performance in the linear driving range with a sufficiently well-adapted model and comparatively simple parameterisation. The necessary inversion is easily done. The curvature κ can be derived from the track specification observed later. The movement equations for the single track model lead to curvature κ of the transmission function H_{FV} for steering wheel angle δ. The parameters to be identified are the result of the equations, Eq. (1-4).

$$H_{FV} = \frac{\delta_h}{\kappa} = V_{FV} \cdot \frac{T_{z2}\, s^2 + T_{z1}\, s + 1}{\frac{1}{\omega_0^2} s^2 + \frac{2D}{\omega_0} s + 1} \quad \text{Eq. (1)}$$

$$V_{FV} = (EG \cdot v^2 + l) \cdot i_l \cdot \kappa \quad \text{Eq. (2)}$$

$$\omega_0 = \sqrt{\frac{c_h \cdot l}{J_z}} \quad \text{Eq. (3)}$$

$$D = 1/2 \cdot \sqrt{\frac{c_h \cdot l}{J_z}} \cdot \frac{l_h}{v} \quad \text{Eq. (4)}$$

They are yaw moment of inertia J_Z and skew rigidity at the front (c_v) and rear (c_h). All other parameters can be recorded with simple measuring instruments on the vehicle. The vehicle transmission performance is recorded experimentally using open loop measurements [1, 9]. The parameters are identified using a maximum likelihood cost function that is based on a quadratic function of the model error at each measuring point. The result is that the single track model reproduces real performance in the relevant frequency range with sufficient quality.

3.3 Controlled Driver Performance

The driver model's control component is intended to reproduce the driver's control performance in the linear driving range. An experimental basis is required here that allows the control parameters to be identified. The essential assumption behind the subsequent procedure is that the individual driver-vehicle performance is independent of the vehicle, as mentioned above. This means that individual drivers attempt to regulate the same transmission performance for the overall control loop for each vehicle in the transverse dynamic linear driving range – after becoming familiar with the vehicle. The driver therefore compensates for differences in the vehicle performance. A trial with average drivers has to reproduce the driver-vehicle dynamics in the swerve test. The trial is therefore designed for a change of lane in the linear range because the change clearly describes the system's performance from a control perspective. To trigger largely controlled driving performance on the part of the driver, pilot control has to be minimised. The test takes place in the vehicles' linear driving range. As a result, areas of variation from the measured lanes can be fixed over the vehicle, **Figure 1**.

An interpersonal comparison of the variation areas between the two vehicles shows that the width of the scatter range is larger than the difference between the two calculated middle paths. If it is assumed that a test subject is trying to travel along the same trajectory in each attempt, then the width of the variation area reflects the maximum positioning accuracy of the average driver in question. If the maximum deviation between the two middle paths of both vehicles is within this driver's positioning accuracy, it can be assumed that the driver is attempting to follow the same path with both vehicles. This can be used as the basis for developing the driver model's control component. The structural approach should be kept as simple as possible when it comes to the parameterisation's range of solutions. The change of lane represents a PDT_1 performance that can be constructed from the input parameters transverse deviation and track angle deviation [5, 8, 13]. In addition, an integral part is provided that compensates for a lasting transverse skew. This results in the structure of the control, **Figure 2**.

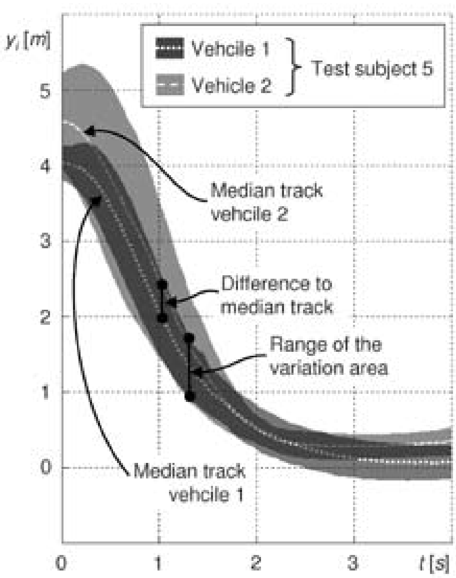
The transmission performance for both paths is determined from Eq. (5-8):

$$H_{FQ}(s) = \frac{\delta_{HRQ}(s)}{\Delta y(s)} = V_{Fy} \cdot \frac{1 + T_y \cdot s}{T_y \cdot s \cdot (1 + T_y \cdot s)} \quad \text{Eq. (5)}$$

$$H_{FK}(s) = \frac{\delta_{HRK}(s)}{\Delta \chi(s)} = V_{F\chi} \cdot \frac{1}{1 + T_\chi \cdot s} \quad \text{Eq. (6)}$$

$$T_y = \frac{k_y}{k_{yi}} \quad \text{Eq. (7)}$$

$$V_{Fi} = k_{vi} \cdot k_i \quad \text{Eq. (8)}$$



Test subject	Median range of the variation area s_{sy} [m]	Median track difference veh. 1 and 2 $\lvert\Delta y_{track1,2}\rvert$ [m]
2	0.32	0.37
3	0.51	0.29
4	0.51	0.53
5	0.43	0.30
6	0.67	0.16
7	0.44	0.44
8	0.30	0.12
9	0.26	0.10
10	0.91	0.78
12	0.78	0.44
13	0.26	0.26
14	0.67	0.34
15	0.68	0.21
16	0.76	0.42
17	0.31	0.17
18	0.57	0.32
19	0.39	0.33
20	0.77	0.14
22	0.35	0.17
24	0.31	0.14
Mean	0.51	0.30

Figure 1 : Areas of variation to the lane change from the trial with test subjects

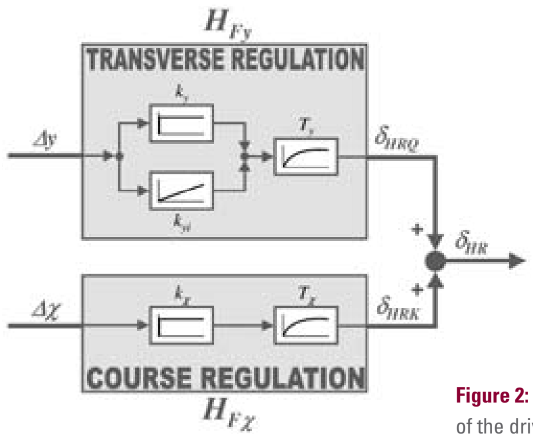


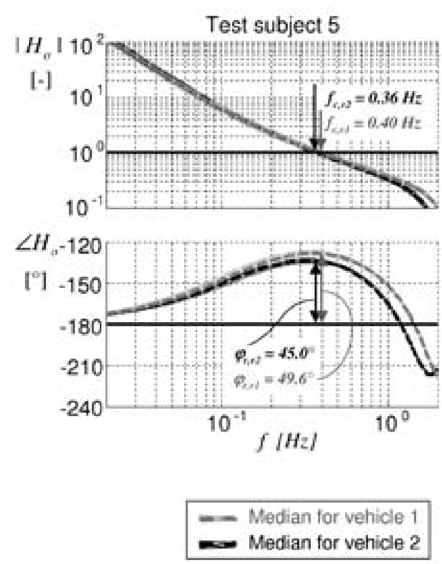
Figure 2: Control component of the driver model

The control parameters are identified by simulating the driver-vehicle control loop in the linear driving range. The single track model used for pilot control is used as the vehicle model here, including extended functions for tyre breaking-in performance and vehicle roll performance [9]. The lane changes recorded in the trial with test subjects are applied as the target specification. An iterative parameter variation adjusts the control parameters until the lane change is represented as well as possible. The process is repeated successively for discrete driving speed specifications, in order to take account of the control parameters' dependence on the speed. To confirm the statement that the driver-vehicle control loop is constant throughout the frequency range, the crossover frequency model [5, 6, 7, 11] can be consulted, which is commonly used for observing stability in system theory. The quality criteria phase margin φ_r and crossover frequency f_c – which characterise the quality of the control loop in the context of dynamic performance – are used to evaluate independence from the vehicle. A comparison of the average values, **Figure 3**, shows only minimal deviations between the two quality criteria for the two vehicles, **Table**. This confirms the statement that the driver-vehicle performance remains constant. The driver therefore largely compensates for the differences in the vehicle characteristics. A median lane change is taken as representative and set as the standardised driving characteristics for the comparison with further vehicles. The driver model therefore represents the transmission performance of a real average driver.

3.4 Validation in the Double Lane Change

The accuracy of the driver model at representing the average driver is shown by means of the double lane change driving manoeuvre [14]. The driving manoeuvre is adjusted on the basis of the tracks driven by the test subjects and the driver parameters identified individually for each driver.

One of the tasks for each test subject is to carry out the double lane change three times in the linear driving range. There is an identifiably similar angle to the steering wheel and, consequently, a similarity between the tracks of the three driving trials. The road trial using the driver model based on the individual median track for each test subject leads to a largely similar movement of the steering wheel in the double lane change, **Figure 4**. It should also be mentioned that a track with a precision of at least 5 cm can be repeated in the linear driving range. This degree of accuracy is not seen in any driver.



	Crossover frequency difference veh. 1 and 2	Phase margin difference veh. 1 and 2
Test subject	$\lvert\Delta f_{c1,2}\rvert$ [Hz]	$\lvert\Delta\varphi_{r1,2}\rvert$ [°]
2	0.015	4.1
3	0.111	5.4
4	0.036	5.3
5	0.038	4.6
6	0.057	2.3
7	0.077	1.9
8	0.053	2.9
9	0.031	2.0
10	0.041	0.4
12	0.031	1.2
13	0.087	3.4
14	0.041	0.4
15	0.038	3.0
16	0.025	0.0
17	0.024	1.2
18	0.050	5.2
19	0.040	3.7
20	0.020	3.0
22	0.064	4.0
24	0.044	0.3
Mean	0.046	2.7

Figure 3: Driver-vehicle control loop performance

Table: Transverse dynamic vehicle properties

Vehicle		1	2	3	4	5	6
Vehicle class		Compact	Compact	Compact	Compact	Midsize	SUV
Drive layout		Front	Front	Front	Front	Allrad	Allrad
Mass*	[kg]	1727	1727	1720	1782	2053	1639
Front axle load	[%]	58	58	59	57	53	51
Wheelbase	[m]	2.58	2.58	2.58	2.58	2.71	2.49
Front skew rigidity	[N/rad]	131770	109570	114760	121110	121140	78250
Rear skew rigidity	[N/rad]	192620	140500	150100	173750	187180	150130
Yaw inertia**	[kgm²]	2700	2650	2700	2800	3500	2400
Front tyre braking-in	[m]	0.62	0.79	0.57	0.48	0.72	0.67
Rear tyre braking-in	[m]	0.51	0.63	0.52	0.54	0.54	0.50

* including 2 people and measuring equipment (approx. 40 kg)
** estimated

4 Driver Model in the Road Trial

To evaluate the driving characteristics, the target path has to be set identically for all vehicles. With this as the basis, the average driver model can be used to measure and then evaluate any vehicles in the double lane change.

4.1 Determining the Target Path

To evaluate all vehicles equally in the double lane change, the specified target path has to be fixed. Taking account of the positioning accuracy of between 27 cm and 91 cm (identified in the lane change) and the driving line dimensions of between 43 cm and 78 cm for the vehicles under observation, the average driver is forced to select an approximately central route between the driving line limits. For this reason, a trajectory is specified on the basis of the analytically formulated approach according to [6], using Eq. (9-11):

$$y_i(x) = \frac{S_n}{L_n}\cdot\frac{4}{3}\cdot\left(\frac{3}{4}\cdot(x-x_n) - \frac{L_n}{2\pi}\cdot\sin\left(\frac{2\pi\cdot(x-x_n)}{L_n}\right) + \frac{L_n}{16\pi}\cdot\sin\frac{4\pi\cdot(x-x_n)}{L_n}\right) + y_n \qquad \text{Eq. (9)}$$

$$\chi_i(x)=\frac{S_n}{L_n}\cdot\frac{4}{3}\cdot\left(\frac{3}{4}-\cos\left(\frac{2\pi\cdot(x-x_n)}{L_n}\right)+\frac{1}{4}\cdot\cos\left(\frac{4\pi\cdot(x-x_n)}{L_n}\right)\right) \qquad \text{Eq. (10)}$$

$$\kappa(x) = 2\pi\cdot S_n/L_n\cdot\frac{4}{3}\cdot\left(\sin\left(\frac{2\pi\cdot(x-x_n)}{L_n}\right) - \frac{1}{2}\cdot\sin\left(\frac{4\pi\cdot(x-x_n)}{L_n}\right)\right) \qquad \text{Eq. (11)}$$

The parameters are identified using the tracks driven by the test subjects.

4.2 Evaluating the Vehicle up to its Limits

It can be categorically demonstrated that the driver model-vehicle control loop has a similar stability to the average driver that it is based on. To evaluate the different vehicles in a uniform way, it is first necessary to determine the track using the findings mentioned in the previous paragraph. Assuming that the driver-vehicle control loop is constant, it is then possible to identify a set of driver model parameters for this standardised average driver and for each vehicle examined. This information is used to carry out road trials with a double lane change where the driving speed is increased discretely. In order to keep the longitudinal dynamics as constant as possible, the change of lane is carried out while towing. **Figure 5** illustrates the degree to which the trial is fulfilled across the median speed (this is one possible assessment criterion). The area shown in light grey indicates the range in which the driving task was achieved in full. The middle area involved an infringement of the driving line regulations. In the dark grey area, the driver-vehicle system shows unstable driving characteristics, resulting in skidding. The different vehicle classes can be clearly separated, Table. The speed is a measure of the average driver's ability to control the car. The faster the speed in the middle or dark-grey areas, the easier it is for the average driver to control the vehicle in a difficult situation using his learnt skills. As a result, vehicles that largely retain their linear performance up to high speeds, even in the dynamic case, are easier for the average driver to control.

5 Outlook

The transverse dynamic model of the average driver allows to investigate vehicles up to their limits in a reproducible manner. These conditions make it possible to reconsider the criterion of maximum speed in the double lane change. It reflects the vehicle's transverse dynamic performance capabilities. Further criteria for evaluating

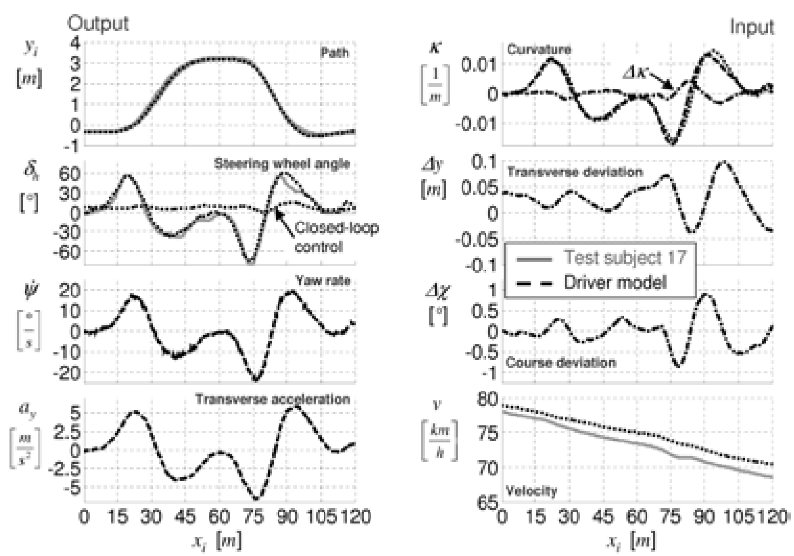


Figure 4: Reproducibility in the linear driving range

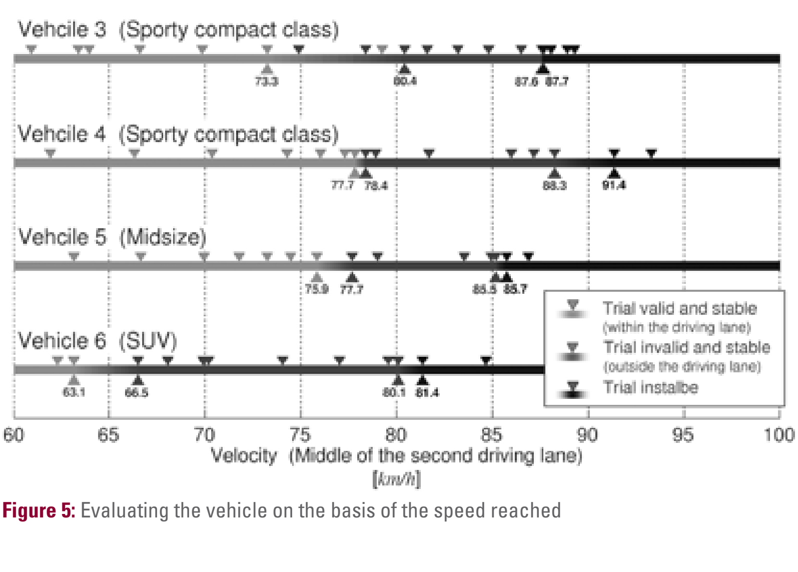


Figure 5: Evaluating the vehicle on the basis of the speed reached

the vehicle performance are developed allowing for better comparability between vehicles. The vehicle evaluation is broadened to include a driving manoeuvre with longitudinal dynamic influence. An investigation of the combination of a "normal" driver and a real vehicle was previously only possible for a few vehicles, for economic reasons. Mapping the driver model has made it possible to carry out this type of investigation for all vehicles. It opens up an additional option that allows us to tailor the driving characteristics more closely to the customer.

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Pilot control

$$H_{FV} = \frac{\delta_h}{\kappa} = V_{FV} \cdot \frac{T_{z2}^2 s^2 + T_{z1} s + 1}{\frac{1}{\omega_0^2} s^2 + \frac{2D}{\omega_0} s + 1} \quad (1)$$

$$V_{FV} = (EG \cdot v^2 + l) \cdot i_L \cdot \kappa \quad (2)$$

$$\omega_0 = \sqrt{\frac{c_h \cdot l}{J_z}} \quad (3)$$

$$D = \frac{1}{2} \cdot \sqrt{\frac{c_h \cdot l}{J_z}} \cdot \frac{l_h}{v} \quad (4)$$

Closed-loop control

$$H_{FQ}(s) = \frac{\delta_{HRQ}(s)}{\Delta y(s)} = V_{Fy} \cdot \frac{1 + T_y^* \cdot s}{T_y^* \cdot s \cdot (1 + T_y \cdot s)} \quad (5)$$

$$H_{FK}(s) = \frac{\delta_{HRK}(s)}{\Delta \chi(s)} = V_{F\chi} \cdot \frac{1}{1 + T_\chi \cdot s} \quad (6)$$

$$T_y^* = \frac{k_y}{k_{yi}} \quad (7)$$

$$V_{Fi} = k_{vi} \cdot k_i \quad (8)$$

Target path

$$y_i(x) = \frac{S_n}{L_n} \cdot \frac{4}{3} \cdot \left(\frac{3}{4} \cdot (x - x_n) - \frac{L_n}{2\pi} \cdot \sin\left(\frac{2\pi \cdot (x - x_n)}{L_n} \right) + \frac{L_n}{16\pi} \cdot \sin\left(\frac{4\pi \cdot (x - x_n)}{L_n} \right) \right) + y_n \quad (9)$$

$$\chi_i(x) = \frac{S_n}{L_n} \cdot \frac{4}{3} \cdot \left(\frac{3}{4} - \cos\left(\frac{2\pi \cdot (x - x_n)}{L_n} \right) + \frac{1}{4} \cdot \cos\left(\frac{4\pi \cdot (x - x_n)}{L_n} \right) \right) \quad (10)$$

$$\kappa(x) = \frac{2\pi \cdot S_n}{L_n^2} \cdot \frac{4}{3} \cdot \left(\sin\left(\frac{2\pi \cdot (x - x_n)}{L_n} \right) - \frac{1}{2} \cdot \sin\left(\frac{4\pi \cdot (x - x_n)}{L_n} \right) \right) \quad (11)$$