

Driver–vehicle interaction during straight-line acceleration: A time-domain analysis

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ABSTRACT

This paper presents an experimental investigation of the behavior of the driver–vehicle–environment system during straight-line vehicle acceleration. Although the driver attempts to maintain the desired straight-line trajectory, small steering corrections and throttle pedal adjustments are continuously applied in response to vehicle motion disturbances and road surface irregularities. The objective of this study was to determine the relationships between the driver's control actions and the dynamic response of the vehicle in the time domain.

Experimental tests were conducted on a heavy goods vehicle under real driving conditions. The steering wheel angle and vehicle speed were considered as input variables, whereas lateral acceleration and trajectory curvature radius were analyzed as output variables. The recorded signals were processed using correlation analysis and impulse response identification techniques. Cross-correlation coefficients and impulse responses were determined in order to quantify the dynamic interactions within the driver–vehicle system.

The obtained cross-correlation coefficients revealed significant relationships among the analyzed variables, while the impulse responses provided insight into the transient characteristics of the system. The proposed approach proved suitable for identifying the dynamic properties of the driver–vehicle–environment system and for assessing directional stability during straight-line accelerated motion.

KEYWORDS

Driver–vehicle–environment system, Road behavior, Vehicle acceleration, Correlation analysis, Impulse response.

1. INTRODUCTION

Maintaining a straight-line trajectory is one of the fundamental requirements for safe and efficient vehicle control. Although straight-line motion is often regarded as the simplest driving condition, the actual behavior of a heavy vehicle is influenced by numerous internal and external disturbances. Road surface irregularities, tire non-uniformities, powertrain torque fluctuations, aerodynamic forces, and environmental influences continuously affect vehicle motion. Consequently, the driver must perform small but continuous steering and throttle corrections in order to preserve the desired direction of travel and maintain directional stability.

The dynamic interaction between the driver and the vehicle has been the subject of extensive research for several decades. Early studies primarily focused on vehicle handling characteristics, steering system response, and directional

stability [1–17], whereas later investigations incorporated driver behavior as an integral component of the closed-loop control system [18–25]. Numerous experimental and theoretical studies have been devoted to vehicle cornering, lane-change maneuvers, obstacle avoidance, and transient steering responses. However, considerably less attention has been paid to the dynamic behavior of the driver–vehicle system during straight-line acceleration, despite the fact that this operating condition frequently occurs in everyday driving and significantly affects vehicle controllability and ride comfort [2].

During acceleration, the generation of longitudinal forces at the driving wheels may produce disturbances that influence the directional behavior of the vehicle. Variations in tire forces, torque transmission characteristics, and road adhesion conditions may cause small deviations from the desired trajectory. To compensate for these deviations, the driver continuously applies corrective steering actions and adjusts the throttle pedal position. The resulting dynamic interaction forms a complex feedback system in which vehicle responses influence driver actions, while driver actions simultaneously affect vehicle motion.

In recent years, increasing attention has been devoted to advanced driver assistance systems (ADAS), lane-keeping assistance systems, lane-centering controllers, and automated driving technologies [18–24]. The development of such systems requires a detailed understanding of driver corrective behavior and vehicle dynamic responses under real driving conditions. Accurate driver–vehicle models are essential not only for the design of autonomous and semi-autonomous vehicles but also for the improvement of active safety systems and vehicle stability control strategies. Therefore, the identification of dynamic relationships between driver inputs and vehicle responses remains an important research topic.

This study investigates driver and vehicle behavior during straight-line acceleration under real driving conditions. Particular attention is devoted to the relationships between steering wheel angle and vehicle speed, as well as to their influence on lateral acceleration and the trajectory curvature radius.

In recent years, research on the driver–vehicle–environment system has expanded significantly owing to the development of advanced driver assistance systems (ADAS), intelligent transport systems, and automated vehicles [18–24]. Contemporary approaches increasingly incorporate driver behavior modelling, vehicle trajectory prediction, real-time dynamic state identification, and the application of machine-learning methods for analyzing complex human–vehicle interactions. Particular attention has been given to cooperative driver–vehicle control, driver behavior modelling, and the analysis of vehicle stability under acceleration conditions.

2. METHOD

The methodology applied in this study is based on an experimental approach to the analysis of vehicle dynamic behavior under conditions of non-stationary straight-line motion during acceleration. The starting point of the investigation consists of experimentally acquired data obtained by measuring relevant variables during real vehicle acceleration maneuvers.

Although contemporary literature increasingly employs methods based on state-space models, predictive control, and artificial intelligence algorithms, correlation techniques and impulse response identification remain important tools in experimental investigations. Their main advantages are the possibility of direct application to measured data, the physical interpretability of the results, and the capability to identify dynamic relationships between inputs and outputs without the need for complex mathematical system models. Consequently, these methods continue to be widely used in vehicle behavior analysis, simulation model validation, and investigations of driver–vehicle interaction under real operating conditions. In this respect, the research presented in this paper complements contemporary studies, since it is based on experimental data collected during actual driving and enables direct insight into the mutual influences between driver control actions and the dynamic response of the vehicle during straight-line acceleration.

In order to perform a more detailed analysis of the behavior of the driver–vehicle system under accelerated motion, experimental investigations were carried out, as described below.

The test vehicle was a Zastava TERVO NTV with a 4×4-wheel configuration, whose principal parameters are given in [26]. During testing, the vehicle was in roadworthy condition and equipped with additional measuring instrumentation. A schematic representation of the measuring system is shown in Figure 1.

Three sensors were employed during the measurements: a Kistler S-350 sensor, a brake pedal force transducer, and a potentiometer for recording the steering wheel angle.

The Kistler S-350 is an optical sensor capable of measuring vehicle velocities and accelerations along the three principal axes (X, Y, and Z). It also records angular accelerations about the X, Y, and Z axes (roll, pitch, and yaw). The sensor was mounted at the midpoint of the right-hand side of the vehicle at a height of 150, mm above the ground.

The potentiometer was connected to the steering shaft by means of a toothed belt and pulley arrangement, enabling slip-free transmission of steering wheel rotation to the potentiometer.



Figure 1: Schematic diagram of the measurement system employed

The tests were conducted on the concrete runway surface of an airport. The duration of the recorded acceleration maneuver was approximately 21.14, s, and data acquisition was performed with a sampling interval of 0.02, s. This provided reliable frequency-domain information within the range of 0.047–25 Hz [27,28], which is entirely adequate for motor vehicle investigations [1]. Vehicle acceleration was performed under full-throttle conditions. During the experiment, lateral deviation and vehicle wandering occurred and were recorded by the instrumentation described above.

It was considered advantageous to apply methods originating from automatic control theory, as previously employed in [10,12]. The vehicle was therefore modelled as a dynamic system with two input variables: steering wheel angle and vehicle speed. The output variables were chosen as the lateral acceleration of the vehicle center of gravity and the trajectory curvature radius, thereby enabling a quantitative assessment of lateral deviation and vehicle wandering during non-stationary straight-line motion.

For the identification of vehicle behavior during accelerated motion along a straight path, methods commonly used in automatic control theory may be employed [29]. More specifically, the procedure adopted corresponds to a Multi-Input Multi-Output (MIMO) system approach. For analysis purposes, the MIMO system is transformed into a set of Multi-Input Single-Output (MISO) systems, requiring the input variables to be mutually independent. In the present study, the driver's uncontrolled steering wheel angle (SA) and the partially controlled vehicle speed (VS) were considered as input variables, whereas the lateral acceleration of the vehicle center of gravity (LA) and the trajectory curvature radius (RC) were treated as output variables. For illustration, Figure 2 presents the block diagram of the MIMO system (a) and the transformation procedure into MISO systems (b, c). Since this procedure is well documented in [29], it will not be discussed further here.

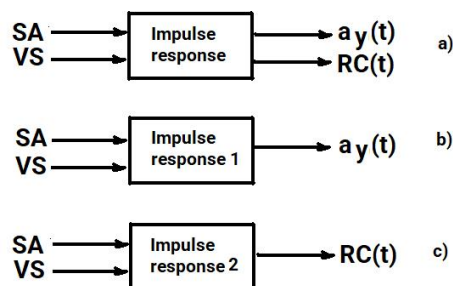


Figure 2: Transformation of the MIMO system into MISO systems (input signals: steering wheel angle SA and vehicle speed VS; output signals: lateral acceleration a_y and trajectory curvature radius RC)

An important question arises regarding the most appropriate domain for system identification, namely the time domain or the frequency domain. Practical experience has shown that neither domain can be considered universally superior. Both approaches possess specific advantages and limitations: The time domain is more suitable for model identification, transient process analysis, short-duration records, and nonlinear systems. The frequency domain is more suitable for resonance detection, analysis of relationships between channels, assessment of measurement quality through coherence functions, and modal analysis.

In vehicle dynamics investigations, the most reliable results are generally obtained by combining both approaches: identifying impulse responses and state-space models in the time domain, followed by verification and physical interpretation using spectral and transfer functions in the frequency domain. Considering that vehicle acceleration is a relatively short-duration process and that the vehicle represents a nonlinear dynamic system, it was considered appropriate to perform the identification of vehicle behavior in the time domain.

The dynamic behaviour of the driver–vehicle–environment system was therefore investigated in the time domain using correlation analysis and impulse response identification techniques. The measured input and output signals were processed as discrete time series recorded during straight-line vehicle acceleration.

Using a Pascal-based computer program developed for this purpose, the cross-correlation coefficients of the observed variables were calculated. Since the theoretical background of these coefficients is well established in [27,28], it will not be discussed further here.

In addition, impulse response functions were estimated in order to characterize the transient behavior of the driver–vehicle–environment system. The impulse response describes the reaction of an output variable to a unit impulse applied at the system input and provides insight into the dynamic coupling and time-dependent characteristics of the system. In the present study, the impulse responses were estimated from experimentally obtained correlation functions, assuming locally linearized behavior within the analyzed operating range.

To provide an overview of the nature of the recorded variables, their time histories are presented in Figure 3. It is evident that, despite the driver's efforts to maintain a straight-line course during the acceleration process, continuous corrections of the steering wheel angle and, to a lesser extent, vehicle speed are required, resulting in lateral accelerations and vehicle wandering.

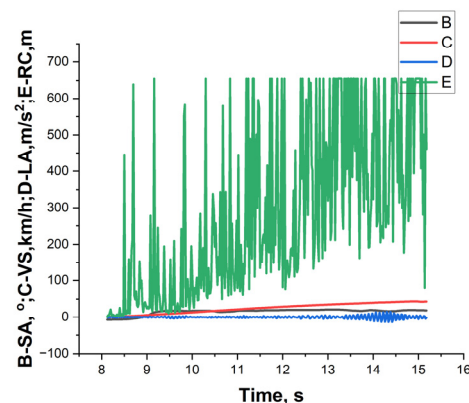


Figure 3: Time histories of the recorded variables (B – steering wheel angle; C – vehicle speed; D – lateral acceleration of the vehicle center of gravity; E – trajectory curvature radius)

From Figure 3, it is evident that the recorded variables predominantly belong to the class of stochastic processes. Consequently, their analysis requires the application of methods described in [27,28].

Considering the adopted MIMO approach, which is transformed into a MISO formulation requiring uncorrelated input variables, it was considered useful to calculate the cross-correlation coefficient between the steering wheel angle and vehicle speed. The obtained result is presented in Figure 4.

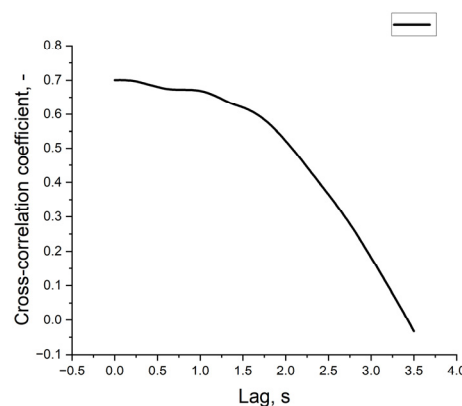


Figure 4: Cross-correlation coefficient between the recorded steering wheel angle and vehicle speed

It is evident that the coupling between these variables decreases as the time lag increases. This behavior may be explained by the presence of nonlinearities or measurement noise within the system. The values of the cross-correlation coefficient range from zero to approximately 0.7, indicating the possibility of coherence between the two variables. In order to verify this assumption, the Singular Value Decomposition (SVD) method was applied. However, analysis of the so-called V matrix confirmed that the variables are clearly separated and can therefore be used in their original form for further analysis. Since this method is described in detail in [30], no further discussion is provided here.

Using the developed software, cross-correlation coefficients were calculated for all combinations of input and output variables. In addition, the Wiener–Hopf equation was solved in the time domain in order to determine the corresponding impulse response functions. For illustration, the obtained results are presented in Figures 5–8.

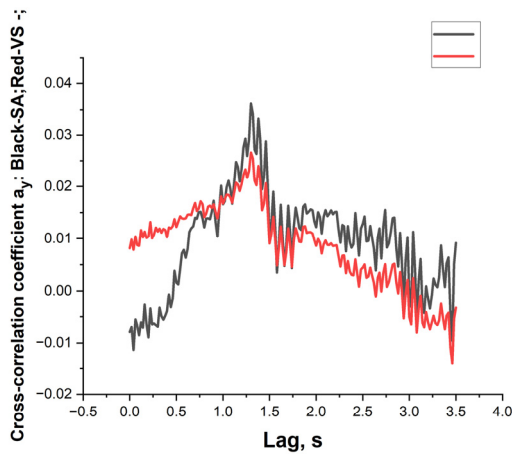


Figure 5: Cross-correlation coefficients between lateral acceleration, steering wheel angle, and vehicle speed

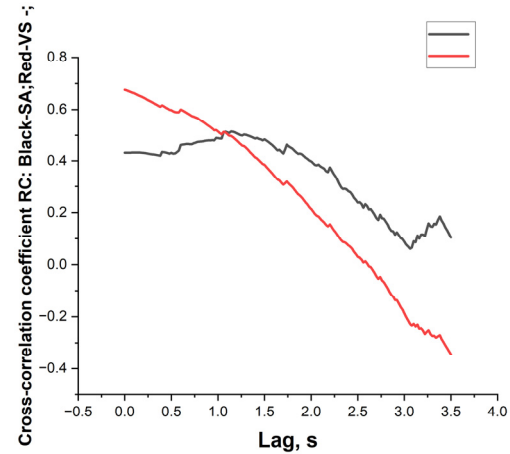


Figure 6: Cross-correlation coefficients between trajectory curvature radius, steering wheel angle, and vehicle speed

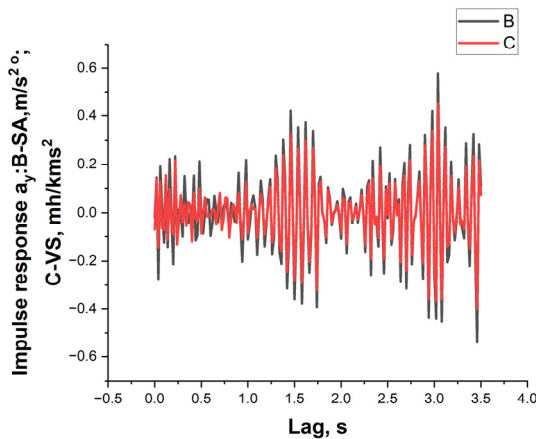


Figure 7: Impulse response of lateral acceleration to steering wheel angle and vehicle speed

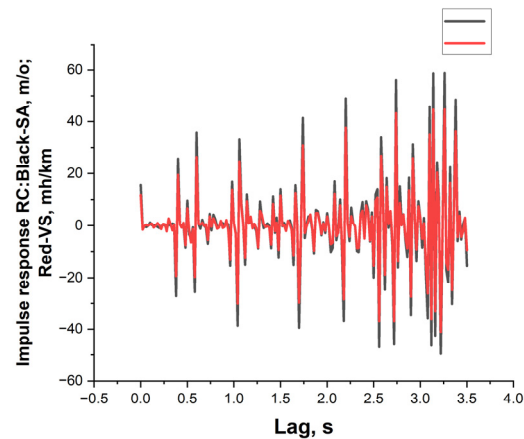


Figure 8: Impulse response of trajectory curvature radius to steering wheel angle and vehicle speed

3. DATA ANALYSIS

From Figure 5, it can be observed that, at the beginning of the analyzed interval, there is only a weak correlation between lateral acceleration and steering wheel angle. As the time lag increases, the correlation coefficient rises and reaches a maximum value of approximately 0.035 at a lag of about 1.35, s. Thereafter, it decreases rapidly and oscillates around positive values.

The cross-correlation coefficient between lateral acceleration and vehicle speed also increases, reaching a value of approximately 0.026 at a lag of about 1.35, s, after which it decreases monotonically and eventually enters the negative region. This indicates that lateral acceleration exhibits its strongest dependence on vehicle speed at a delay of approximately 1.35, s. Such behavior may be associated with tire dynamics, steering system response, and the inertia of the vehicle mass.

Analysis of Figure 6 shows that the cross-correlation coefficient between the trajectory curvature radius and steering wheel angle increases with time lag and reaches a maximum value of approximately 0.5 at a lag of about 1.3, s. Subsequently, the coefficient decreases and falls to approximately 0.1 at around 3 s, indicating that the relationship between the input and output weakens with time but remains positive.

The cross-correlation coefficient between the trajectory curvature radius and vehicle speed has an initial value of approximately 0.67, indicating a very strong relationship. It then decreases almost linearly to approximately 0.35 at the end of the observed lag interval. This suggests that vehicle speed exerts a stronger influence on trajectory curvature than steering wheel angle, although the relationship is less stable over time. Negative values of the correlation

coefficient imply that, after a certain delay, the output responds in a direction opposite to the initial trend. Such behavior usually indicates the presence of oscillatory dynamics, a change in phase relationship, or the dominance of another dynamic mode of the system.

The analysis of the impulse responses shown in Figure 7 reveals an oscillatory behavior with a mean value close to zero, while the amplitude varies with time. Up to approximately 1.2 s, the oscillations remain relatively small. Between 1.3 s and 1.8 s, a pronounced increase in amplitude occurs, reaching approximately 0.4, which coincides with the location of the maximum cross-correlation coefficient. At a lag of about 3 s, another group of large-amplitude oscillations appears. This indicates that the system possesses several dominant dynamic modes. Such an impulse response is characteristic of a lightly damped system, a system with multiple resonant frequencies, or a vehicle in which lateral motion, yaw motion, and tire deformation effects overlap. In other words, the response cannot be described as a first-order process but rather exhibits a multimodal dynamic character.

The analysis of the impulse response of the trajectory curvature radius with respect to the considered input variables shows that the amplitudes are considerably larger than those observed in the previous case. The amplitudes increase gradually and reach a maximum value of approximately 60 at about 3.4 s. Such growth of impulse-response amplitudes towards the end of the analyzed interval often indicates an insufficient length of the experimental record, poor conditioning of the Wiener–Hopf matrix, the presence of measurement noise, or strong interdependence between data samples. From a physical standpoint, these results indicate that both steering wheel angle and vehicle speed have a particularly strong influence on the occurrence of curvilinear vehicle motion. It should be noted, however, that the corresponding trajectory radii are very large, which consequently results in relatively small values of lateral acceleration at the vehicle center of gravity.

The foregoing analyses indicate that the driver–vehicle–environment system exhibits nonlinear dynamic behavior and that the application of the MIMO identification approach [28] is appropriate for its analysis and identification.

4. CONCLUSIONS

Based on the analysis of the cross-correlation coefficients and impulse responses, it may be concluded that the investigated dynamic system exhibits a pronounced time delay of approximately 1.3–1.5 s, at which the maximum relationship between the input and output variables is achieved.

The impulse responses display an oscillatory character with several dominant modes of oscillation, indicating the presence of a multi-degree-of-freedom dynamic system. The observed sign changes of the cross-correlation coefficients at larger time lags indicate variations in the phase relationship between the inputs and outputs and confirm the existence of resonant phenomena as well as interactions among several dynamic subsystems.

The results demonstrate that the behavior of the system cannot be described with sufficient accuracy by a first-order model. Instead, its representation requires a higher-order model incorporating several characteristic time constants. More precisely, the obtained results indicate that the driver–vehicle–environment system should be analyzed and modelled within the framework of nonlinear Multi-Input Multi-Output (MIMO) system theory in order to capture adequately its complex dynamic behavior.

Although advanced state-space identification and machine-learning methods are increasingly used, correlation-based identification remains attractive because of its transparency, physical interpretability and direct applicability to experimentally measured signals.

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