Performance Evaluation of a Purpose-Built, Low-Cost, Multi-Sensor Platform for Supporting a Truck Driver Coaching System

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Key words: truck driver coaching, GNSS-INS, Business Intelligence, FMS bus, fuel consumption optimization, automotive sensor technologies

SUMMARY

This paper elaborates on the performance evaluation of a custom-built, low cost, multi-sensor measurement system employed to serve as the backbone for setting up an advanced truck driver coaching system. The proposed sensor platform aims at retrieving, processing and analyzing a multitude of heterogeneous field data (i.e., location, kinematics, ambient conditions, vehicle functional characteristics, etc.) in order to compute and compare the running state of the target vehicle against a set of reference values derived using BI (Business Intelligence) analyses and long-standing historic data. Moreover, the study presents the conceptual approach for trajectory/road geometry segmentation facilitating optimized suggestions to the driver aiming at ensuring safety as well as reducing fuel consumption. The proposed segmentation approach is evaluated using real truck data. The outcome of this ongoing process reaches the user in a stream of suitable audio proposition updates to ensure a safe and efficient as possible drive. Highlights of the strengths and weaknesses concerning the investigated sensor set capabilities and options as well as the developed segmentation approach point out possible system refinements and future development.

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1. INTRODUCTION

Driven by the pertinent need for increased safety, reduced emissions and minimized fuel consumption, truck operators constantly strive to achieve optimal transport operations and peak profitability. Within this scope, a number of telematics systems have been developed in order to provide fleet operators with appropriate tools for monitoring the performance of vehicles and drivers. The specialized functionality of driver behavior monitoring and consequent feedback in the form of instructions for maintaining optimal driving parameters is known as driver coaching (Winder 2016, Sanguinetti 2018, Sciarretta and Vahidi 2019). Despite the fact that a number of driver coaching systems is already available in the market offering standalone operation for data collection, visualization and reporting, the majority of the provided data logging capabilities is confined to geolocation information and potentially to visual event documentation (Heyes et al. 2015, Zonar, Ref). Embedded driver coaching systems offered by a limited number of truck manufacturers provide specialized capabilities, however they usually operate as “black boxes” restricting further experimentation or backwards compatibility (Volvo 2021, Scania 2021). Systems aiming at reducing driver-induced, non-optimal operations are mainly divided in two groups; namely, driver behavior analysis systems and driver coaching systems and generally refer to multi-sensor, vehicle class/type-independent systems. Data driven behavioral analysis of drivers has been an active field of study providing innovative methods for the extraction of useful information from heterogenous data streams (Jacobs and Fung 2017, Kanarachos et al. 2018, Alluhaibi et al. 2018, Papadimitriou et al. 2019).

The proposed approach is based on an in-house built driver coaching system under development (Stratakos et al. 2021, Gikas et al. 2021) which aims at bridging the gap between the existing driver coaching systems and driver behavior analysis systems. More specifically, this study aims at building driver and vehicle fuel consumption profiles by appropriately modifying Business Intelligence (BI) analysis techniques, and consequently using them to provide feedback to the driver in a timely manner implementing a driver coaching system. This system comprises an application specific multi-sensor setup utilizing only low-cost devices. Also, this study introduces the concept of “road geometry segmentation”; that is to say, using the knowledge the upcoming road segments leads to vehicle state optimization in a timely manner. System performance evaluation is performed comparing utilized sensors against reference equipment.

The remainder of the paper is structured in 5 sections with Section 2 presenting the overall system design, section 3 describing the experimental set-up for system testing, while Section 4 outlines the performance assessment of positioning and inertial sensors. Section 5 presents initial evaluation results for the proposed segmentation approach and finally Section 6 includes concluding remarks and suggestions for future work.

2. SYSTEM DESIGN

This study is carried out as a part of PEGASUS research project which aims at designing, building and testing a novel professional truck driver coaching prototype. The overall system architecture heavily relies on the development of a data acquisition and transmission system able to handle large volumes of data in a reliable and cost-efficient manner.

2.1 Overall system architecture

The currently working prototype of the On-Board Data Hub (OBDH) is based on an Esp32 variant microcontroller which acts as a high-rate data-logging system as well as data broadcasting unit through a WLAN connection to an on-board tablet (Gikas et al 2021, Stratakos et al. 2021). The two main data streams are: (a) the FMS bus interface, and (b) the external sensors.

(a) An on purpose-built data logging unit was designed and developed to retrieve vehicle data via the FMS bus interface (i.e., subset of the CAN bus) (J1939-71, 2001; FMS Standard, 2002). As opposed to commercial of-the-shelf FMS Bus loggers this approach was deemed preferable as it provides easier access and control in the low-level FMS bus subsystems while ensuring system scalability.

(b) External sensors provide additional information that is not available via the FMS bus interface. Information regarding vehicle state (position, attitude, speed) is available in the current version of the system, while additional capabilities for collecting ambient parameters (i.e., air temperature, rain, humidity) as well as geo-spatial awareness features (e.g., distance to vehicle in front) using a camera / lidar sensor are being integrated in the system.

Figure 1 illustrates the data collection / communication system layout at a high-level including an overview of the relations among individual sub-systems.

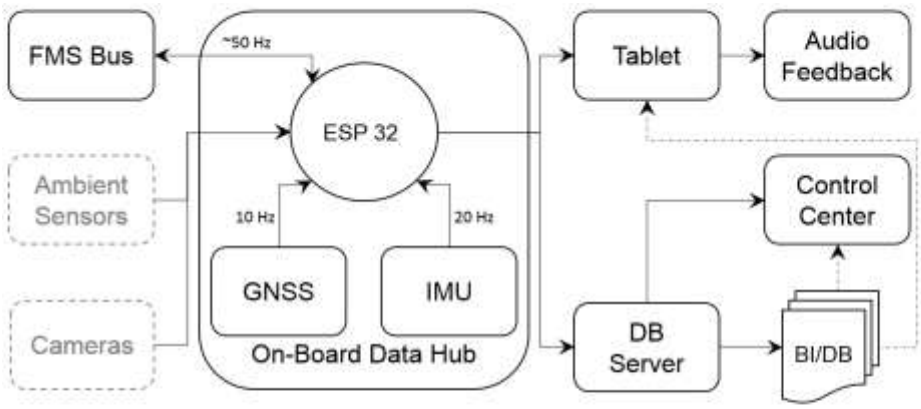

Fig. 1: Data flows and system architecture

2.2 Employed apparatus

The proposed system employs a number of modules to ensure efficient data collection and transmission. Ad hoc hardware and software development was carried out in order to integrate individual sensors / devices and subsystems so the end result is functioning as a unified system.

At the core of the system lies the *LilyGo TTGO T-Call V1.3 SIM800L* module with an *ESP32* microcontroller which performs data collection and processing tasks as well as serves as a communication gateway either with the on-board tablet or via the cellular communication network. The CAN Bus Shield *Keyestudio MCP2515* is employed as a basis of the FMS Bus data logger providing data at ~50 Hz. The *DP0201 (NEO-M8U GNSS + LIS3MDL compass)* single-frequency, multi-constellation module provides fused GNSS/IMU positioning data at 10 Hz sampling rate. Finally, the *Waveshare 10 DOF IMU* module serves as a ten-degree of freedom (DoF) recorder of inertial data (3D accelerometer, 3D gyroscope, 3D magnetometer and 1D barometer) at 20 Hz.
Table 1 provides an overview of the individual sensors employed in the system and their data recording capability.

Table 1: Overview of the employed sensors

Type	Device Model	Data rate
Processing/ communications	LilyGo TTGO T-Call V1.3 BLE, WiFi, GPRS	up to 200Hz
CAN Bus shield	Keyestudio MCP2515	ca. 50Hz
GNSS / INS	DP0201 (NEO-M8U GNSS + LIS3MDL compass)	10 Hz
10 DOF IMU + barometer	Waveshare 10 DOF IMU (MPU9255 + MP180)	20 Hz

2.3 Data handling

A critical issue for the functionality of the system is its ability to log and manipulate FMS bus data at a sampling frequency of 20-50Hz along with the data of each individual aiding sensor. Thanks to the ESP32 multi-thread capabilities as well as through implementing asynchronous code execution techniques, the system delays are kept well below 5 msec; and thus, it is capable to process measurement messages to a frequency of up to 200Hz. The retrieved data is then forwarded in real-time to the API of the staging data base (DB) using WebSocket communications protocol. (Fette & Melnikov 2011). A secondary *http* server is used for retrieving data buffered on the SD card for the cases of real time connectivity loss.

2.4 Business Intelligence

Research undertaken recently by the authors (Stratakos et al. 2021) has proved that BI technique suits to reveal useful information concerning the vehicle state and driver habits using sensor data. The basic principle of operation of the system implements the following steps:

- firstly, field data obtained from a number of vehicles are transferred and stored in a database where a special relational model is applied. This model features quantities acting as aggregation attributes, known as “system dimensions” and quantities suitablly aggregated, known as “system measurables”,
- BI techniques and transformations are applied to extract useful information from the initial raw data; particularly, fuel consumption in relation to road geometry, cargo weight and driving pattern. For instance, the BI unit is queried to provide aggregated information about the gear shifting pattern of a specific driver in contrast to another driver and compare them in terms of fuel consumption,
- the BI system compiles a multidimensional database (i.e., a “cube”) that is uploaded on an on-board tablet. Subsequently, the real-time incoming measurements are compared against the information stored on the cube using an on-purpose built software application, and finally
- if the current measurements are significantly diverging from those in the reference database, a vocal suggestion is issued by the system.

Notwithstanding, the aforementioned approach has been confirmed conceptually, its implementation revealed two downsides addressed in this study. The first drawback originates from the fact that the produced results refer to the running state of the vehicle, which in certain cases (high dynamics) might be obsolete. The second weakness stems from the sequential (point fix to point fix) character of computations. In effect, fluctuations in the raw data due to measurement noise may issue suggestions with contradictory content in very short time leading to false voice recommendations.

In order to address both issues, a more robust approach is proposed and adopted to process roadway geometry in terms of geometric features than subsequent point fix basis. This approach enables processing of the upcoming geometric features beforehand in order to provide in-time voice suggestions to the driver. Moreover, processing greater groups of points enables filtering of the inherent measurements noise providing greater stability to the system.

To achieve this, road geometry needs to be considered differently at the analytical level of the developed BI system. This is carried out by analyzing and grouping the individual vertical roadway alignment points into segments of similar geometric characteristics. For each class of segments, the BI preconceives the best set of driving conditions by comparing a large volume of driving conditions, all referring to the same class of geometric characteristics. The same approach is applied in the horizontal alignment too. In this case however, the comparison is related only to safety, not fuel economy. Figure 2 describes the possible geometric entities addressed.

Level 1 of the proposed hierarchical dimensional model is extracted from the sign of the grade (uphill, downhill, or flat segment). Level 2 contains the sign of the grade derivative (positive or negative rate of change). Level 3 reflects the horizontal alignment design element, which may be a straight line (zero curvature), an arc (constant non-zero curvature), or a transition curve (non-zero curvature derivative). Each group is addressed with different rules and checks.

Vertical profile segments are used for fuel consumption optimization whilst horizontal segments are used mainly for speed and safety considerations.

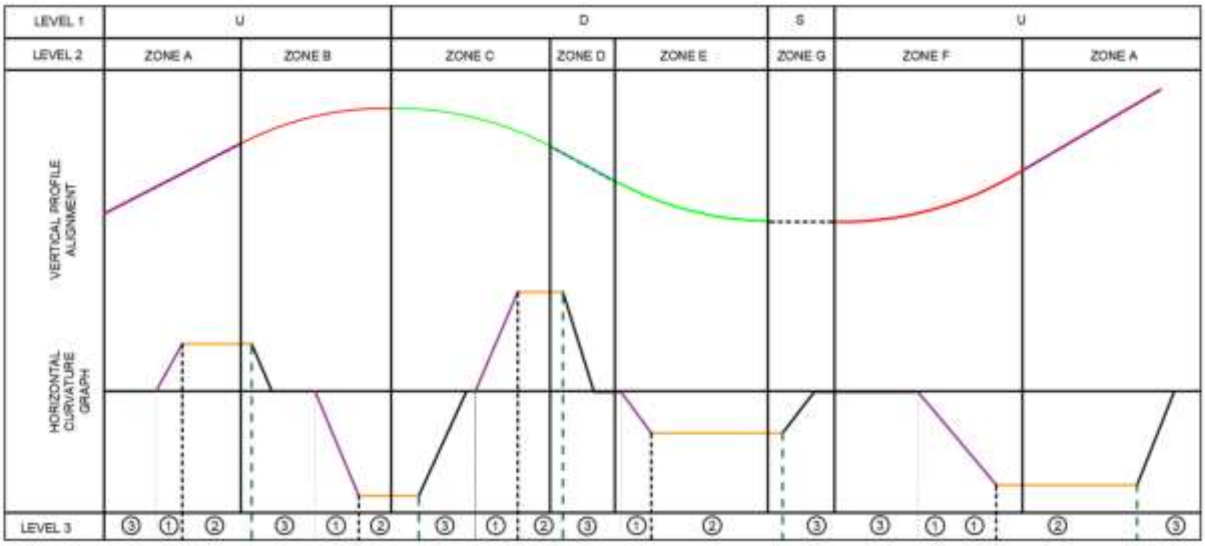

Fig. 2: Formulation of the roadway segmentation hierarchy levels using the vertical roadway alignment and the horizontal curvature graph.

For example, type segments shown in Zone A, suggest lowering driving gear and consequently speeding down to a certain speed value. In Zone B type segments, due to decreasing road slope the engine's load is decreasing too; therefore, a gear upshift may be expected. In Zone C, a gradual acceleration due to gravity is anticipated, which may involve breaking. Zone D denotes the previous situation but with a constant grade equal to the maximum of the previous segment. Breaking is anticipated in this case too. Zone E suggests the vehicle can gain speed due to gravity up to the speed limit allowed by the road signs or by checks performed on Level 3 of the hierarchy. Zone F denotes uphill segments with increasing slope. Vehicle is expected to eventually shift gear down. Finally, Zone G is a special type of segment with constant characteristics, inherited by the previous segment. It is thus appended to the previous segment. Zone changes of relatively small length that occur due to noise are automatically absorbed by the leading and trailing zone, if they both are of the same type. Level 3 segments are used for speed limit checks, especially in the inbound clothoid curves where the driver needs to adjust vehicle speed to the limits imposed to road signs and horizontal curvature.

Dealing with dimension hierarchies instead of discrete dimension members introduces several advantages (Oracle 2006):

- Hierarchical structuring is easier to understand and implement as the data present certain logical order.
- Filtering is more efficient and robust as hierarchies improve overall database query performance.
- Hierarchies are flexible in the long-term changes of the BI model.

- Hierarchies can be used in conjunction, simplifying both the presentation layer and the underlying model itself. Hierarchies of few levels can encode a large number of distinct members and their combinations.

Beyond these benefits, the introduction of hierarchies in the specific BI model resolves the issues encountered due to measurement oscillations and provides voice suggestions ahead of the control points.

3. EXPERIMENTAL SET-UP

Recently, a continuously increasing number of low-cost, high capability micro sensor systems, including GNSS/IMU modules, have broadly flooded the market. This has motivated the integration of such sensors with data streams drafted from the CAN bus of a truck, and processing them all together using cheap Arduino-like processing units in real-time. However, the low-cost state of such modules and compatibility issues arising from their coupling with the CAN bus information dictates careful selection of individual sensor components and extensive testing of the raw data quality.

In order to assess the positioning and raw measurement performance of the OBDH GNSS/ INS receiver and IMU module correspondingly, an evaluation measurement campaign took place in and around the NTUA Campus in Athens, Greece. The selected test area comprises typical peri-urban highway conditions, corresponding to a driving environment with varying sky visibility (i.e., open sky, low masking angles, high hills and mountains mostly on one side of the road and short windows of obstructed sky visibility due to bridges overpasses or tree canopies). Furthermore, in order to assess specifically the UDR (Untethered Dead Reckoning) functionality of the *u-blox M8U* GNSS receiver, which incorporates 3D inertial sensors providing a combined dead reckoning navigation solution, the test area includes an underground parking lot passage. This underground part imposes driving through totally obstructed sky visibility, which is a common situation for vehicles driving in a highway environment, due to tunnels. Figure 3 shows an overview of the test area (left) and a detailed view of the underground parking lot area (right).

During the measurement campaign the reference trajectory is generated using the integrated GNSS/IMU *SPAN®* system by *NovAtel®*. The system features a high-end, multi-frequency, multi-constellation GNSS receiver and antenna (*NovAtel® PwrPak7 and VEXXIS GNSS-850*) and a tactical-grade IMU system (*iMAR® IMU-FSAS*) along with a base station GNSS receiver occupying a reference point of known coordinates. The fused and smoothed navigation solution was generated through the advanced Kalman filter of the commercial post-processing software *NovAtel® Inertial Explorer* for minimizing the effects of GNSS signal outages and multipath effect. In addition, sensors lever arms were compensated in order to estimate the navigation solution for a common reference point on-board the vehicle. The OBDH system that incorporates the GNSS/INS receiver under test is placed behind the back windshield of the vehicle in order to test the receiver in a challenging configuration that the vehicle's rooftop and windshield obstructs most sky visibility simulating final sensor placement in the truck. Figure 4 shows the sensors setup.

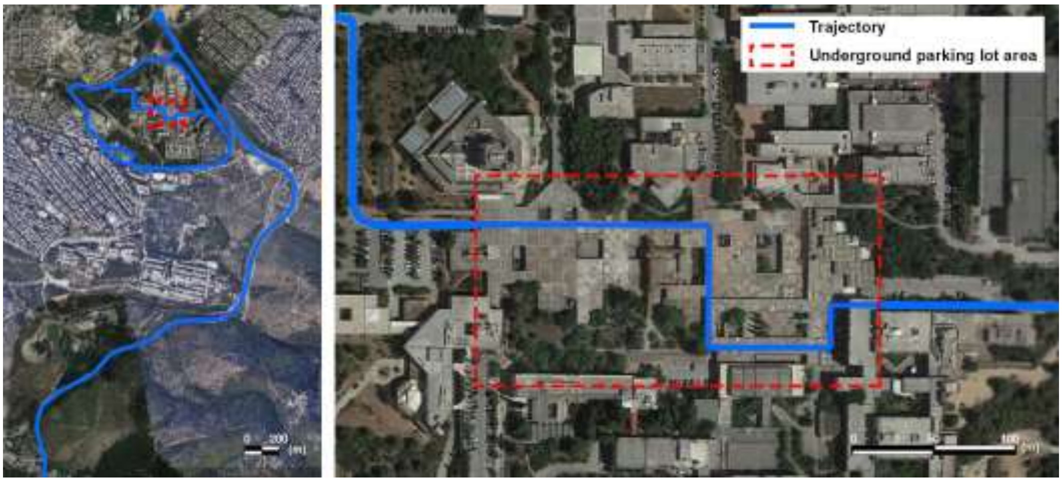

Fig. 3: Test area overview (left) and underground parking lot area (right). (source: google earth)

Moreover, the test trajectory driving was performed twice, toggling UDR functionality between enabled and disabled in order to assess the impact of UDR under totally obstructed sky visibility conditions. Apart from the varying UDR settings (on /off state), the *u-blox* receiver was constantly set to use the multi-constellation capability in a SPP (Single Point Positioning) configuration, at a maximum measurement rate of 10 Hz and employing a land vehicle profile in the embedded filtering algorithm. Finally, the speed readings from the vehicle's OBD2 port were assessed against the speed calculated through the reference trajectory.

4. SENSORS EVALUATION

4.1 Positioning sensors analysis

The performance analysis of the GNSS positioning solution relies on 3D trajectories comparison obtained from the *u-blox* M8U receiver against the reference trajectory (Gikas and Perakis 2016). The CDF plot of the 2D differences for the UDR-on trajectory (Figure 5) reveals a mean trueness value of the order of 4m, while the 95% of the 2D trueness estimated at just below 9m, which adheres the limits of typical SPP accuracy, considering also the errors possibly induced due to the receiver unfavourable antenna setup.

The UDR-off trajectory presents similar performance for the partially obstructed sky visibility environment. A significant difference between the two configurations is depicted in Figure 6. This plot points out the underground parking lot vehicle crossing, having UDR on and off and the corresponding CDF plots. The figure depicts the expected superior performance of UDR enabled positioning solution with accuracy and availability improvement about 75% and 50% correspondingly. It should be noted that this underground parking lot area has some open sky parts allowing for partial NLOS (multipath) signals leading to a degraded solution.

Fig. 4: Sensors setup during assessment trajectory data collection

Figure 7 illustrates the OBDH positioning performance along the vertical axis, namely the ellipsoidal height differences from the reference trajectory. The height profile is adequately estimated with an exception at the beginning of the trajectory before a navigation solution is obtained as well as after underground signal loss around 11:30 timestamp. Even though the absolute height value is not be correctly estimated, relative (consecutive) values that are critical for road grade estimation as implemented in our study, closely follow the pattern of the reference trajectory.

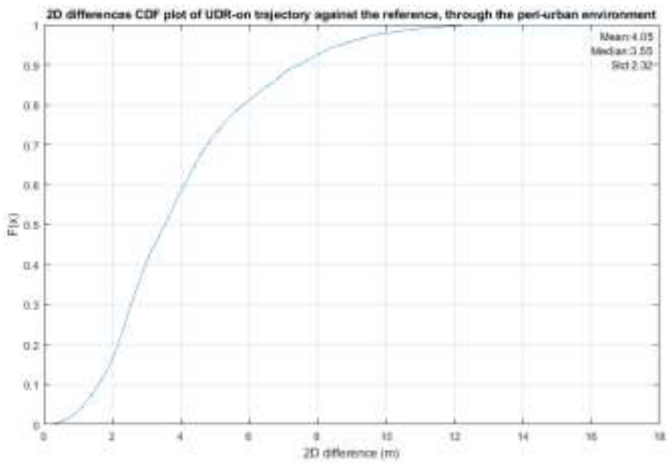

Fig. 5: 2D differences of UDR-on trajectory against the reference

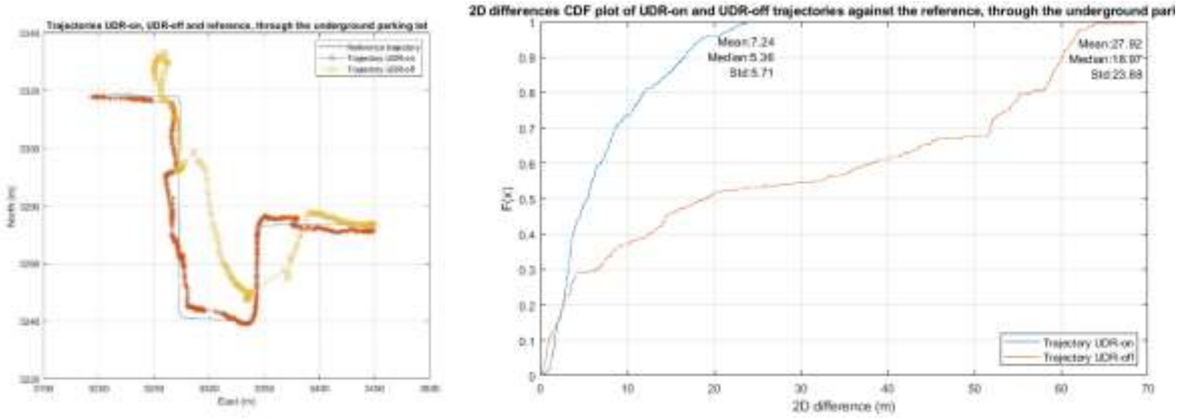

Fig. 6: 2D differences at the parking lot area of UDR-on and UDR-off trajectory against the reference

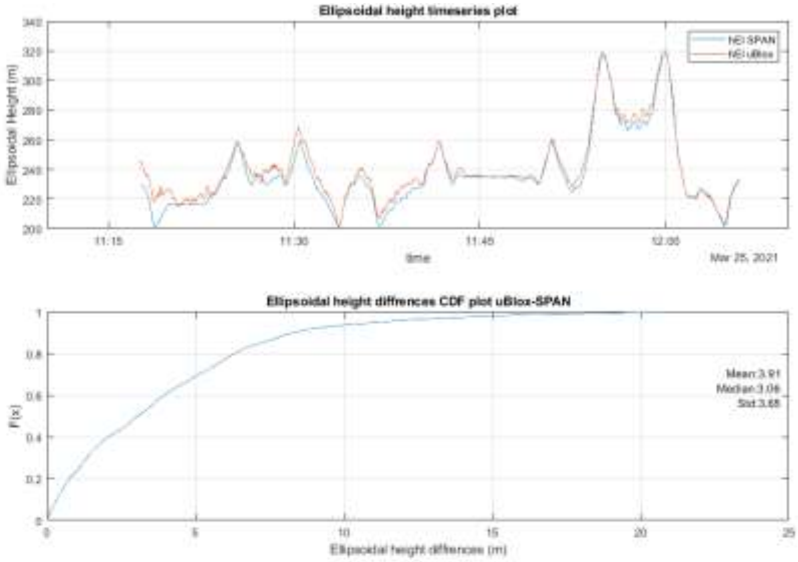

Fig. 7: Ellipsoidal height differences for the total trajectory

4.2 Inertial sensors analysis

The IMU module performance analysis is based on the estimation of the differences between the OBDH's IMU against the reference IMU. As this field campaign aims at studying the sensitivity and accuracy of the IMU readings to describe the vehicle dynamics, particular attention is given on the X and Y acceleration values, as well as the Z angular rate values with regard to the body frame reference system, considering that these measures sufficiently describe the dominant motion characteristics of the vehicle. Figure 8 illustrates the acceleration X, Y and angular rate Z values timeseries and their corresponding differences CDF plots. A close match is observed between the OBDH's IMU readings with the ones obtained with the reference system, indicating the capability of the proposed system's IMU to sufficiently describe the vehicle motion characteristics for the needs of the research project. Furthermore, the OBDH's IMU accuracy conforms with the values provided by the manufacturer.

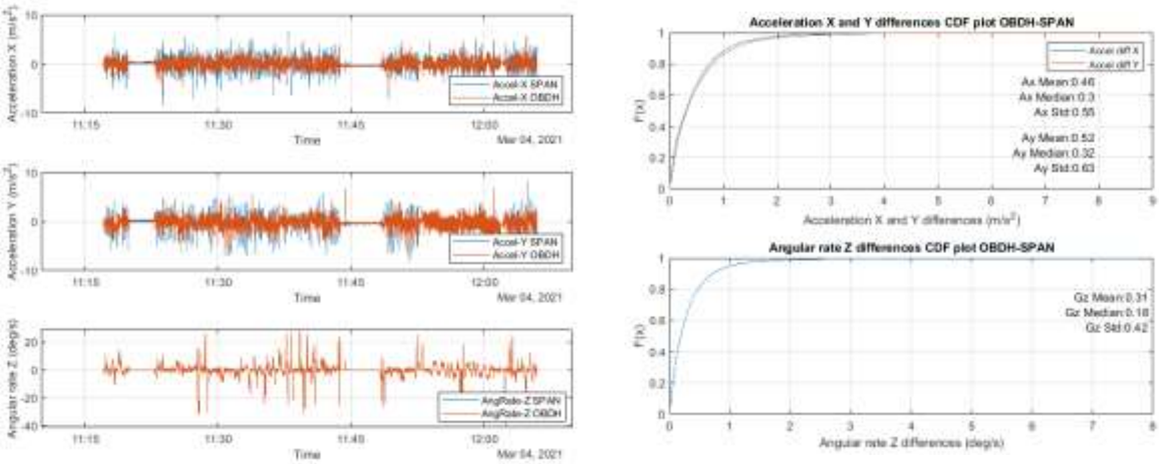

Fig. 8: Acceleration X, Y and angular rate Z timeseries (left) and corresponding differences CDF plots (right).

Figure 9 depicts the same analysis for a specific sharp turn along the trajectory, while the speed measure obtained through the OBD2 port is also analyzed with Figure 10 depicting the OBD2 port and reference trajectory speed readings and the corresponding differences CDF plots.

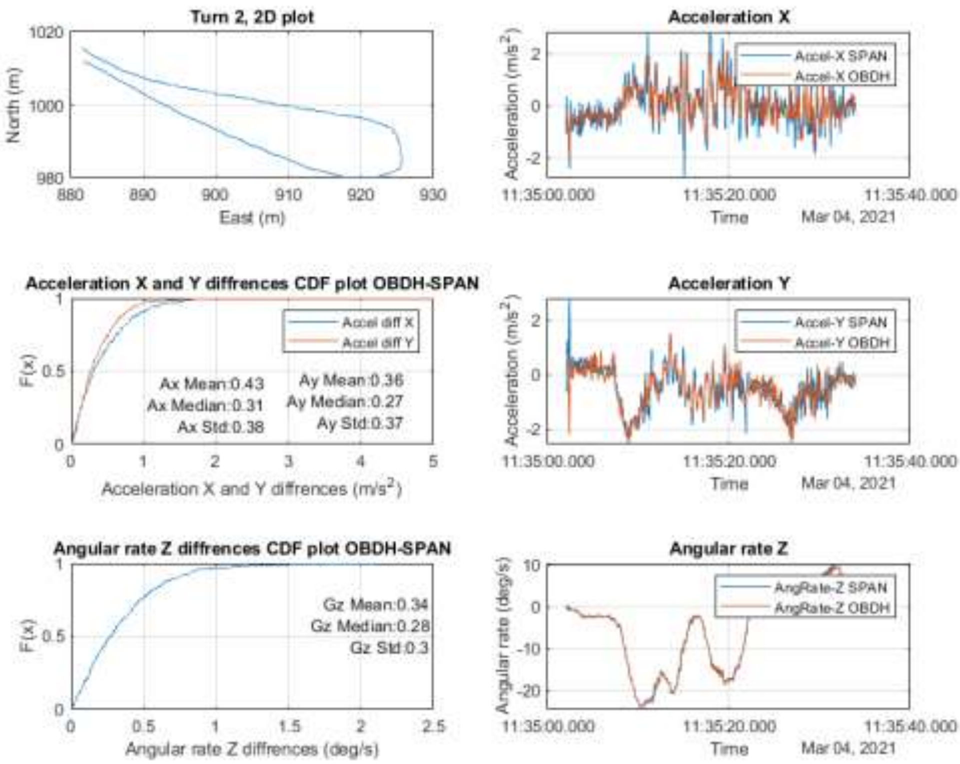

Fig. 9: IMU quality statistics for a sharp left-turn

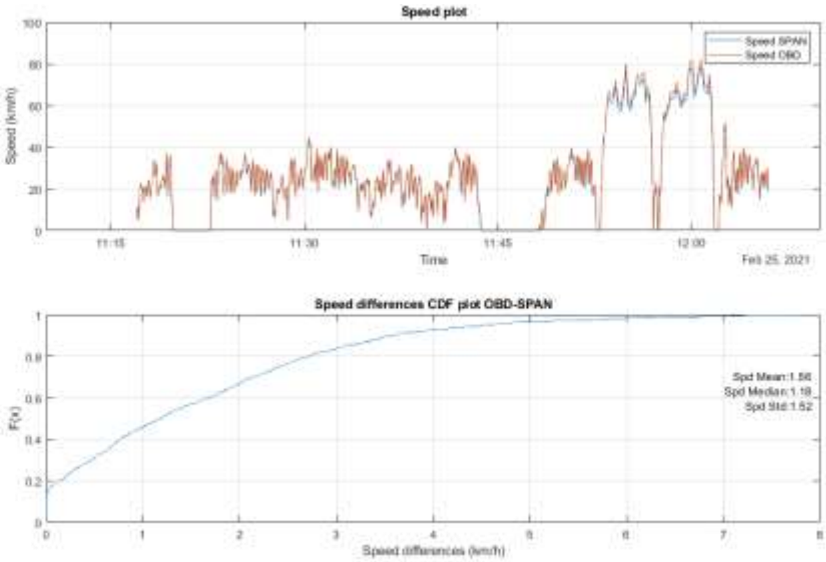

Fig. 10: Speed timeseries and corresponding difference CDF plot

5. SEGMENTATION IMPLEMENTATION

The implementation of the segmentation function was tested against a different dataset, obtained by an OBDH installed on a *DAF XF 105-340* truck. The truck was assigned a trip from the City of Patras, Greece to the city of Skala, Lakonia, Greece. Figure 11 displays a 40 km part of the total trip, where the segmentation zones are used to color-code the engine speed. Additionally, the gear ratio is also plotted for comparison. For simplicity, only the Level 2 elevation segments of the Curve Type hierarchy are displayed. Zones A and D have been appended to the leading segments. It can be noted that most of the upshifts consistently occur in the Zone C (blue color) while most of the downshifts occur in the Zone B (orange color). For each segment, all available vehicle passes from that segment will be used to extract an average fuel rate per dimension member. Eventually, this group of optimal dimension members along with the optimal measurable value, the average fuel rate, is extracted and stored in the data-warehouse of the BI. The aggregation will consider all the passes from the exact segment for the same cargo weight and vehicle. Any other segments of the same characteristics found in other locations or other trips will be used too.

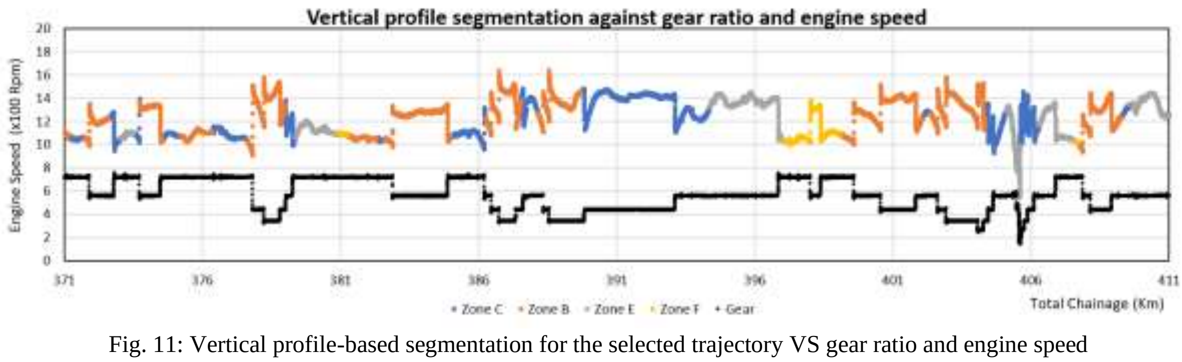

Fig. 11: Vertical profile-based segmentation for the selected trajectory VS gear ratio and engine speed

The information extracted from the compilation of the Curve Type Hierarchy is consequently used as an additional filter to exclude contradicting voice suggestions issued due to measurement noise that are not in accordance with the general character of the current or the next segment. Apart from this, the approach of segmentation provides the capability to transfer a second database on the vehicle with a complete dataset of the road network, loaded with metadata information concerning the optimal driving conditions at each segment. Then, as the vehicle moves along the stored trajectory, the tablet will perform a “playback” of the respective optimal driving conditions with a lead-in distance of 300m—that is, 18sec of driving time at 60km/h— providing the driver with an optimal suggestion adequate time before the actual road segment.

Verification of the suggested methodology has been carried out using trips processed with the initial methodology. The performance of the proposed solutions was examined against known locations where the original algorithm had provided erroneous indications and the results show that the current modifications achieve better overall performance. Figure 12 demonstrates the impact of the modified methodology on the driving conditions for a smaller part of the above graph, ranging from 380km to 394km positions. The graph contains the engine speed, the instantaneous fuel rate, the actual engine torque % and the altitude in different scale factors. An example of the improved behavior of the proposed methodology is evident at locations ca. S+382km and S+386km, where the driver lets the vehicle to roll. Around these locations the fuel rate and the engine torque fall significantly. With the previous methodology, this was considered a good situation, as the fuel consumption was lower than the anticipated for the specific slope. With the new methodology, that considers the upcoming segment’s properties, driver is advised to maintain speed and momentum in order to save fuel on the uphill segment which follows. It should be noted that although Figure 12 makes straightforward what the best driving behavior should be relatively to the upcoming type of segment, driver is not always in position to perceive the same conclusion as the horizontal layout may allow view of just the next few tens of meters or even less.

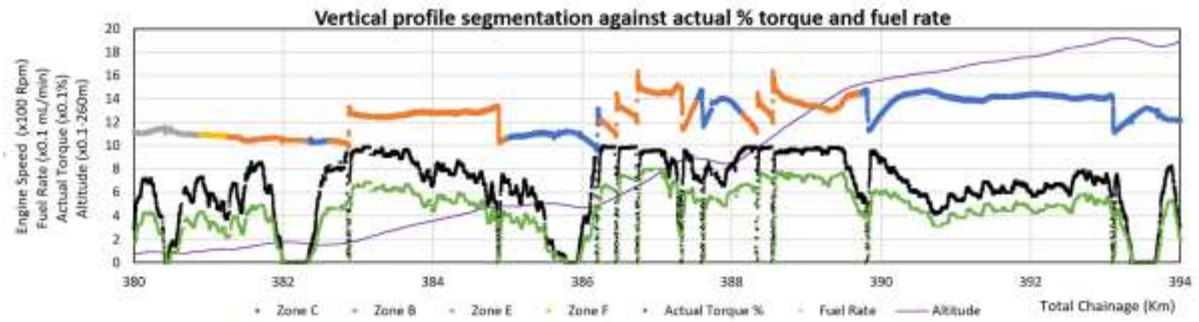

Fig. 12: Vertical profile-based segmentation for the selected trajectory VS actual torque % and fuel rate

Validation of the modified methodology is currently in progress given that long term data collection and processing is required. It is anticipated to provide an improved overall fuel consumption result, well beyond the mark of 3% that the initial methodology was estimated to achieve (Stratakos et al. 2021) as well as smoother user experience. Comparison of the long-term fuel consumption before and after the implementation of this methodology will provide an accurate assessment of the impact of the proposed modifications.

6. CONCLUSIONS - FUTURE WORK

This study focuses on specific aspects of a novel driver coaching system for professional truck drivers. The system integrates data from a variety of sensors along with data extracted from in-vehicle sources through the FMS bus. The low-cost sensor set used in this project was evaluated against a reference system of a high precision / accuracy GNSS system in tandem with a tactical grade IMU. While the superiority of the reference system is evident in both the positioning and the inertial characteristics, the obtained results highlight the capability of the selected sensor system for the specific purpose of developing a truck driver coaching system. Moreover, a novel conceptual approach for trajectory / road geometry segmentation facilitated by the implementation of dimension hierarchies in the BI's analytical model was presented. Usage of this approach improves the stability of the system, provides the driver with optimized suggestions ahead of the upcoming road segment and improves safety level and fuel consumption.

A further step forward would include the long-term collection of data using the proposed hierarchy-driven BI model and the comparison of the achieved performance with long standing historic data gathered before the usage of this methodology. Additionally, a procedure that would record issued suggestions along with the driver's response will provide valuable analytical feedback about the operation of the system itself and its interaction with the driver.

7. ACKNOWLEDGMENTS

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BIOGRAPHICAL NOTES

Ioannis Stratakos received the Dipl. lng. in Surveying Engineering from the National Technical University of Athens, Greece (2001) and the PhD degree in Rock Mechanics from the same School (2008). His research interests include fractal geometry, kinematics and emerging technologies such as IoT, Analytics and Big Data.

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