OPTIMALNO PLANIRANJE BRZINE VOZILA NA OSNOVU PROCENE PROFILA PUTA U CILJU POBOLJŠANJA KOMFORA VOŽNJE I EFIKASNOSTI POTROŠNJE GORIVA

OPTIMIZED VEHICLE SPEED PLANNING BASED ON ROAD PROFILE ESTIMATION FOR ENHANCED RIDE COMFORT AND FUEL EFFICIENCY

Abdukarimov Nurmukhammad[1], Ruzimov Sanjarbek[2],

Dilshod Muydinov[3]

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Rezime: Ovaj istraživački rad ima za cilj da ispita uticaj hrapavosti površine puteva na ključne operativne karakteristike vozila kao što su komfor tokom vožnje i potrošnja goriva. Predloženi pristup zasniva se na upotrebi ugrađenih senzora, kao što su inercijalne mereće jedinice (IMU) ili senzori pametnih telefona, za merenje vertikalnih ubrzanja i uglova nagiba vozila u cilju precizne procene stanja profila puta. Da bi se obezbedilo stalno ažuriranje i unapređenje podataka o profilu puta, integrisana je platforma zasnovana na kraudsorsingu (eng crowdsourcing) u klaudu (eng. Cloud) koja pruža informacije o uslovima puta u realnom vremenu.

U ovom radu se predlaže prediktivni algoritam za planiranje brzine kao rešenje problema integracije informacija o profilu puta radi istovremenog postizanja boljeg komfora tokom vožnje i veće efikasnosti potrošnje goriva. Algoritam formuliše objektivne funkcije koje smanjuju nelagodnost putnika minimizovanjem vertikalnih vibracija i ljuljanja vozila, kao i potrošnju goriva optimizacijom profila brzine vožnje. Ključna ograničenja ugrađena u algoritam uključuju maksimalne i minimalne dozvoljene brzine, bezbednosne margine, dinamičke performanse vozila, saobraćajne propise i geometriju puta.

Razvijena metodologija ima potencijal da se koristi kao algoritam za kontrolu brzine kod autonomnih vozila ili kao napredni sistem pomoći vozaču (ADAS), koji savetuje ljudskog vozača o najoptimalnijim brzinama za održavanje. Bezbedna, udobna i energetski efikasna vožnja predstavljaju glavne rezultate ovog istraživanja, koje omogućava proaktivno prilagođavanje brzine vozila u skladu sa očekivanom hrapavošću puta.

Ključne reči: hrapavost puta, komfor vožnje, efikasnost potrošnje goriva, optimizacija brzine, procena profila puta, dinamika vozila, napredni sistemi pomoći vozaču (ADAS), autonomna vozila, kraudsorsing.

Abstract: This research work aims to examine the effects of road pavement roughness on critical vehicle operating characteristics such as ride comfort and fuel consumption. The proposed approach is based upon onboard sensors like Inertial Measurement Units (IMUs) or smartphone sensors to measure vertical accelerations and pitching angles of the vehicle for accurate estimation of the road profile state. To ensure that the road profile data is being

[1] Prof. dr Abdukarimov Nurmukhammad, Mechanical and Aerospace Engineering Department, Turin Polytechnic University in Tashkent, Uzbekistan. ORCID: https://orcid.org/0000-0002-1661-7908

[2] Prof. dr Ruzimov Sanjarbek Traffic Engineering and Management Department, Kimyo International University in Tashkent, Uzbekistan. ORCID: https://orcid.org/0000-0002-1836-780X

[3]Prof. dr Dilshod Muydinov Ministry of Higher Education, Science and Innovation, Uzbekistan https://orcid.orcid=0000-0001-8408-2813

constantly updated and improved, a cloud-based crowdsourcing platform is integrated to provide real-time and dynamically updated road condition information.

This paper proposes a predictive speed-planning algorithm as a solution to the problem of integrating this road profile information for the purpose of simultaneously achieving good ride comfort and fuel efficiency. The algorithm formulates objective functions that reduce passenger discomfort by minimizing vertical vibrations and pitching of the vehicle and minimizes fuel consumption by optimizing the driving speed profiles. The key constraints that are incorporated into the algorithm are maximum and minimum allowable speeds, safety margins, vehicle dynamic performance, traffic rules, and road geometry.

The developed methodology has the potential to be used as a control algorithm for autonomous vehicle speed control and as an Advanced Driver Assistance System (ADAS) that advises human drivers about the most efficient speeds to maintain. Safe, comfortable, and energy-efficient vehicle operations are the outcomes of this research that enables proactive adaptation of vehicle speeds according to the anticipated road roughness.

Keywords: Road roughness, Ride comfort, Fuel efficiency, Speed optimization, Road profile estimation, Vehicle dynamics, Advanced driver assistance systems (ADAS), Autonomous vehicles, Crowdsourcing.

1 INTRODUCTION

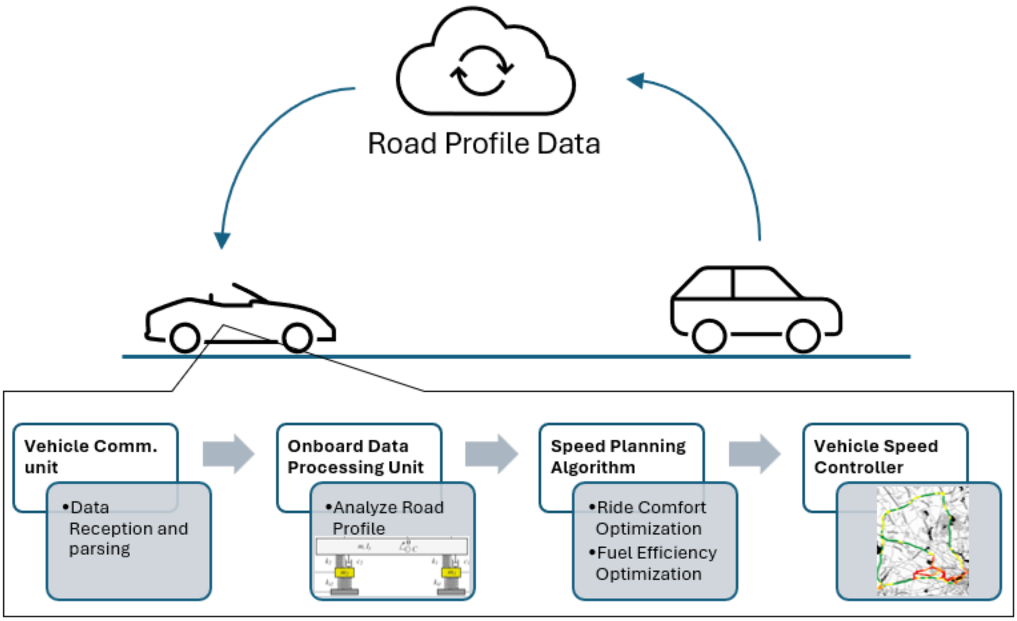
Road surface conditions have a significant effect on vehicle performance, passenger comfort, and fuel economy in terms of energy loss and vibrations experienced inside the vehicle due to uneven or rough roads. Studies have shown that a rough road yields poor ride quality and causes an increase in vehicle fuel consumption [1]. For example, in urban driving conditions, badly maintained roads can increase fuel usage by up to 15%, due to higher rolling resistance and energy dissipation [2]. With the increase in intelligent cars and inexpensive sensors, there is an opportunity to effectively use road surface information to enhance driving experiences.

Traditionally drivers rely on road signs and their own feelings, for comfort, driving without specific details of upcoming road conditions. However, with modern *onboard sensors (accelerometers, gyroscopes)* and connectivity, vehicles can detect road irregularities in real time. If this information is shared and aggregated, drivers or autonomous systems can adjust speed before reaching rough areas. This helps in providing smoother ride experience and saving fuel that would otherwise be wasted on unnecessary braking, acceleration, or vibration-induced losses.

Problem Definition: We address the problem of *optimal speed planning based on road profile estimation.* The goal is to determine an ideal driving speed for each segment of a road, by taking into account its surface roughness profile in order to *enhance both ride comfort and fuel efficiency simultaneously.* This is highly significant in modern transportation where vehicles are becoming smarter and more connected and dynamic speed optimization could complement existing eco-driving and active suspension technologies. Improving ride comfort not only enhances passenger experience but also can mitigate motion sickness and reduce vehicle wear. Improving fuel efficiency align both with economic and environmental goals.

This study focuses on the intersection, between of intelligent transportation systems, vehicle dynamics, and cloud computing technology usage in a way by suggesting the using crowdsourced data from many vehicles to generate a continuously-updated map of road surface conditions, so that vehicles can operate more intelligently, on different terrains by adjusting speeds accordingly for a smoother ride and minimizing the effects of uneven road surfaces. This method is especially useful for *autonomous vehicles and cars with driver assistance systems (ADAS)* that can automatically adjust speed, but it can also support human drivers through advisory systems. The framework also helps road maintenance organizations by identifying areas of the road that are deteriorating (as a by-product of crowdsourced data), aligning with the broader goal of *smart infrastructure* management [3].

In the sections we will explain how road profiles are estimated based on vehicle vibrations and discuss a cloud-based approach, for gathering and sharing this information through crowdsourcing efforts. We will also introduce the speed optimization algorithm focusing on its goals and limitations while addressing the aspects of applying it to autonomous and assisted driving scenarios. The diagram in Figure 1 gives an overview of the system where vehicles gather road data which is then processed by a cloud platform to provide recommendations for speeds back, to the vehicles.



2 ROAD PROFILE ESTIMATION FROM VEHICLE VIBRATIONS

Before optimizing speed based on road conditions the system needs to establish a dependable method to measure *road profile roughness*. Vehicle response measurements of vibrations including vertical acceleration and angular motion (pitch) enable the determination of *road surface profiles* under tires. The vehicle functions as a sensor or "filter" for detecting road irregularities [2]. When a car drives over a bump or pothole, the resulting acceleration signal can be analyzed to estimate the size and shape of that road disturbance.

Sensors and Data: Modern vehicles and smartphones are equipped with *Inertial Measurement Units (IMUs)* that measure acceleration in three axes and angular velocities. Road profile estimation requires the vertical acceleration and vehicle pitch angle/rate to be the most useful measurements. These signals contain information of road unevenness. For example, a sudden spike in vertical acceleration may indicate a pothole, while sustained oscillations can indicate rough pavement texture or washboard patterns. And also, the vehicle's position data obtained from GPS along with speed information enables researchers to identify particular road sections associated with detected vibration patterns.

Car Suspension Models: A well-established method to relate vehicle accelerations to road profile is through a *quarter-car suspension model* [2]. A quarter-car suspension model consists of a vehicle body quarter as the sprung mass and wheel assembly as the unsprung mass which are linked through suspension components and wheel contact stiffness (this system includes two masses with two spring-damper elements). The suspension system enables wheel movement from road profile changes (ground height irregularities) while the vehicle body adjusts through its suspension elements. The system modeling enables researchers to determine how road inputs affect the sprung mass acceleration measurements.

Using such a dynamic model, techniques like *Kalman filtering or observers* are often applied to reconstruct the road profile from sensor data. In prior studies, researchers have successfully estimated road roughness by assuming a quarter-car model and processing accelerometer data to infer the road elevation changes [1]. The method requires removing gravitational acceleration from the data using gyroscope orientation or vertical acceleration averages to reach 1g upward and then analyzing the high-frequency signals that result from road irregularities [3]. The signals become velocity or displacement measurements through appropriate integration with drift correction or the observers use them to estimate *road profile heights* as states.

Roughness Indices: Rather than reconstructing the exact profile geometry, many systems reduce the data to a *roughness index* such as the *International Roughness Index (IRI)*. IRI is defined as the accumulated suspension travel (relative motion) over a standard distance [4]. Transportation departments traditionally measure road profiles using laser profilers to simulate quarter-car suspension (*Golden car*) response which determines IRI. In this approach, we measure vehicle responses to derive an "equivalent IRI". The *Carbin project* (MIT) transforms smartphone acceleration data into road roughness metrics that align with IRI standards [2]. The virtual quarter-car model applied to accelerometer data enables Carbin to compute road roughness measurements which also forecast the impact on fuel usage [2]. The data obtained from crowd sensing demonstrates equivalent precision to traditional measurements of surface roughness.

Data Processing: The process of estimating road profiles using vehicle vibrations requires multiple steps in real applications:

- **Sensor calibration and orientation:** The accelerometer axis requires proper alignment or transformation into a standard coordinate system (such as matching device directions to vehicle directions) [3]. Remove the gravity component from the vertical acceleration (either by high-pass filtering or using gyroscope to subtract tilt).
- **Noise filtering:** Different filtering techniques should be used to remove noise and unimportant vibrations like engine or driveline vibrations as well as door slams and other irrelevant events. The road disturbance frequencies can be isolated by using a high-pass filter and logic can be applied to exclude road-unrelated events such as sudden lateral acceleration spikes indicating turns instead of bumps.
- **Feature extraction:** Measure the acceleration signal output after processing to find roughness-related features. The *RMS* acceleration value of a segment serves as a roughness indicator [1], [5] as well as vertical acceleration *power spectral density* analysis for road texture wavelength detection.
- **Model-based estimation:** An observer (e.g., a Kalman Filter) should utilize vehicle model data with sensor information to predict *road elevation profiles* through model-based estimation. Some advanced methods use both suspension deflection (if available from

vehicle CAN data) and body acceleration to estimate profile heights directly [1]. Others derive a simplified roughness index by regression: for example, relating the variance of acceleration to IRI through a calibration formula [5].

- **Road Event Detection:** Identify and categorize events like potholes or speed bumps versus general rough pavement. Sharp spikes might be classified as potholes, whereas continuous moderate roughness indicates overall poor pavement. This classification can be useful for different actions (e.g., a large pothole might warrant a stronger braking for safety/avoidance, whereas gentle roughness suggests a modest speed reduction for comfort).
- **Mapping to Location:** Tag each measurement or roughness segment with GPS coordinates. Since GPS errors can occur, data may be aggregated in road segments (e.g., averaging readings over 20 m intervals) to get stable estimates for that road stretch [6].

The output of this step is a representation of road surface quality – either as a profile (a sequence of heights or bumps) or simply an index like IRI or a roughness score for each segment of road. This information will feed into the speed optimization algorithm. Before that, however, it needs to be shared and aggregated across many vehicles to build a comprehensive, up-to-date road condition map.

3 CROWDSOURCED CLOUD-BASED ROAD PROFILE MAPPING

A single vehicle can identify the bad stretches on the roads it travels, but to get data for the entire road network and keep information updated, a *crowdsourcing approach* is adopted. *Crowdsourced road monitoring* means that several vehicles and people provide sensor data to a central system, which combines all the information into a coherent map of road conditions [3], [5]. It is based on the fact that although an individual vehicle's data may be noisy or a particular driver may swerve to avoid a pothole, other vehicles will contribute additional data so that the rough spot will be captured [3].

Cloud Infrastructure: We propose a cloud-based platform that receives processed road condition data from vehicles (smartphones or built-in telematics units). Each contributing device periodically uploads its latest findings: e.g., "road roughness = 5 mm RMS at location (x, y)" or "pothole detected at coordinate (x_p, y_p) at time t". The cloud aggregates this data spatially and temporally. Spatial aggregation involves grouping reports by road segment; temporal aggregation means updating the values over time as new data comes in (to account for road changes or more measurements).

In systems like *SmartRoadSense* and others, the server collects roughness readings and *averages the values for each road region* to obtain a stable estimate [6]. For example, all acceleration-derived roughness scores within a 100-meter road segment can be combined to produce a confident roughness index for that segment. *Outlier filtering* is crucial: the cloud can employ algorithms to disregard inconsistent data (perhaps due to a sensor error or an outlier event). *A probabilistic crowdsourcing filter* can compare multiple reports – if most devices report a bump but one does not, the system can still flag a bump with high confidence [5].

Real-Time Updates: One advantage of crowdsourcing is the ability to *continuously update* the road condition map in near real-time [3]. Unlike traditional road surveys done annually, this system is dynamic. Every passing vehicle effectively *re-surveys* the road. If a new pothole forms or a road is resurfaced, the changes will reflect in the sensor data (suddenly many vehicles hit the pothole and report a spike, or a once-rough road now shows low vibration levels). The cloud platform can quickly incorporate these changes. Essentially, the more vehicles on the road, the more frequent the updates – achieving a live "weather map" of road quality.

Data Aggregation Model: The cloud could store an indexed database of road segments (for instance, divided by road between intersections, or by fixed length segments). Each segment record contains the latest roughness metric (and timestamp) and perhaps a list of recent detected anomalies (like potholes or bumps with their severity). When new data arrives:

- If it's a roughness measurement, the system updates the segment's roughness value (e.g., via a weighted moving average giving more weight to recent reliable readings).
- If it's a discrete event (pothole), the system adds it to a map layer of road hazards, possibly averaging multiple detections to pinpoint location.
- The system may also estimate *confidence* for each entry based on number of observations and agreement between sources [3].

Techniques from *spatiotemporal data fusion* are applied: readings that cluster in space and time are given higher trust. By fusing data from thousands of smartphones and vehicles, the platform can achieve high accuracy and coverage without dedicated sensors on every mile [3].

Privacy and Data Volume: Each vehicle need not transmit raw sensor traces (which are large); instead, the computation of roughness/potholes is preferably done on the device or in an edge unit in the car, and only summarized results are sent. This reduces bandwidth. Also, to address privacy, data can be anonymized – only the road information is relevant, not who collected it.

Open Access to Data: The aggregated road profile map would be accessible to vehicles querying for upcoming road conditions. This could be done via a standard API. For example, a vehicle could request: "give me the roughness and anomaly data for the next 5 km of my planned route." The cloud responds with a segmented profile. This *cloud-to-vehicle communication* allows each equipped car to download the needed road profile information ahead.

Such cloud-based models have been demonstrated in research projects. In a 2015 system called *Roadroid*, smartphone roughness data was uploaded to a server and integrated into a web-based GIS map for road managers [7]. The data was transmitted via web service to an internet server with spatial filtering, and could then be exported or visualized. Similarly, the Carbin app uploads user-collected road roughness to a public map (e.g., the fixmyroad.us platform) [2]. These examples prove the feasibility of large-scale, low-cost road monitoring through the cloud.

In our framework, the cloud not only gathers data but also acts as a *computation hub* if needed – for example, running heavy algorithms like retraining a machine learning model for pothole detection using all data. The system would deploy the updated models to the vehicles as examples for improving their detection capabilities.

To summarize, the crowdsourcing model provides a live road profile database. Now, given that a vehicle can know in advance the condition of the road ahead, we move to the core of the work: planning the optimal speed.

4 SPEED OPTIMIZATION MODEL FOR COMFORT AND FUEL EFFICIENCY

With road profile information at hand, the vehicle faces the decision of how fast to drive on each road segment. The problem is inherently a *multi-objective optimization:* higher speeds help reduce travel time, but on rough roads, high speed magnifies vibrations (reducing comfort) and can also increase fuel consumption disproportionately [8]. We formulate a theoretical model for *optimal speed planning* that balances these factors.

Objective Functions: The two primary objectives are:

1. **Ride Comfort:** We quantify ride comfort in terms of vehicle vertical acceleration (and perhaps jerk) experienced by passengers. A common measure is the *RMS of vertical acceleration* over a period, or specific frequency-weighted accelerations as per ISO 2631 (human comfort standard). For simplicity, one can assume the *vertical acceleration amplitude grows with speed on a given rough road* – if you go twice as fast over a bump, the impact is sharper and the acceleration peak is higher. We denote a discomfort cost $J_{Discomfort}(v)$ that increases with velocity v on a rough segment. For example, $J_{Discomfort}$ could be proportional to $v^2 \cdot roughness$, based on the idea that suspension deflection velocity increases with v. The goal is to minimize this discomfort. In multi-objective terms, we seek to minimize the peak/total acceleration [9].
2. **Fuel Consumption:** Fuel usage per distance is generally a function $f(v)$ that has an optimum at a moderate speed and rises at very low or very high speeds (due to engine inefficiency and aerodynamic drag, respectively). Additionally, on rough roads, fuel consumption increases due to energy dissipated in the suspension and tire deformation. Empirical studies correlate higher IRI with higher fuel use for the same speed [2]. Our model incorporates a fuel cost $J_{FuelCost}(v)$, which represents fuel burned per meter at speed v on a given road segment. On smooth pavement, $J_{FuelCost}(v)$ might be lowest at, say, 60 km/h, and higher if we go slower or faster. On rough pavement, $J_{FuelCost}(v)$ is effectively increased (i.e., a roughness factor multiplies the rolling resistance).

We can combine these into a single composite cost (with a weighting factor to adjust the trade-off) or treat it as a Pareto optimization to find a set of speed choices that are efficient in both metrics. A simple weighted sum objective could be: $J(v(x))=\alpha \cdot J_{Discomfort}(v(x))+\beta \cdot J_{FuelCost}(v(x))$, integrated over the route. Here $v(x)$ is the speed as a function of position x (or time), and α, β weigh the importance of comfort vs fuel. In an extreme case, $\alpha=1$, $\beta=0$ yields a pure comfort optimization (perhaps for a luxury autonomous shuttle in "comfort mode"), whereas $\alpha=0$, $\beta=1$ yields a pure eco-driving optimization (e.g., a freight truck saving fuel).

Constraints: The optimization must respect several real-world constraints:

- **Speed Limits:** Obviously, $v(x)$ cannot exceed the legal speed limit of that road, or a lower limit set by traffic regulations and conditions. Let $v_{max}(x)$ be the allowed maximum at position x (this could vary if, for example, there's a sharp curve or an urban area).
- **Safety Constraints:** Apart from legal limits, safety may dictate lower speeds on certain road geometries (sharp curves, steep downhill). If the road profile includes curvature data, lateral acceleration limits might impose a speed cap on curves. Similarly, if a pothole is extremely severe, there might be a recommended maximum speed to avoid damage (this could be an input from the cloud if the pothole is flagged as hazardous).
- **Vehicle Dynamics Constraints:** The vehicle cannot change speed instantaneously. There are limits on acceleration and deceleration (due to engine power and brake capabilities, as well as passenger comfort limits on jerk). Thus, if an optimal plan says to slow

to 30 km/h for a rough patch then resume 50 km/h, the plan must allow adequate distance for braking and accelerating smoothly. This can be formulated as constraints on *dv/dt* (acceleration) or distance to change speed.

- **Traffic Conditions:** While not the focus here, in practice one must consider other vehicles. In an autonomous scenario, if traffic is flowing faster or slower, the ego vehicle's speed plan might be influenced by a need to keep up or avoid collisions. For the theoretical model, we assume an isolated vehicle or that traffic is sparse enough to follow the optimal profile (this could be applicable in a connected platoon all using similar optimization).

Optimization Approach: This can be handled as an optimal control problem or a dynamic programming problem along the route. One strategy is to break the route into sections (each section being almost equal in roughness and of a certain length) and then determine the best speed for each section. Transitions between segments must not exceed acceleration limits. This is similar to a shortest path problem in which the cost of each segment is a function of the speed chosen in that segment and the state (speed) entering the next segment. A dynamic programming algorithm or Pontryagin's minimum principle could determine the speed profile that results in the least total cost.

In simpler terms, for each segment of road:

- If the segment is rough (high roughness index), the algorithm will prefer a lower speed to reduce vibration cost.
- If the segment is smooth, a higher speed is okay provided it doesn't affect the fuel consumption too much.
- If a segment is uphill (we could also include the road grade from maps), it may increase the fuel cost at higher speeds, etc.
- The algorithm might choose to slow down before a very rough patch (to avoid a spike in discomfort) and then speed up after that. This is like the reasoning that people employ when slowing down for a speed hump and then picking up speed.

Multi-objective optimal speed planning for comfort has been studied in some cases. For example, Zhou et al. (2021) obtained the optimal speed of a vehicle when passing over a speed hump using a full-car model and optimizing a combination of vertical displacement and acceleration [9]. They supposed the road profile (hump) is given and calculated that there is a certain speed at which the impact is minimum, using Pareto optimization on comfort criteria [9]. The results of this study show that the idea of an optimal speed for comfort is correct – too fast or even too slow can sometimes make the ride worse and that there is an intermediate velocity at which the bump disturbance is minimal [9]. In our case, we generalize this idea to any irregularities and take into account the fuel consumption.

Fuel-Comfort Trade-off: In some instances, the best answer may be a middle ground. For instance, consider a moderately rough road. Reducing the speed will enhance the comfort in a linear manner but may lead to an increase in fuel consumption if the speed is lowered beyond the optimal range of the engine (for a combustion engine, driving at very low speed in a low gear may be bad on fuel). On the other hand, going very fast increases drag and also bangs the car around, which costs both fuel and comfort. Hence the optimization may determine a particular speed that provides a good comfort and reasonable fuel consumption. This is similar to driving at the "most economical speed" which for many cars is in the range of 50–70 km/h [10], but in this case, it is adapted to the road roughness. On rugged terrain, the most efficient speed is likely to be lower because the additional fuel required to combat vibrations at high speed is substantial.

Output: The result of the optimization is a speed profile, which is recommended speeds for the upcoming road sections. This can be presented in the form of a sequence, for instance, 60 km/h for the next 200 m (smooth), then 40 km/h for the next 100 m (rough patch), and so on. In an online implementation, the system could be recalculated frequently as the vehicle moves and new data is available (especially if traffic or other conditions cause deviations).

5 AUTONOMOUS AND ADAS IMPLEMENTATION

The speed planning system will be implemented in a different way depending on the degree of automation of the vehicle:

- **Autonomous Vehicles:** An autonomous car that has this system installed in it will use the cloud-downloaded road profile data as an input to its motion planning module. Most of the time, autonomous vehicles also plan speed profiles to adhere to speed limits, maintain safe distances and react to traffic lights. The *road-adaptive speed planner* would add an additional criterion: Any rough road segments in the road ahead reduce the planned speed of the vehicle. For instance, if 200 meters to the front the map shows several potholes or a high roughness value, the autonomous vehicle will slow down a bit and prepare for that section, drive through it comfortably and then pick up speed again. This is similar to how a very attentive human driver would slow for a rough section or how off-road drivers soften tires and reduce speed on washboard roads. The autonomous system can do it with precision and consistency. Furthermore, an autonomous vehicle could co-ordinate this with its *active suspension* if available – for instance, reduce the speed and softening of the suspension to get maximum comfort.
- **Advanced Driver-Assistance Systems (ADAS):** For human-driven cars, several ways of implementation are possible:
  - ***Advisory System****:* The most basic one is a *driver advisory*, where the car's dashboard or navigation system shows suggested speeds or warnings: "Rough road ahead, recommended speed 30 km/h for comfort." The driver then decides whether to follow it. This is somewhat like the navigation systems telling the driver to slow down for a school zone or to turn for a sharp bend, but here it is based on road surface.
  - ***Adaptive Cruise Control (ACC)*** *Enhancement:* An ACC system could automatically adjust its set speed when roughness info is available. If the driver sets the cruise at 100 km/h on a highway but 1 km ahead a very rough bridge expansion joint is known, the ACC could temporarily slow to, say, 90 km/h to mitigate the bump impact, then resume 100 km/h. All without driver intervention, as long as the driver has enabled such a comfort-optimal mode.
  - ***Active Suspension vs. Speed****:* Some luxury vehicles already have *road preview suspension*, using cameras or sensors to detect bumps and instantly adjust suspension stiffness [11]. Our approach is akin to that but acting on speed. In cars without expensive active suspension, adjusting speed is a viable way to "absorb" a bump by simply not hitting it so hard. A semi-autonomous ADAS could combine both: slightly loosen suspension and reduce speed proactively.

- ***Integration with Navigation and Routing***: On a higher level, if the system knows certain roads are extremely rough, it could even suggest an alternate route (trading a longer distance for smoother pavement and better fuel economy). This goes beyond speed on a given road to route optimization, which is an added benefit. Many current navigation systems allow options like "avoid unpaved roads" – in the future, they could consider "avoid very rough roads" if the data is available.

Human Factors: In ADAS use, care must be taken in how speed changes are implemented so as not to surprise the driver or conflict with their expectations. The system should likely operate only when cruise control is on (so the driver has effectively delegated speed control). Sudden deceleration for comfort might confuse a driver if they don't know why it's happening; thus the HMI (human-machine interface) should communicate the reason ("Slowing for poor road surface"). Alternatively, haptic feedback could encourage manual drivers – e.g., a slight resistance on the accelerator pedal when the system thinks you should slow down (some cars do this for speed limit assist). The driver can override, but it nudges towards the optimal behavior.

Safety Considerations: Reducing speed for comfort should not compromise safety. The system will always respect that safety comes first – e.g., it won't slow the car below the speed of surrounding traffic on a highway in a manner that could cause a hazard. It's primarily meant for situations where the driver would benefit from slowing anyway. If a road hazard is severe (like a deep pothole that could cause damage), the system essentially acts as a safety system too by ensuring a safe speed. In that sense, it overlaps with hazard detection warnings – a pothole map from the cloud could prevent wheel damage if acted upon.

Vehicle Communication: Vehicles under V2X connectivity can distribute safety warnings through direct communication between them. The cloud model currently provides extensive data sharing but vehicles equipped with this technology can broadcast real-time speed adjustment alerts to following cars after detecting an unexpected leading vehicle bump. The speed planning becomes more effective when vehicles share warnings through this system even when all bumps have not been mapped.

The deployment of this system across autonomous systems and ADAS platforms would produce major ride quality improvements. Self-driving taxis that use this system would provide passengers with a smoother ride by minimizing bumps which reduces motion sickness symptoms. Although individual rough patches may not produce significant fuel savings the combined effect of optimal speeds and drag reduction and braking control leads to substantial efficiency gains particularly in heavy vehicles operating over long distances. Society would gain from widespread adoption because many vehicles that optimize speed would produce uniform traffic flow and reduced road wear due to lower impact forces on pavement caused by slower speeds over bumps.

6 REFERENCES

[1] T. L. B. &. W. Y. D. Nguyen, "Response-based methods to measure road surface irregularity: A state-of-the-art review.," European Transport Research Review, 11(1), 43, p. 1, 2019.

[2] Logan, "Crowdsourcing data on road quality and excess fuel consumption," MIT News, 14 May 2021. [Online]. Available: https://news.mit.edu/2021/crowdsourcing-road-quality-and-excess-fuel-consumption-0514.

[3] M. A. A.-K. a. A. M. A.-K. N. A. Al-Masaeed, "A comprehensive review of smartphone and other device-based techniques for road surface monitoring," Eng., vol. 5, no. 4, p. 3422, 2024.
[4] M. W. S. a. S. M. Karamihas, The Little Book of Profiling: Basic Information About Measuring and Interpreting Road Profiles, Ann Arbor: MI: University of Michigan Transportation Research Institute, 1998.
[5] M. A. S. T. A. L. R. M. A. V. a. A. B. D. K. Harris, "Crowdsourced road surface condition monitoring: A review of current trends and future directions," Computers, Environment and Urban Systems, vol. 69, no. May, pp. 51-62, 2018.
[6] S. L. a. M. C. S. Sattar, "Road surface monitoring using smartphone sensors: A review," Sensors, vol. 18, no. 11, p. 3845, 2018.
[7] L. F. a. H. Jones, "Roadroid: Continuous road condition monitoring with mart phones," Journal of Civil Engineering and Architecture, vol. 9, pp. 485-496, 2015.
[8] E. A. J. R. F.-J. U. M. T. a. A. L. M. Botshekan, "Smartphone-enabled road condition monitoring: from accelerations to road roughness and excess energy dissipation," Proc. R. Soc. A, vol. 477, no. 2246, p. 20200701, 2021.
[9] H. M. Y. W. a. S. C. G.-F. Zhou, "Vehicle velocity optimization for ride comfort improvement of automated driving in speed hump conditions," IFAC-PapersOnLine, vol. 54, no. 10, p. 410–417, 2021.
[10] C. C. T. A. Care, "10 Fuel-Saving Tips for Drivers To Maximize Mileage," Crown City Tire Auto Care, 31 May 2024. [Online]. Available: https://www.crowncitytire.com/10-fuel-saving-tips-for-drivers-to- maximize- mileage.
[11] J. M. Gitlin, "The Lincoln Aviator uses cameras to read the road, smooth out big potholes," Ars Technica, 22 Jun. 2019. [Online]. Available: https://arstechnica.com/cars/2019/07/the-lincoln-aviator-uses-cameras-to-read- the-road-smooth-out-big-potholes/.