

Automatic Dynamic Headlamp Leveling utilizing Camera-based Vehicle Pitch Detection

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Abstract

The optimal setting of the low beam's viewing range, which is mostly influenced by the angle of the vertical cut-off line, plays a crucial role in ensuring safe and comfortable driving at night. However, despite the initial headlamp aiming process in the factory or workshop, the actual vehicle's pitch angle in operation, and consequently its light output angle, is subject to constant changes due to loading, propulsion dynamics or road excitation. Their compensation is referred to as "Headlamp Leveling". The European Union mandates the compensation of load-induced changes to a vehicle's pitch angle, highlighting the importance of accurate headlamp leveling. Ford has developed and, in 2024, introduced an innovative camera-based automatic dynamic leveling system which uses the Advanced Driver Assistance Systems (ADAS) camera to observe the environment and measure the vehicle's pitch angle in real-time. By leveraging the existing ADAS camera, this system provides a contactless in-situ measurement of the body's angle over ground, eliminating the need for dedicated travel or angle transducers. This contribution provides an in-depth examination of the camera-based leveling system, outlining its operating principle and key aspects, and presents measurement results that demonstrate the high level of precision that can be attained using this approach.

Keywords: *Automatic Headlamp Leveling, Vehicle Pitch Measurement, Smart Sensor*



1. Introduction

1.1 Headlamp Aiming and Headlamp Leveling

The viewing range available to a driver at night can vary significantly due to headlamp setting, load condition, and dynamic influences, which can compromise road safety. For a given headlamp, the vertical light output angle of the vehicle's low beam (also dipped beam), more specifically the vertical cut-off line over ground, is the primary factor determining the viewing range. This angle is often expressed in terms of a slope i , which is typically very flat ($\sim 1\%$) for a passenger car. Proper adjustment of the headlamp is therefore an essential prerequisite for safe and comfortable driving at night, as misalignment can significantly reduce the viewing range. To address this issue, a process referred to as "Headlamp Aiming" is performed at the end of the factory line or in a workshop as part of a service action. It establishes an initial baseline for the vertical light output by compensating manufacturing and assembly tolerances.

In contrast to this static process, "Headlamp Leveling" involves the continuous compensation of all subsequent changes of the vehicle pitch that consequently would change the light output angle relative to this initial target state. These operational pitch changes can be caused by loading, propulsion dynamics, or road excitation. In widespread applications, Headlamp Leveling involves mechanically rotating the frame carrying the module that generates the light output, using a motor. This process intends to compensate for measurable deviations of the vehicle's condition in operation from its nominal conditions set at the point of aiming, ensuring optimal headlamp performance and road safety.

1.2 Factors Affecting Headlamp Leveling

The following section will explore the primary factors that affect the vehicle's pitch and consequently impact the light output generated by the low beam. It will first address static pitch changes due to loading and then provide an overview of the effects of vehicle dynamics.

1.21 Effect of loading conditions

The change of the vehicle pitch induced by changes of passengers and/or load typically ranges from a baseline of 0° (e.g., driver only, unladen) to approximately -1.5° (vehicle nose up) for a typical passenger vehicle, corresponding to a substantial upward deviation of the light beam's effective inclination from its target (e.g., a change of inclination from 0% up to 2.6%).

The precise magnitude of this pitch alteration is highly sensitive to the distribution of the applied load: while the presence of a driver and front passenger, often situated near the vehicle's wheelbase center, may have a relatively minor impact, the addition of passengers in the rear seats induces a more noticeable pitch effect. Load placed within the trunk,

however, typically exerts the most significant influence due to its positioning aft of the rear axle, maximizing leverage. Indeed, the extreme pitch scenario for many passenger vehicles, reaching approximately -1.5° for the mentioned typical passenger vehicle, is often realized under "load case 6" as defined in UN ECE R48 homologation testing, which involves loading the trunk to the maximum permissible rear axle weight while all passenger seats, including those in the rear, remain unoccupied.

1.22 Effect of dynamic conditions

Beyond the quasi-static changes induced by passengers / loading, the vehicle pitch is also subject to significant, albeit transient, variations arising from longitudinal vehicle dynamics, particularly during acceleration and braking maneuvers.

For the example vehicle, acceleration events can induce a transient upward pitch (nose up) of up to approximately -1.5° or -2.61% , while hard braking can precipitate a downward pitch (nose down) of up to 1° or 1.74% . These differing pitch responses under dynamic conditions arise from, e.g., the achievable rates of positive and negative longitudinal acceleration or physical limitations, such as bump stops, which may prevent excessive brake dive. Such dynamic pitch deviations can cause the low beam to project above the horizontal plane, thereby glaring other road users. This regularly happens in everyday traffic situations, e.g. when vehicles accelerate from a standstill at traffic lights. Even low-powered vehicles can generate significant dynamic pitch changes in these situations.

1.3 Regulatory Requirements for Headlamp Leveling

Headlamp leveling systems are not universally mandated in all markets (e.g., under FMVSS and CMVSS in North America), but within the European Union the UN ECE Regulation No. 48 (UN ECE R48) [1] serves as the principal standard defining requirements for these systems. This regulation directly links the permissible vertical inclination of the dipped beam to the headlamp's mounting height (h) above the ground. For vehicles with a headlamp mounting height $h < 0.8\text{m}$, such as the exemplary, typical passenger car, UN ECE R48 typically sets the following limits:

- general inclination limit -0.5% and -2.5%
- initial aiming -1.0% to -1.5%

Under UN ECE R48, a headlamp leveling device is not universally mandated for all vehicles. The fundamental compliance criterion dictates that as long as a vehicle's dipped beam, with or without a leveling device, remains within the prescribed inclination limits under specified load conditions, it meets the regulation. If, without further compensatory measures, a specific vehicle model cannot inherently satisfy this criterion across all load conditions, then the inclusion of a headlamp leveling device becomes a prerequisite for that

vehicle to achieve homologation. This is typically the case for passenger vehicles like pointed out in the previous sections.

UN ECE R48 currently requires that a leveling device must be fully automatic if it is required. An exception to this requirement, however, applies to headlamps where the objective luminous flux of the modules producing the dipped beam does not exceed 2000 lumens. In such cases, the headlamp can alternatively be set manually by the driver, who is then responsible for selecting a suitable leveling value from a range of preset options that corresponds to the current load condition of the vehicle. In contrast to this, vehicles equipped with Advanced Front-lighting Systems (AFS), which are regulated under UN ECE R123 [2], the associated leveling devices are required to function automatically, without exception.

1.31 Change to UN ECE R48

The mentioned regulatory requirements will be updated with revision 09 of UN ECE R48. Figure 1 shows the timeline for the integration of this update. From September 2027 onwards, the exception permitting the use of manual headlamp adjustment will expire, leading to all headlamp leveling systems integrated into passenger vehicles marketed within the European Union will be required to operate fully automatic. The rollout of this more stringent requirement is scheduled to affect new vehicle type approvals beginning September 2027, and will apply to all new vehicle registrations from September 2030.



Figure 1: Timeline for introduction of revision 09 of UN ECE R48

All of this give strong reasons to rethink common headlamp leveling systems and how to sense vehicle pitch. This need pushes the search for new methods that meet future demands in price sensitives categories.

2. Working Principles of Automatic Dynamic Leveling

For clarity and precision, a more detailed definition of vehicle pitch is necessary, as it is a critical parameter in understanding the behavior of headlamp leveling systems. The term vehicle pitch (φ) refers to the general, instantaneous vehicle pitch over ground, which is constantly changing due to various factors (see Figure 2).

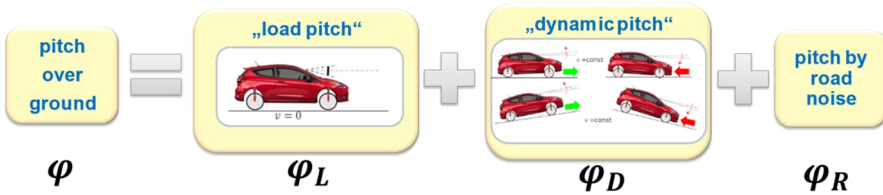


Figure 2: Breakdown of Pitch Over Ground into Load Pitch, Dynamic Pitch and Pitch by Road Noise

The concept of vehicle pitch can be broken down into several components, each with its own distinct characteristics and effects on the vehicle's pitch. Zero vehicle pitch is defined as the vehicle pitch over ground in a reference condition, such as the pitch of the unladen vehicle at the point of aiming. This reference point serves as a baseline for measuring changes in vehicle pitch caused by various factors, including load pitch, dynamic pitch, and road input.

Load pitch (φ_L) is a critical component of vehicle pitch, referring to the pitch deviation from zero caused by vehicle load. It is a quasi-constant or slowly changing parameter in practice, although it can change when the vehicle load condition is altered. Load pitch is typically measured at standstill and on level ground, which is the same condition used for homologation-related measurements.

In addition to load pitch, dynamic pitch (φ_D) is another important component of vehicle pitch, caused by forces and torques resulting from propulsion dynamics such as braking and acceleration.

Finally, road input (φ_R) is a component of vehicle pitch caused by road noise and other external factors, which can introduce random noise and movements into the vehicle's behavior. While road noise is considered to be zero on average in this contribution, it is essential to recognize that this assumption may not hold true for arbitrarily short time frames.

2.1 Mechanical Pitch Sensing

Many Original Equipment Manufacturers (OEMs), including Ford, commonly use mechanical sensors to determine vehicle pitch. These sensors measure how much the suspension moves, typically with one sensor at the front axle and another at the rear. Then, the vehicle's pitch angle is derived by dividing the differential measurement from the axle sensors by the known vehicle wheelbase. A notable advantage of this mechanical sensing approach is its direct applicability in static conditions, such as during homologation, where it directly provides the static load pitch component (φ_L) because pitch due to road noise (φ_R) and dynamic pitch (φ_D) are zero by definition.

A fundamental and inherent limitation of conventional mechanical headlamp leveling systems is their inability to account for the influence of tire characteristics – such as variations in pressure or the progressive effects of wear – on the vehicle's effective height and, consequently, its true pitch angle relative to the ground. This deficit arises because their measurement of suspension deflection typically occurs between the vehicle chassis and a suspension control arm, inherently bypassing any alterations in the tire's effective rolling radius or overall state. As a result, changes in the tire's contribution to the vehicle's stance are not captured by this sensing method.

In addition, such mechanical systems often create a number of operational challenges. These include difficulties related to their physical integration, such as demanding packaging requirements for adequate space, intricate wiring, and the necessity for robust protection against harsh environmental influences, all of which can contribute significantly to overall system cost and complexity.

2.2 Camera-based Pitch Sensing

In 2024, Ford launched its first vehicle model with a camera-based dynamic headlamp leveling system. This new system is used as an alternative to traditional systems that need separate mechanical sensors to figure out the vehicle's pitch. In the rest of this paper, the basic way this system measures pitch is explained.

The inherent principle of camera systems make them well-suited for angular measurements, a principle illustrated by the widely recognized pinhole camera model. Fundamentally, in this principle, each pixel on the camera sensor corresponds to a defined angle of incoming light it observes (see Figure 3).

Consequently, once an object is detected within the image space, its angle relative to the camera's optical centerline becomes known. For the specific application of headlamp leveling, the "object" of interest for angular measurement is the horizon line, which is defined as the locus of points within the image that correspond to light rays arriving parallel to the ground level.

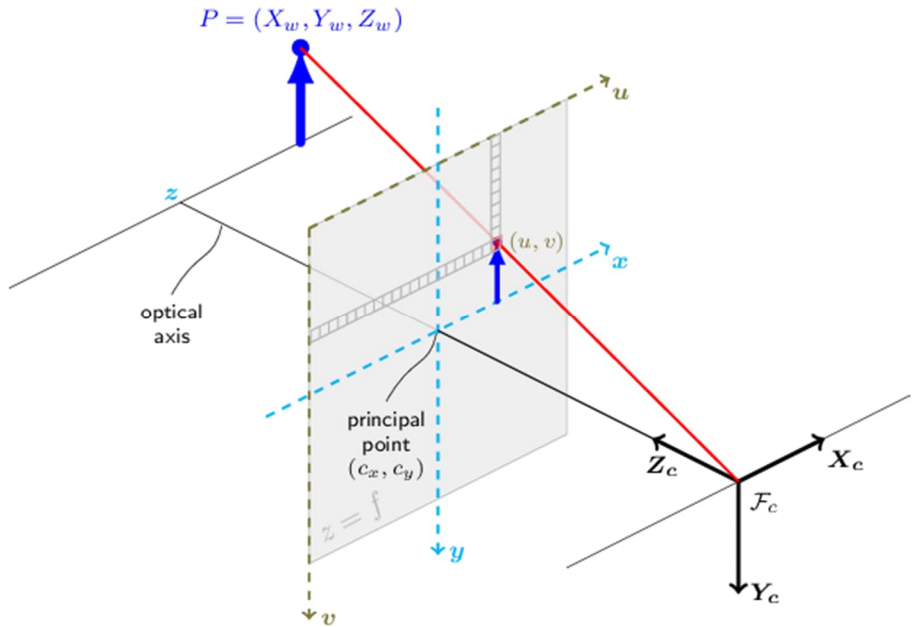


Figure 3: Principle of the Pinhole Camera [3]

Measuring the apparent position of the horizon line while driving and comparing it to a pre-established calibration or reference state directly reveals any change in the vehicle's pitch angle; for instance, if the horizon during a drive appears at a lower location within the image than expected for the calibration state, this signifies that the vehicle has pitched upwards. However, the simplistic notion of "detecting" the horizon by merely recognizing it within a single image frame, while feasible for idealized scenarios like a perfectly straight and level road, proves inadequate for application in more general and dynamic driving conditions. For example, while on a straight road, the horizon might be inferred from the visual transition between ground and sky, this method fails where such visual cues are absent, such as during nighttime when clear sky-ground transitions are not visible.

To overcome this limitation, a more robust approach to horizon detection during driving does not rely on identifying the horizon in a single static image but rather determines it from analyzing a sequence of images where the movement of objects or distinct visual features across these successive frames is tracked (see Figure 4).

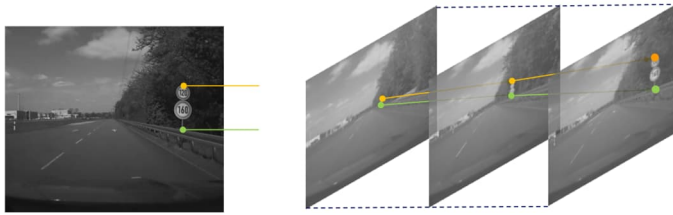


Figure 4: Object movement within a series of images

The underlying principle of this dynamic detection method is that the true horizon within the image corresponds to the location towards which the vehicle, and specifically its camera, is moving – often referred to as the focus of expansion. This focus of expansion is identified by observing optical flow patterns: as the vehicle moves forward, objects located above the camera's height will appear to travel towards the top of the image, objects below camera height will travel towards the bottom, while objects directly on the path towards the horizon will appear relatively static or expand outwards from this point (see Figure 4). This requires that the vehicle's orientation is steady compared to ground which, in reality, does not apply (e.g. accelerating, driving on a slope). But it can be assumed that the angular pitch movement with respect to ground zero on average unless the vehicle load is changed. In the context of a camera-based leveling system, detecting the horizon during drive means identifying the average focus of expansion from a sequence of images.

This results in the following points that need to be considered for the operation strategy:

- detection only operates when driving
- measurement results from a set of images (not only from a single frame)
- images must be collected in a representative state where vehicle dynamics do not exceed specific thresholds

3. Effects of vehicle dynamics on the horizon detection during drive

By respecting the beforementioned points regarding the operation strategy, a closer look into measurements shall be taken that were recorded during a road test drive in the Austrian alps.

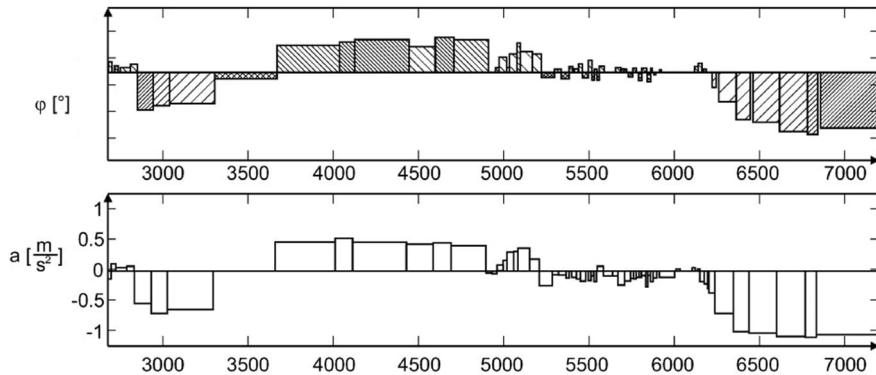


Figure 5: Road test drive measurements a) resulting measurements of the camera-based vehicle pitch vs. reference pitch b) average acceleration of the vehicle during the timeframe of respective measurements [4]

Figure 5 a) shows the measurements of the pitch angle by the ADAS camera versus the reference pitch. Data collection depends on the vehicle to be in a defined, representative state that is suitable for measurements. This consequently leads to varying times for data collection. Significant variations can be seen between the individual measurement results compared to the reference pitch. These variations would already take up a large portion of the admissible tolerance range presented in Section 1.3.

To better understand the reason for these variations, the average measurement of the vehicle's acceleration sensor output during the time of the camera pitch measurement was calculated. As depicted in Figure 5 b) the results of both sensor inputs highly correlate to each other. In combination with knowledge of the terrain during the road test, the results can be explained by the following: When driving uphill, additional propulsion forces are needed to overcome gravity which result in the vehicle's nose pitching upwards (pitch measurements were smaller). And, consequently, when driving downhill, constant speed can be achieved by less propulsion forces or even applying brake forces, leading to the vehicle's nose being lower than expected.

This results in the following findings for a camera-based leveling system:

- Visual measurements are systematically influenced by the dynamic pitch and need to be compensated to determine the pitch resulting from vehicle load
- Acceleration measurements are suitable to determine the dynamic pitch and compensate the camera measurement; to do so, a model which describes the dynamic behavior of the specific vehicle for measured accelerations is required
- The correlation observed between the camera's pitch measurements and the average longitudinal acceleration during the corresponding measurement periods demonstrates the ADAS camera's capability to provide reliable and precise inputs for headlamp leveling systems once the dynamic effects are compensated

4. Summary and conclusion

The headlamp leveling system described in this paper offers a new way to adjust headlamps without directly measuring suspension movement by using mechanical sensor. Instead, it utilizes the vehicle's existing ADAS camera to accurately determine the vehicle's pitch relative to the ground. An advantage of this camera-based method is that it also considers how tire conditions, like air pressure changes or wear, affect the vehicle's pitch. This approach leads to an accurate leveling system that also uses already existing vehicle hardware.

5. References

- [1] UN/ECE Regulation No 48 - Uniform provisions concerning the approval of vehicles with regard to the installation of lighting and light-signalling devices
- [2] UN/ECE Regulation No 123 - Uniform provisions concerning the approval of adaptive front-lighting systems (AFS) for motor vehicles
- [3] OpenCV Documentation, OpenCV: Camera Calibration and 3D Reconstruction. https://docs.opencv.org/4.x/d9/d0c/group__calib3d.html
- [4] M. Reiter, L. Lottner, and J. Glorer, "Camera-based Vehicle Pitch Detection for Automatic Dynamic Headlamp Leveling," presented at the 16th Int. Munich Chassis Symp. chassis.tech plus, Munich, Germany, June 3-4, 2025.