A Retrospective Study of Evolving Vehicle Architecture on Pitch and Vertical Kinematics using NHTSA Frontal Barrier Tests

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I. INTRODUCTION

Frontal collisions remain a primary cause of traffic fatalities in the United States, accounting for 63.4% of single- and two-vehicle crash fatalities in 2023 [1]. Frontal vehicle kinematics are primarily influenced by the frontal vehicle structure, the specific impact angle and pulse severity, and the vehicle's inertial properties. These kinematics, combined with the occupant's initial positioning and the performance of the restraint system, govern the response of the occupant and, consequently, the injury risk patterns. In severe impacts, excessive pitch can alter an occupant's trajectory, compromising intended head-to-airbag contact [2].

The principal dynamic responses in a frontal crash involve a coupling between vehicle pitch (rotation) and vertical displacement, both driven by the vehicle's inertial moment created during rapid deceleration. Traditional body-on-frame trucks and sport-utility vehicles (SUVs), characterized by a high center of gravity (CG) relative to the impact force, generate a large vertical lever arm that induces significant "nose-down" pitch [3]. Conversely, modern vehicles have undergone a fundamental redesign over the past years, driven by the rise of Hybrid and Electric Vehicles (H/EVs). H/EV architecture is distinct due to the replacement of the engine block with a heavy battery pack (400-550 kg), distributed low in the vehicle's floorpan. This architectural shift results in a lower and more centralized CG compared to traditional internal combustion engine vehicles. This study investigates the progression of vehicle pitch kinematics by analyzing 15 years of National Highway Traffic Safety Administration (NHTSA) frontal barrier crash tests, correlating observed dynamics with evolving architectural frameworks.

II. METHODS

Kinematic data were derived from the NHTSA crash test database filtered for frontal rigid barrier impacts (54–58 km/h), "vehicle into barrier" test configuration, impact angle of 0°, and vehicle model year from 2010-2025. Tracking of high-speed lateral videos at 1000 fps were taken with an orthogonal view to the direction of travel which was used to measure the vehicle's kinematics. Vehicle inertial properties, including center of gravity height, were obtained from the NHTSA New Car Assessment Program (NCAP) Static Stability Factor reports to correlate architectural features with observed dynamics. Tests not including these parameters were excluded from the study. The final dataset comprised 368 tests.

Fig. 1. 2D rigid body tracking methodology. Fiducial marker selection before and during the crash phase.

Vehicle motion was measured using the META Post-Processing Suite (BETA CAE Systems). Four fiducial markers were tracked on the vehicle cabin (Fig. 1), treating the occupant compartment as a 2D rigid body and avoiding deformation of the structures. Pixel-to-distance scaling was established via the known vehicle wheelbase. Coordinates were mapped to the SAE J1733 sign convention, where positive pitch denotes a "nose-up" rotation.

Vehicle pitch was determined by finding the optimal rotation of the fiducial marker rigid body via a 2D least-squares pose (LSP) estimator based on Singular Value Decomposition [4]. To account for minor out-of-plane

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motion, the LSP estimator distinguished true rotation from marker deformation, ensuring the rotation corresponds to the optimal planar fit. To ensure the accuracy of the rigid-body model, any frames with a root-mean-square deviation exceeding 5.0 mm were excluded. This threshold was used to filter out tracking errors and marker dropouts caused by video artifacts. All signals were filtered to CFC 60 (SAE J211). Time-alignment was achieved via barrier-contact detection, followed by Dynamic Time Warping of the velocity curve to ensure longitudinal comparability [5].

III. INITIAL FINDINGS

Pitch data was categorized into nose-down (n = 322) and nose-up (n = 46) groups. These categories showed a skewed representation of Internal Combustion (IC), Hybrid, and Battery Electric Vehicles (BEV). Specifically, the nose-down group comprised 91.3% of IC, while the nose-up group showed 32.6% of Hybrid and 4.3% of BEV. Nose-down rotation exhibited a range of peak rotation from 0 to -10°, while nose-up rotation ranged from 0 to 5°, with varying peak timing in both groups. The nose-down group showed a median CG height of 0.62 m, whereas the nose-up group showed a median of 0.56 m. Additionally, the lower CG height in the nose-up group reflects a more modern vehicle distribution, influenced by newer EV architecture (Fig 2.) Track width and longitudinal CG showed no observable correlation with pitch, while the influence of weight and wheelbase remained inconclusive (data not shown).

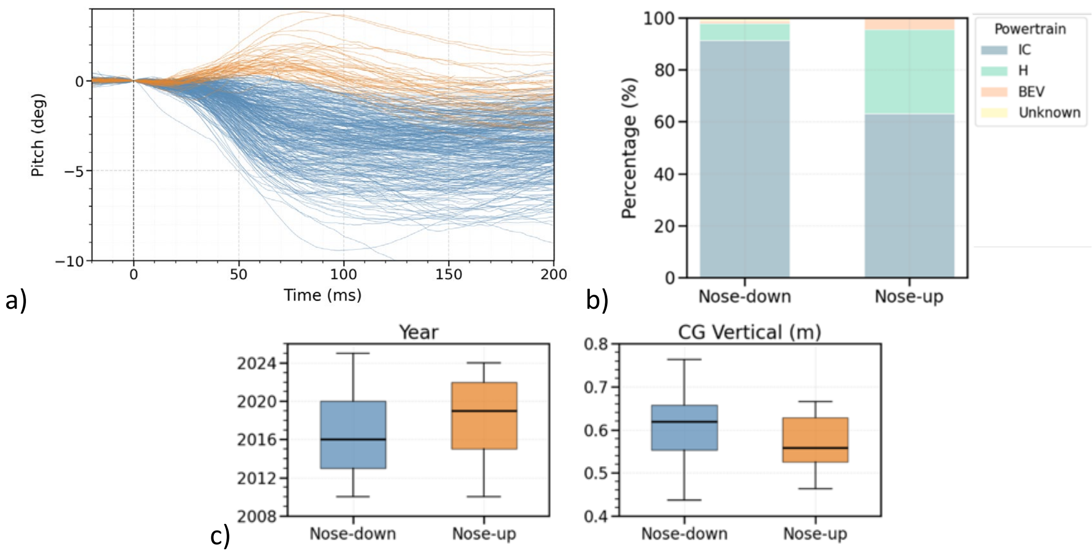

Fig. 1. Analysis of pitch dynamics and vehicle architecture. a) Time-series pitch data for nose-down (blue) and nose-up (orange) groups. b) Powertrain distribution across both pitch categories. c) Model year and CG height distributions highlight the shift toward modern, lower-CG architectures in the nose-up group.

IV. DISCUSSION

Preliminary data suggest that the transition from IC engines to a Hybrid or BEV architecture reflects a small shift in pitch dynamics from canonical nose-down towards nose-up rotation. Several matched pairs of similar vehicles showed a nose-up shift in pitch dynamics (e.g., 2013 Ford Focus, Test 8001, nose-down, h_{CG} = 0.56 m vs. BEV pair, Test 8081, nose-up, h_{CG}= 0.53 m). The observed inversion is likely driven by the reduction in group median CG height (0.62 m to 0.56 m), which alters the inertial moment relative to the pitch axis. However, this shift wasn't true for all vehicles such as a 2021 Toyota Prius (Test 11394, nose-down, h_{CG} = 0.54) whose rotation showed a pronounced nose-down rotation which may indicate that other vehicle architecture parameters may have a significant effect (e.g., front-end geometry). Nevertheless, such a shift in vehicle pitch may be critical for occupant safety, as it may fundamentally the timing of head-to-airbag engagement. Further work will assess the implications for occupant's injury risk for these vehicle dynamics.

V. REFERENCES

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