

# Preliminary Development of a Wrong Way Rumble Strip using Ultra High-Performance Concrete



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# Executive Summary

The study focuses on the development of a Wrong Way Rumble Strip (WWRS) using Ultra High-Performance Concrete (UHPC) to address the rise of wrong-way driving incidents in Connecticut. The preliminary WWRS design aimed to provide tactile and auditory feedback to drivers traveling in the wrong direction, thereby reducing the risk of crashes. The research in the study involved designing and testing various rumble strip geometries to maximize driver alertness through vibrations and noise upon incorrect travel. This study utilized finite element analysis to create three cross-sectional designs—triangular, curved, and trapezoidal—evaluating their performance in terms of vibration feedback at different vehicle speeds. The trapezoidal design was found to be most effective. Additionally, the project proposed a recessed rumble strip to avoid damage during snow clearing, addressing concerns common in snowy regions.

A literature review examined existing rumble strip designs and their effectiveness, highlighting that traditional and directional rumble strips often do not meet safety needs in snow-prone areas. The project methodology was divided into two phases: first, creating a numerical model to optimize the strip design, and second, physically testing the prototypes on a selected roadway. The testing involved measuring vehicle acceleration and noise levels as a sedan drove over the rumble strips in both correct and incorrect directions.

Results indicated that the designed rumble strips successfully produced higher accelerations and noise levels when vehicles traveled in the wrong direction compared to the correct direction, although the differences were not as pronounced as the model predicted. Furthermore, the study emphasized the need for more extensive testing and refinement of the rumble strip design to enhance its effectiveness in deterring wrong-way driving. Overall, the research suggests that while the concept of the asymmetric recessed rumble strip is valid, further development is necessary before implementation.

## 1. Introduction

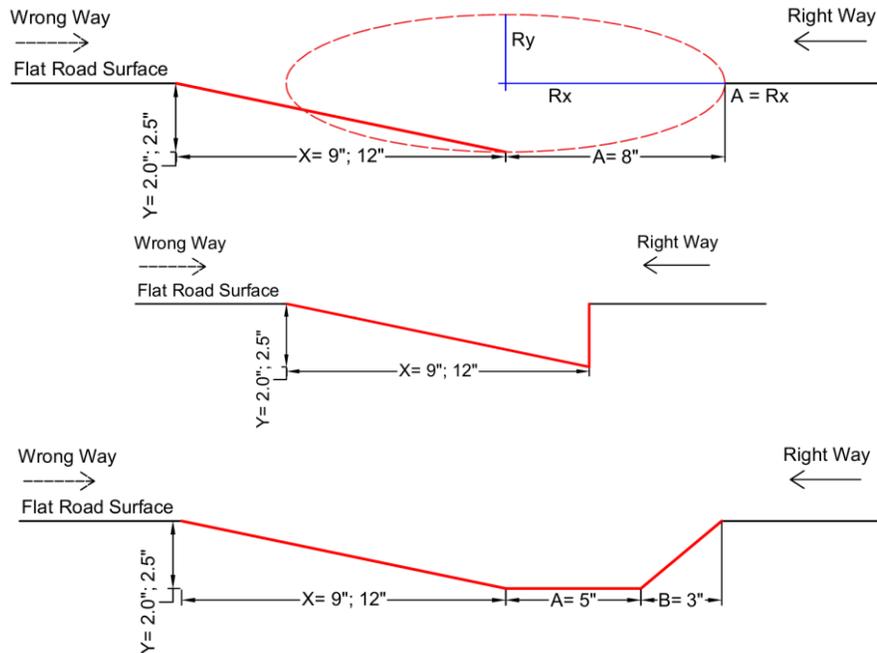
### 1.1. Background

On March 10, 2023 the Connecticut Department of Transportation hosted a press conference to draw attention to the dangers and current trends in wrong-way driving. Transportation Commissioner Garrett Eucalitto stated that “Wrong-way driving deaths in Connecticut are up 500% and we are doing everything we can to reverse these trends,” Wrong-way driving (WWD) crashes in Connecticut more than tripled in 2022 with 13 wrong-way crashes resulting in 23 deaths [1]. This is significantly higher when compared to average years, which experience 4 wrong-way crashes and less than 6 resulting fatalities annually. These collisions often occur at night or early morning and are often deadly due to higher speeds from vehicles traveling on an interstate in opposing directions.

WWD is the cause for about 1.5% of roadway fatalities, with 704 of 42,514 total roadway fatalities nationwide being associated with wrong-way driving in 2022 [2]. One of the critical locations for wrong-way driving incidents is the off-ramps on freeways. These locations can serve as a point where the driver can be made aware of their direction of travel, and potentially preempt these incidents. Even though WWD is a random event, the cause of such events and the characteristics of wrong-way drivers have

been quite extensively studied. Studies have shown that a significant portion of such drivers are found to be under the influence of drugs or alcohol and the crashes that are caused by relatively young and middle-aged drivers are mostly due to inattention [3]. If these inattentive drivers are made aware of this error, they will often correct themselves, thereby avoiding a major collision. Research has been carried out to find an effective measure to warn these drivers and some of the proposed techniques include use of signs, pavement markings and various other Intelligent Transportation Systems (ITS) [4]. However, these measures seem to be either economically unfeasible (e.g., ITS) or significantly ineffective (e.g., signs and markings). To overcome these issues, a new technique of transverse rumble strips (TRSs) has been proposed.

To alert drivers that they are traveling the wrong direction quickly and effectively while still at low to moderate speeds on the ramp, UConn has been working with a contractor to develop the Wrong Way Rumble Strip (WWRS). WWRSs are designed to alert a driver they are traveling the wrong direction through dynamic feedback in the form of vibration or noise when the vehicle is traveling in the wrong-way direction, while giving minimum feedback while traveling in the right-way direction. UConn funded a separate project to support the physical design of WWRS through finite element analysis to find an optimum rumble strip design that produces maximum vibration at driver's seat while driving in the wrong direction. Three rumble strip cross-sections were designed: triangular, curved, and trapezoidal as shown in Figure 1. Each of these cross-sections were analyzed for two lengths, 9 in and 12 in, and have a depth of 2 in and 2.5 in. A default sedan available in Adams/Car was made to ride over the rumble strips placed at one section of the road. The vehicle was run for four speeds: 10 mph, 20 mph, 30 mph and 45 mph in both right-way and wrong-way directions. The reaction of the vehicle in terms of acceleration at driver's seat and tire reaction forces for both the directions were analyzed. They found that a trapezoidal profile with minimum depth of 2 in and length of 12 in gave better results compared to the other shapes investigated.



*Figure 1. Cross Sections Developed using Finite Element Modeling. a) Circular, b) Triangular, c) Trapezoidal*

Currently, most directional rumble strips are raised from the surface of the pavement. While these have shown positive results in existing literature, this extruded design is infeasible in regions of the country that experience snow. This poses the issue of damage from snowplows during snow clearing operations. Therefore, a recessed rumble strip would be required as it would not be damaged during plowing operations.

This study builds on previous analytical work and aims to demonstrate a proof of concept for a post-installed precast recessed directional rumble strip. Additionally, it seeks to test whether vehicle acceleration and noise levels differ between right-way and wrong-way travel over the strip. It begins with a numerical model of the asymmetric recessed rumble strip to further refine the geometry of the rumble strip. Following the modeling, a final trial geometry was determined, and a negative made out of insulating foam to cast the rumble strips from UHPC. These were then physically tested to record accelerations and air pressures within the vehicle.

## 1.2. Literature Review

The existing literature on this subject is divided into four sections, detailing the literature related to traditional rumble strips, directional rumble strips, Ultra High-Performance Concrete, and numerical modeling techniques for vehicle suspension system modeling.

### 1.2.1. Traditional Rumble Strips

Donnell et al. (2009) delves into the various factors influencing the noise levels inside a vehicle when interacting with highway rumble strips. This research developed a statistical model using seemingly unrelated regression to analyze how rumble strip design factors like length, width, groove depth, and vehicle speed impact in-vehicle sound intensity, frequency, and duration [5]. The results suggest that larger rumble strips at higher vehicle speeds generally produce louder in-vehicle noises. The model also incorporates environmental factors such as pavement type and wetness, which affect the noise levels.

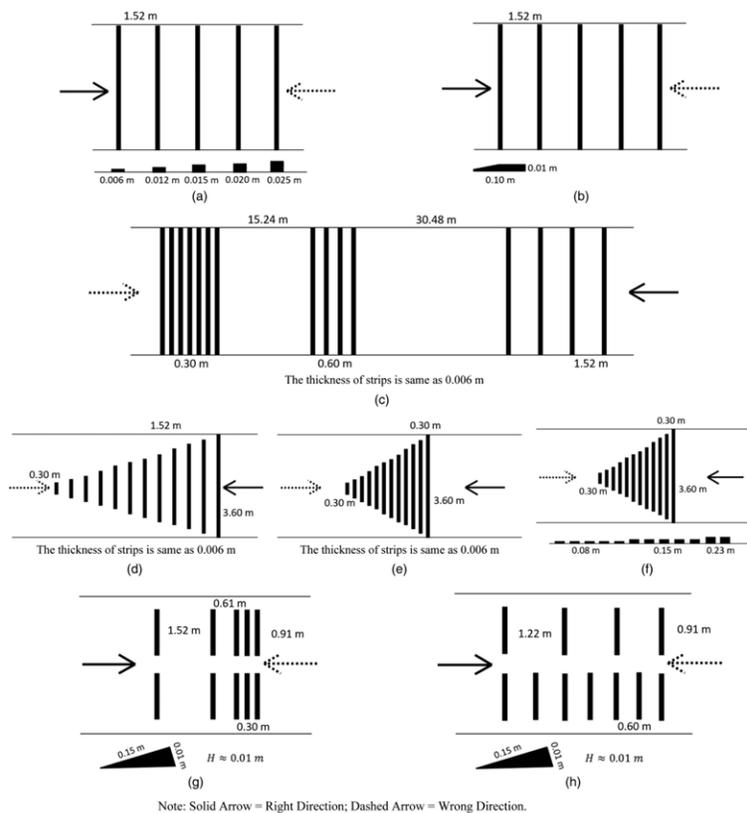
The Federal Highway Administration provides a guide focusing on addressing potential noise complaints and educating safety professionals related to rumble strips. The guide highlights the effectiveness of rumble strips in preventing roadway departures and discusses methods to mitigate noise concerns [6]. It details strategies like varying rumble strip placement and design to reduce external noise while maintaining safety features.

Oregon DOT explores the design of rumble strips with the intent of minimizing noise pollution while maintaining their safety features. Utilizing FEA, the study developed and tested 20 new rumble strip designs, with a focus on exterior noise levels [7]. The evaluation identified designs that effectively alert drivers through tactile and audible signals without causing excessive noise. The study analyzes the noise and vibration characteristics of conventional, sinusoidal, and sawtooth rumble strip designs under varying vehicle speeds for both passenger cars and trucks. The report provides a comprehensive analysis of how different dimensions and patterns of rumble strips affect the sound output levels [8]. It suggests that certain sinusoidal and sawtooth designs can significantly reduce external noise while still effectively alerting drivers.

Kasess et. al. (2021) investigates the impact of various design features of rumble strips on acoustic properties, vibrations, and human perception. The study evaluates 16 different types of rumble strips, including those with irregular spacing, and measures both interior and exterior noise levels as well as the effects on drivers of different vehicles [9]. The study confirms that the type of vehicle significantly influences the effectiveness of rumble strips in terms of noise generation and perception.

### 1.2.2. Directional Rumble Strips

Yang et. al. (2018) developed five conceptual DRS designs based on existing guidelines and tested them for efficacy in alerting drivers. The DRS patterns investigated are shown in Figure 2. Extensive field tests and a national survey involving transportation professionals assessed these designs' ability to produce noticeable vibrations and sound differentials between correct and incorrect driving directions [10]. Results indicated that certain DRS configurations effectively enhanced the auditory and tactile warnings for wrong-way drivers without disrupting right-way traffic, particularly DRS patterns C, D3, and E.



a) Pattern A, b) Pattern B, c) Pattern C, d) Pattern D1, e) Pattern D2, f) Pattern D3, g) Pattern E1, and h) Pattern E2

Figure 2. Directional Rumble Strip Configurations. [11]

Xue et. al. (2020) have published extensive work with regards to the practical application and effectiveness of Directional Rumble Strips (DRS) installed at high-risk freeway off-ramps to mitigate WWD incidents. Three specific DRS patterns (D3, C, and E2) were chosen following a series of designs and field tests, based on their ability to produce significant auditory and tactile warnings to drivers inadvertently entering an off-ramp in the wrong direction [11]. The study focuses on the implementation at two specific exits on I-65 in Alabama, assessing the patterns' effectiveness through comparative analysis of

WWD incidents and distances before and after DRS installation. The results showed a dramatic decrease in WWD occurrences by approximately 90% and a reduction in WWD travel distances by about 85%, emphasizing the success of the DRS in enhancing freeway safety.

The findings from Phase II from their project focused on the field verification of three specific DRS patterns (C, D3, and E1) that were optimized to produce distinct sounds and vibrations. These patterns are designed to alert wrong-way drivers by producing intense noise and vibrations while creating normal levels for right-way traffic [12]. The study concludes that these DRS are effective in deterring WWD and recommends specific implementations based on the type and length of off-ramps. It provides a practical guide for transportation agencies on how to install these rumble strips to maximize safety and reduce the incidence of wrong-way entries onto freeways. These three DRS patterns (D3, C, and E2) were then implemented at off-ramps on I-65 in Alabama [13]. The study aimed to deter wrong-way driving and control right-way traffic speeds. It found that DRS effectively reduced vehicle speeds, with significant decreases in off-ramp traffic speeds.

Luo, et. al. (2019) investigates the effectiveness of DRS in reducing wrong-way entries on freeways. A specific off-ramp on I-70 was chosen for field testing due to its high risk of WWD incidents [14]. The study implemented DRS pattern D3 [11], which is a triangular pattern of extruded rectangles from 1 in to 12 in wide 4 in long and 0.25 to 0.50 in tall. They found that DRS did not reduce the probability of WWD, it effectively warned drivers and decreased their speeds, which could significantly lower the risk of collisions.

All these studies on directional rumble strips involve patterns which extend above the roadway surface. This results in a design which would not be feasible in climates which experience snowfall and require plowing to remove the snow, as these extruded rumble strips will be vulnerable to plow blades and will be damaged resulting in damage to both the rumble strip, and the plow.

### 1.2.3. Ultra High-Performance Concrete

As these rumble strips will be used on highway off ramps, they will be exposed to a significant volume of traffic. This will require that they be resilient and be able to maintain their shape and not degrade from use or exposure to the weather. Bituminous asphalt is too soft and will deform during use. The continual pounding of the wheels will subject the rumble strip to damage and so the material should be able to take the continual impact loading. The recessed nature of the rumble strip will also hold water and potentially accelerate damage associated with freeze-thaw and so the material should be resilient to this type of exposure.

UHPC is a cementitious composite material with an optimized granular composition, a water-to-cement ratio below 0.25, and the inclusion of internal fiber reinforcement [15]. Compared to traditional concrete, UHPC demonstrates superior mechanical properties, including compressive strength exceeding 17,500 psi and post-cracking tensile strength greater than 750 psi [16]. The post-cracking tensile strength is largely due to the integration of small-diameter steel fibers within the mix [17]. UHPC boasts exceptional durability, as its dense microstructure and low permeability significantly enhance its resistance to environmental degradation, including freeze-thaw cycles, chemical attacks, and abrasion [18] [19]. This high durability positions UHPC as an ideal material for infrastructure subjected to harsh wearing conditions, such as those found on off ramps.

FHWA-HRT-14-084 Explores the use of UHPC for field-cast connections, particularly in bridge construction. This guide underscores UHPC's superior mechanical properties and durability, which make it ideal for applications demanding robust and long-lasting structural connections [20]. The guide offers comprehensive advice on design considerations, the integration of UHPC in field-cast connections, and practical guidance on construction techniques to maximize the performance benefits of UHPC.

FHWA-HRT-22-065 provides guidance on using UHPC for bridge preservation and repair. This report emphasizes the advantages of UHPC in extending the service life of bridges, noting its superior durability and cost-effectiveness compared to traditional materials. It includes specific recommendations for design and construction for bridge deck overlays [21]. The use of UHPC in bridge deck overlays is the closest equivalent to utilizing it as a precast insert for the roadway as is currently available in the literature.

The durability of UHPC is the key factor being considered in its use for this application. The low permeability allows the UHPC to withstand the loading and environmental factors. The fibers in the UHPC also increase the durability of the rumble strip from continued impact from vehicle tires. They also eliminate the need for shrinkage reinforcement which could pose a risk of corrosion.

#### 1.2.4. Suspension System Modeling

The modeling of vehicle suspension systems is crucial for improving rider comfort, which is directly influenced by how a vehicle responds to road irregularities. Speed bumps, as common road disturbances, present a unique challenge to suspension systems, and understanding how computational models handle these challenges provides valuable insights into selecting the best computational model to design and optimize the rumble strip.

##### *Passenger Comfort*

The use of numerical simulation to provide an analog to a vehicle's suspension system is not a new concept. Mucka (2018) presents a comprehensive study on the use of synthetic longitudinal road profiles in vibration analysis of vehicles and road-vehicle-driver interactions. It discusses the classification of road roughness as defined by ISO 8608, which categorizes roads based on the power spectral density of vertical displacements. The study highlights discrepancies between the road classes used in simulations and the actual road conditions, suggesting that simulations often use idealized road profiles that may not represent current road conditions accurately. It provides some details about using a quarter-car suspension model for simulation and analysis [22]. This model is applied to assess the impact of road profiles on vehicle dynamics, specifically focusing on how different road roughness classifications affect the vehicle's suspension system's response.

Du et al. (2012) explores an integrated control strategy for vehicle seat and suspension systems to improve ride comfort by reducing driver head acceleration under typical road disturbances. The study introduces an innovative model that integrates a quarter-car suspension system, seat suspension, and a four-degree-of-freedom driver body model. This model facilitates the development of an integrated control approach using H-infinity state feedback and static output feedback controllers, focusing on managing both the car suspension and seat suspension simultaneously [23].

Kuznetsov et. al. (2011) discusses optimizing the suspension system of a vehicle by incorporating biomechanical effects of the driver into the model. This research uses a quarter-car model to simulate

and optimize the suspension parameters to improve ride comfort as defined by ISO 2631, which relates to human exposure to vibration. The optimization considers various parameters such as spring stiffness and damping coefficients, which are critical in minimizing the adverse effects of road-induced vibrations [24].

#### *Effect of Modeling Parameters*

Chan et. al. (2003) provides a detailed parametric study of a bridge-vehicle interaction model which they previously developed. They focus on how varying parameters such as vehicle mass, speed, frequency ratio, and axle spacing impact the dynamic response of bridges when subjected to moving vehicles [25]. This research details how vehicle dynamics, especially under varying speeds and configurations, can influence the response.

El Madany et. al. (2011) discusses the design and evaluation of slow-active vehicle suspension systems using a full car model. The system studied combines a limited bandwidth actuator with a passive spring, paralleled by a passive damper. Simulation results demonstrate that the slow-active suspension achieves comparable performance to its fully active counterpart, particularly in controlling body resonances while significantly reducing power consumption [26]. This makes it a promising alternative for enhancing ride quality and safety without the high costs and complexity associated with fully active systems.

#### *Tire-Roadway Interaction*

Farroni and Timpone (2013) explore the development and utilization of a test rig to experimentally characterize tire envelope models. These models are critical for understanding how tires interact with various road irregularities, such as bumps and indents [27]. In their thesis, Frey extensively details the development and evaluation of various tire models, focusing particularly on a rigid ring tire model. This model is designed to simulate ride comfort by capturing both low-frequency and moderate amplitude roadway inputs, particularly important for ride comfort simulations in vehicles. The thesis compares this newly developed model against other traditional tire models, assessing their effectiveness in simulating ride comfort [28]. The approach includes using MatLab Simulink for implementing the rigid ring model, making it efficient for quick adaptation and testing with standardized laboratory methods.

Pesterev et. al. (2004) presents a method for predicting dynamic contact forces that arise when a vehicle, modeled as an undamped multiple-degrees-of-freedom (MDOF) system, encounters road surface irregularities. The model treats the vehicle as a series of independent oscillators in modal space, allowing each oscillator's response to be calculated independently [29]. An equation linking the contact forces in physical space to the modal forces is developed. The methodology is applied to simulate the impact of a "cosine" pothole, providing insights into the effects of parameter modifications on vehicle dynamics.

Yang (2009) presents an advanced tire model that integrates the effects of tire damping and pavement displacement into vehicle dynamics analysis. This revised flexible roller contact (RFRC) tire model enhances traditional models by considering the tire's geometric and flexible filtering effects, providing a more accurate representation of tire-road interactions [30]. The study uses this model in a vehicle-pavement coupled system to predict dynamical responses, showing that the RFRC model offers better alignment with experimental data than traditional single point contact models, especially under conditions of short harmonic wave or impulse road excitations.

### *Modeling of Speed Bumps*

Garcia et. al. (2014) investigates the effects of speed bumps on vehicle dynamics, specifically focusing on vertical movements and how they influence vehicle safety and comfort. The study utilizes a mathematical model to simulate the interaction between vehicle suspension systems and different speed bump geometries, analyzing the vertical dynamics of vehicles as they pass over bumps [31]. The model aims to predict the potential damage to vehicles and the discomfort experienced by passengers, providing a basis for optimizing bump design to enhance both vehicle safety and passenger comfort.

Janczur (2015) focuses on measuring vertical accelerations experienced by a Volkswagen Passat B5 when traversing speed bumps at various speeds and with different shock absorbers. The study evaluates the effects of shock absorbers with distinct damping characteristics on the vertical accelerations of the car body, utilizing advanced measurement equipment and simulation tests [32]. This research offers valuable insights for understanding how suspension systems respond to abrupt road features like rumble strips, particularly in terms of vertical dynamics and overall vehicle stability.

Kranjcevic et. al. (2017) explores the dynamic behavior of tires when encountering extreme irregularities on roads. A 10 degree of freedom (DOF) lumped 2D quarter vehicle model, including a two-point rigid ring follower tire model, is developed and implemented in Matlab Simulink [33]. The simulation results of tire impact against a road step at various speeds and step heights are then compared to finite element (FE) analysis results of the same scenario.

Based on the available literature, a quarter-car model was decided on as it provides a simplified yet powerful representation of a vehicle's suspension system. Matlab was selected as the program to use as it has proven successful. The model utilized will be a two-dimensional model with a two-point rigid tire, interactions will be modeled between both the wheel and the vehicle as well as between the wheel and the roadway.

## 2. Methodology

The primary objective of this project is to demonstrate the feasibility of experimentally evaluating a precast, asymmetric recessed rumble strip insert designed for retrofitting onto highway off-ramps. The concept involves creating an insert that can induce significantly higher levels of discomfort, measured by vertical vehicle acceleration and in-cabin noise levels, when crossed in the wrong-way direction, compared to the right-way direction. These metrics were chosen as they are quantifiable indicators of passenger discomfort. The rumble strip profile is designed to be asymmetric, aiming to maximize acceleration and noise levels in the wrong-way direction while minimizing them for correct travel, thereby generating preliminary data to assess the concept's effectiveness.

This project was conducted in two phases. The first phase involved developing a numerical model to optimize the geometry of the rumble strip, informed by methods established in published literature. This modeling aimed to maximize the likelihood of success in preliminary testing. The second phase focused on producing and testing physical prototypes of the rumble strips. This phase demonstrated the feasibility of precasting and retrofitting an asymmetric recessed rumble strip onto existing asphalt surfaces.

## 2.1. Numerical Simulation

The numerical simulation was done by creating a two-dimensional quarter vehicle suspension system model similar to Kranjcevic et. al. (2017) [33] using Matlab. This method serves as a simple model that can provide a complete interaction between the roadway and the accelerations experienced within the vehicle. This allows the model to account for the elasticity and damping associated with both the tire and the suspension system. This section will describe the development of the numerical model used in the study.

### 2.1.1. Simplified Quarter-Car Suspension System State-Space Model

Building upon methodologies established in published literature, we define the suspension system as a linear system with lumped parameters. The quarter-car body mass ( $m_b$ ) is connected in series with the suspension components: spring constant ( $k_1$ ), damping coefficient ( $b$ ), and actuator force ( $F_a$ ). This assembly is further connected in series with the wheel mass ( $m_w$ ), which in turn is connected to the tire modeled as a spring with spring constant ( $k_2$ ). The vertical displacement of the car body's center of mass (COM) is denoted as  $x_1$ , the wheel's vertical displacement as  $x_2$ , and the vertical road disturbances as  $d$ .

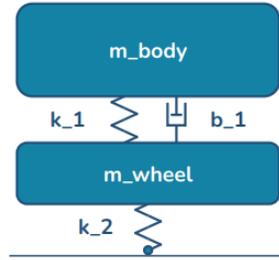


Figure 3. Simplified Model of a Car and Wheel in Contact with the Ground

By splitting the system into two free-body diagrams and applying Newton's second law, we derive the equations of motion:

1. For the Car Body:

$$\ddot{x}_1 = -\frac{k_1}{m_b}(x_1 - x_2) - \frac{b}{m_b}(\dot{x}_1 - \dot{x}_2) + \frac{1}{m_b}F_a$$

2. For the Wheel:

$$\ddot{x}_2 = \frac{k_1}{m_w}(x_1 - x_2) + \frac{b}{m_w}(\dot{x}_1 - \dot{x}_2) - \frac{k_2}{m_w}(x_2 - d) - \frac{1}{m_w}F_a$$

Equation 1. Accelerations of Free Body Diagrams associated with the car body ( $x_1$ ) and the wheel ( $x_2$ )

Using these equations, we can define the linear, time-invariant, continuous state-space model of the system by:

$$\dot{x}(t) = Ax(t) + Bu(t) + Wd(t)$$

$$y(t) = Cx(t) + Du(t)$$

Equation 2. Equations for the Derivative of the State of the System ( $\dot{x}(t)$ ) and the Output of the System ( $y(t)$ )

Where:

- $\dot{x}(t)$ : Derivative of the state vector
- $x(t)$ : State vector  $[x_1, \dot{x}_1, x_2, \dot{x}_2]^T$
- $A$ : System (dynamic) matrix
- $B$ : Input matrix
- $u(t)$ : Input vector  $[F_a]$
- $W$ : Disturbance matrix
- $d(t)$ : Disturbance input (road profile)
- $y(t)$ : Output vector
- $C$ : Output matrix
- $D$ : Feedthrough (direct transmission) matrix, set to zero

Substituting the parameters of the system into these equations gives the open-loop state space equations:

$$\begin{bmatrix} \dot{x}_1 \\ \ddot{x}_1 \\ \dot{x}_2 \\ \ddot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{k_1}{m_b} & -\frac{b}{m_b} & \frac{k_1}{m_b} & \frac{b}{m_b} \\ 0 & 0 & 0 & 1 \\ \frac{k_1}{m_w} & \frac{b}{m_w} & \frac{(k_1 + k_2)}{m_w} & -\frac{b}{m_w} \end{bmatrix} \begin{bmatrix} x_1 \\ \dot{x}_1 \\ x_2 \\ \dot{x}_2 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \frac{1}{m_b} & 0 \\ 0 & 0 \\ -\frac{1}{m_w} & \frac{k_2}{m_w} \end{bmatrix} \begin{bmatrix} F_a \\ d \end{bmatrix}$$

$$y = [1 \quad 0 \quad 0 \quad 0] \begin{bmatrix} x_1 \\ \dot{x}_1 \\ x_2 \\ \dot{x}_2 \end{bmatrix}$$

Equation 3. Open-Loop State Space Equations

where  $Bu(t)$  and  $Wd(t)$  are combined to merge disturbance and control inputs, and defining  $y$  this way will output the displacement of the car body COM,  $x_1$ . From here, the system can be programmed into MATLAB with the function **ss**, from the Control Systems Toolbox, to create the mathematical model: **sys = ss(A,B,C,D)**.

Then, the simulated time response of the dynamic system is plotted to the simulated road input, using the function **lsim**, which takes the dynamic system model, input signal, time sample, and initial state variables as inputs to graph the response of the system: **y = lsim(sys, u, tsim, x0)**.

For the input signal  $u = \begin{bmatrix} F_a \\ d \end{bmatrix}$ ,  $F_a$  is defined as the zero vector to simulate no actuator force, and  $d$  is defined as the road disturbance profile. The initial conditions  $\mathbf{x}_0$  are similarly defined as the zero vector to simulate no initial vertical displacements or velocities. Running `plot(tsim, y)` will then output the system response to the road disturbance profile.

The system response of a car driving 6 simple rectangular grooved rumble strips spaced at even intervals of 0.3 m (12 in), with a width of 0.05 meters (2 in) and a depth of 0.0127 m (0.5 in) is presented.

The suspension system parameters were initially defined as:

```
mb sys = 300; % mass of quarter car body (kg)
mw sys = 60; % mass of wheel (kg)
k1 sys = 16000; % stiffness of suspension spring (N/m)
k2 sys = 190000; % stiffness of tire (N/m)
b sys = 1000; % damping coefficient (N.s/m)
```

This is the system response, the vertical displacement of the center of mass of the car body as predicted by the model:

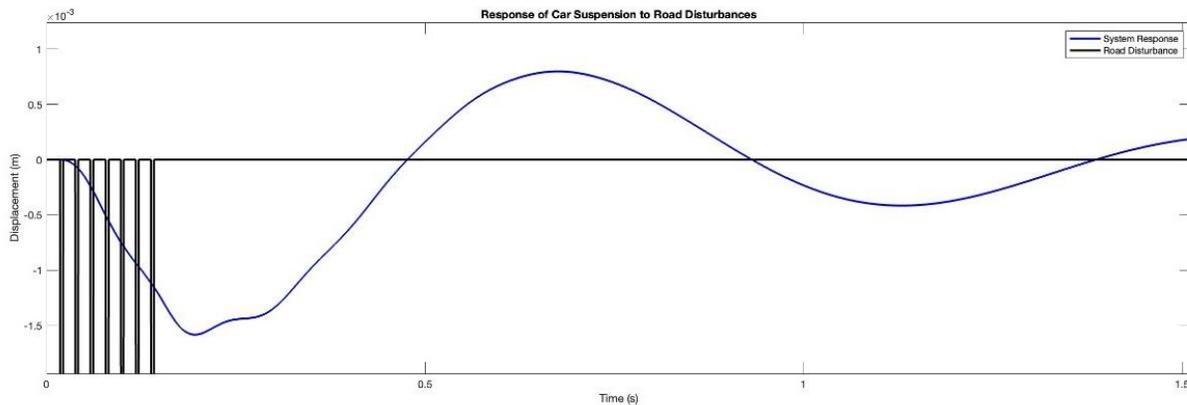


Figure 4. Road Disturbance and System Response

### 2.1.2. Novel Effective Disturbance Matrices

To better address the problem at hand, we refine the model by redefining the output matrix  $CC$  to output the vertical acceleration ( $\ddot{x}_1$ ) of the car body's COM, rather than its displacement. This adjustment allows us to directly analyze the acceleration experienced by passengers, a key measure of discomfort as identified in previous studies.

The modified output equation becomes:

$$y = \begin{bmatrix} -\frac{k_1}{m_b} & -\frac{b}{m_b} & \frac{k_1}{m_b} & \frac{b}{m_b} \end{bmatrix} [x_1 \quad \dot{x}_1 \quad x_2 \quad \dot{x}_2]^T$$

Equation 4. Output Model of Vertical Accelerations

At this point, we recognize a limitation in the existing model. The current state-space representation treats the road disturbance as a point-contact disturbance, where the tire follows the exact profile of the

road. However, the geometry of the asymmetric directional rumble strips, the topic of the study, is not adequately captured by this simplification.

To address this, we introduce two novel effective road disturbance models, inspired by concepts from published research on tire-road interactions:

1. **Projectile Model (Low-Pressure Tire Simulation):** This model approximates the tire as a deformable entity, smoothing out road irregularities. It provides a conservative estimate of the disturbance transmitted to the vehicle.
2. **Modified Rigid Roller Model (High-Pressure Tire Simulation):** This model treats the tire as a less deformable entity, capturing more of the road's geometric features and resulting in higher transmitted disturbances.

These models incorporate creative logic to approximate the complex interactions between the tire and the unique geometry of the directional rumble strips. By implementing these models, we can efficiently simulate thousands of scenarios to optimize the rumble strip geometry without the computational overhead of a full tire deformation model.

### *Projectile Model*

The Projectile Model attempts to incorporate the “jumping” effect of a real tire rolling over a recessed road disturbance. A real tire does not trace the full contour of a dip in the road, but rather “jumps” over it partially. To program this effect into the Matlab simulation, the input signal road disturbance profile  $u_d$  was overlaid with the trajectory of a simple projectile traveling at the velocity of the car, under the influence of gravity.

The tire of the vehicle is going to “fall into” the recess much faster than a simple projectile due to the energy in the spring. Because the spring is initially collapsed to carry the quarter weight of the vehicle  $m_b$ , it will exert an equivalent force when it is released. So, if we consider the acceleration of the wheel,  $a_w = F/m_w$ , where  $F = m_b g$  from the weight of the quarter car. Thus, summing this with gravitational acceleration gives the apparent acceleration of the imaginary particle as  $g(1 + m_b/m_w)$ .

This new effective road profile is then used as the input matrix to the system. Here is an example with a vehicle traveling at 13 mph using the geometry parameters ultimately decided upon for the rumble strip prototype ( $a = 2\text{in}$ ,  $b = 15\text{in}$ ,  $d = 2\text{in}$ ):

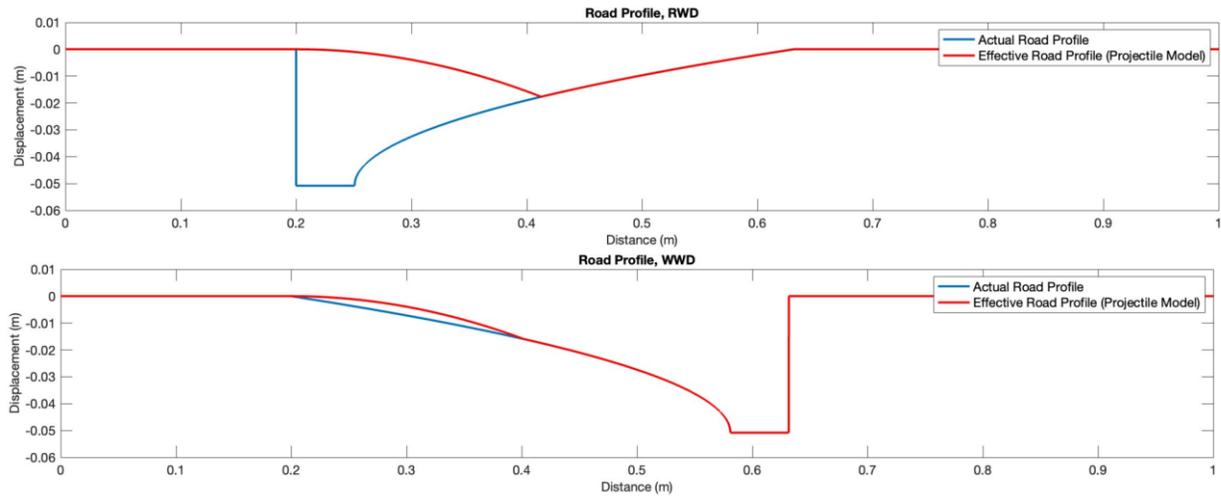
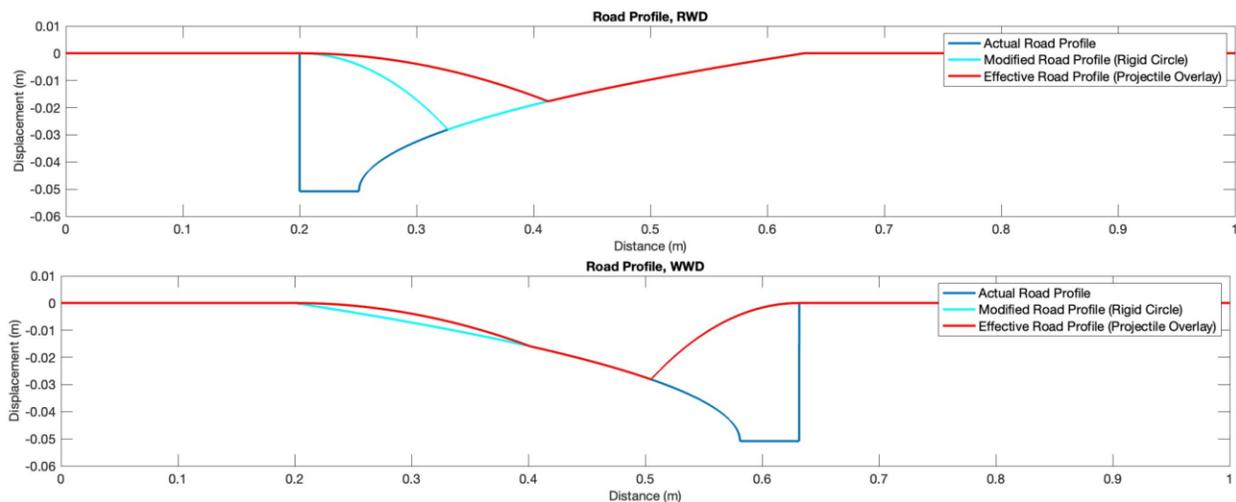


Figure 5. Actual and Effective Road Profiles for the Projectile Model

### Modified Rigid Roller Model

The Modified Rigid Roller Model simply adds another layer of adjustment to the input disturbance matrix, considering the circular shape of the tire. Consider a simple rigid circle rolling across some disturbances in the road - its center of mass will not follow the exact road contour, but rather a modified trajectory which has been smoothed out.

This model simply accounts for this “rigid roller” trajectory, then overlays the Projectile Model on top of this modified road profile to generate the effective road profile. Here is an example utilizing the same velocity and geometry parameters as before, and an assumed wheel radius of 0.3 m:



### Suspension Model

These concepts were used to write the suspension model. The function takes as inputs 5 parameters: Vehicle speed (m/s), Rumble strip direction, contact model (Point Contact, Projectile Model, or Modified Rigid Roller Model), flat length (m), curved length (m), and drop length (m). The function returns the maximum acceleration output. This enables the rest of the code base of the simulation to loop through various velocities and geometry parameters in both the RWD and WWD for optimization purposes.

Figure 6 shows an example system response graph utilizing the same velocity and geometry parameters as before, with the Modified Rigid Roller Model for effective disturbance input.

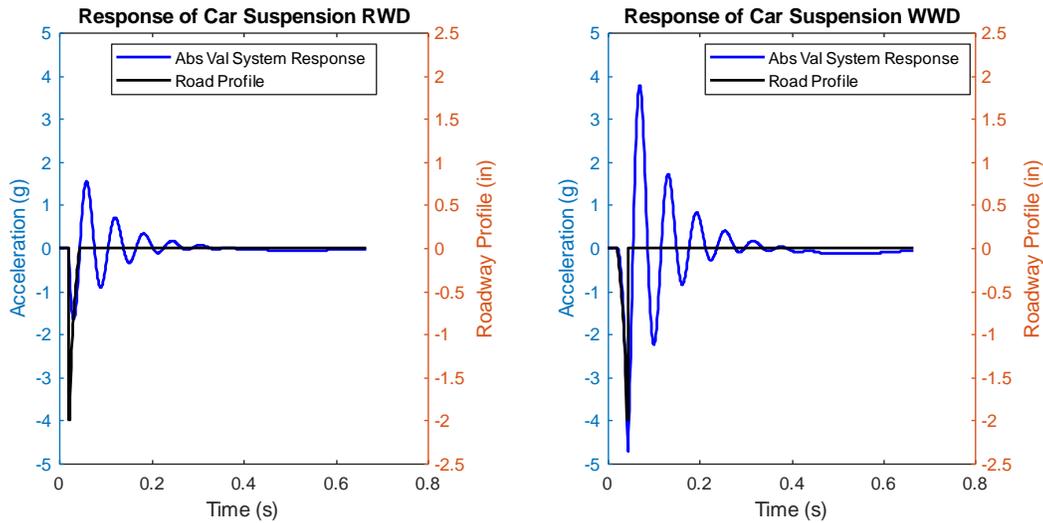


Figure 6. Example Response Graph using the Modified Rigid roller model

### 2.1.3. Optimizing the Rumble Strip Geometry

Following the development of the model, it was used in a parametric study of the geometry of the rumble strip to try and maximize the vertical accelerations associated with traveling over the rumble strip in the wrong-way direction compared to the right-way direction. Based on the findings of the previous work done, it was decided that the shape would involve a steep drop and include a rounded raise to the out of the depression when traveling in the right-way direction, as seen in Figure 7. This provided the most severe gradient when traveling in the wrong-way direction, while minimizing the impact on the tire while traveling in the right-way direction. There were three parameters the team used to describe the shape of the rumble strip: the depth ( $d$ ), the length of the constant depth section ( $a$ ), and the length of the curved section ( $b$ ).



Figure 7. Geometric Optimization Parameters for the Rumble Strip

These three parameters were varied in the numerical model, and the peak accelerations associated with travel over the rumble strip were recorded. These were then normalized by finding the ratio between wrong-way and right-way accelerations. The geometry with the largest ratio would be selected as the geometry utilized in the roadway test.

## 2.2. Roadway Testing

Before conducting roadway testing, the rumble strips must be cast and installed into the pavement. The testing will involve installing the directional rumble strips and driving a sedan over them at speeds ranging from 10 to 45 miles per hour, in both right-way and wrong-way directions. The vehicle will be

equipped with various sensors to record acceleration and interior noise levels as it crosses the rumble strips. This section details the process of creating and installing the rumble strips, as well as the testing procedure.

### 2.2.1. Forming and Casting the Rumble Strips

To minimize the volume of UHPC required, it was decided to design the rumble strip as a pair of formed strips, each intended to accommodate a single tire. This approach reduces the amount of UHPC needed for casting and simplifies handling the precast panels afterward. Each rumble panel was designed to be 24 in long and 28 in wide. With these dimensions, both precast panels and the necessary test cylinders can be cast in a single batch using the Imer 360 mixer. The finished panels would weigh around 100 lbs, allowing them to be handled and installed without heavy equipment.

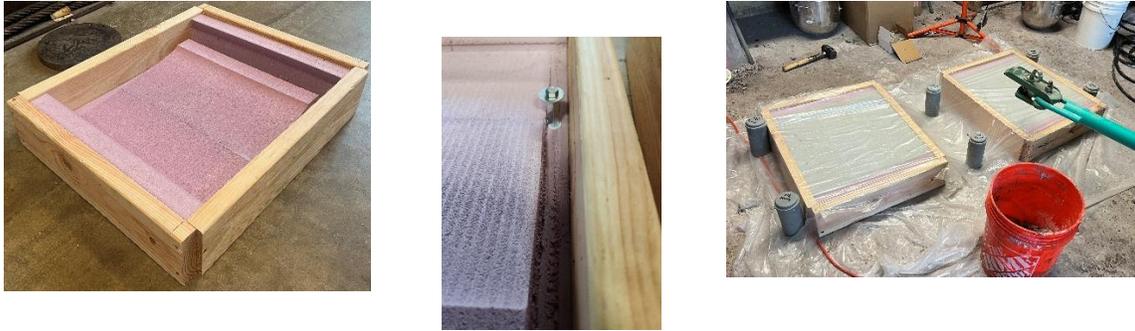
Based on the geometry determined from the numerical model, two casting methods were considered: using a top form or performing an inverted cast. A top form would involve creating a negative mold for the recessed area and securing it to the top of the mold, which would require thicker sidewalls and could lead to voids if the UHPC was less flowable than expected. To avoid these issues, an inverted casting method was chosen. This method involves placing the negative mold at the bottom of the form, making the bottom of the mold the finished top surface, which reduces the risk of voids in critical areas.

To ensure the rumble strip geometry matched the specifications from the numerical model, foam board insulation was chosen to create the casting void. This foam could be precisely shaped using a CNC machine to achieve accurate dimensions. The insulation would form the base and void of the mold, while dimensional lumber would be used for the mold's edges.



*Figure 8. CNC Machining of the Form Bottom and Void*

Once the forms were built, they were prepared for casting. This involved spraying the surface with polyurethane to aid in demolding and to set cast in anchor points to assist with alignment of the two rumble strips. The anchor points were non-structural and were used to help ensure that the two panels are properly aligned and level when installed on the roadway. There was no reinforcement included in the panels. The fiber reinforcement helps to eliminate the need for reinforcement in these panels. The finished panel formwork and casting can be seen in Figure 9.



*Figure 9. The completed formwork, alignment anchors, and panels after casting*

The mixing was conducted in an Imer 360 pan mixer, which can mix up to 2 ft<sup>3</sup>. Each of the panels would require 0.75 ft<sup>3</sup>, so a full 2 ft<sup>3</sup> was mixed to account for the additional material required for making cylinders, and to account for waste when mixing. The panels would be demolded after the UHPC had reached a strength of 10 ksi. This would ensure that the UHPC would not be damaged during demolding.

### 2.2.2. Site Selection and Preparation

A suitable location was identified for installing the rumble strips. The site needed to have low traffic and enough space for vehicles to safely approach, reach the required testing speeds, and decelerate. Additionally, the quality of the road surface was crucial, as it could affect the measured acceleration and noise levels. After a thorough search, a location was selected that met these criteria. The approaches to the site are shown in Figure 10, with the two rumble strip installation points marked in white. This site allowed vehicles to reach speeds up to 45 mph and was sufficiently secluded, enabling the roadway to be temporarily closed to avoid interactions with pedestrians and other vehicles, without impacting surrounding traffic flow.

The primary drawback of this site was the pavement quality, as the rarely used section had developed extensive alligator cracking and potholes. The rumble strips were positioned carefully to minimize the impact of these surface conditions on the test results.



*Figure 10. Southern and Northern Approaches for the selected rumble strip installation*

After selecting the location and marking the installation points with paint, the roadway was cut to accommodate the rumble strip panels. The cutouts were made slightly oversized to allow for 2 in of grout cover on each side and 1 in below the panels (see Figure 11a), ensuring secure placement during testing.

The panels were placed on standoffs within the cutouts to allow for grout clearance beneath them. They were positioned so that the recessed areas aligned with the wheels of a standard sedan. Once positioned longitudinally and transversely, the panels were bolted to a piece of dimensional lumber to maintain orientation (see Figure 11b). The bottom of each panel was then shimmed to ensure the top surface was flush with the existing asphalt, reducing any disturbance when driven over (see Figure 11c).

Non-shrink grout was mixed to a flowable consistency and poured around the panels until the cutouts were filled to the top of the panels (see Figure 11d). Light tapping with a rubber mallet helped eliminate any trapped air voids. Once grouted in place, weight was added to the panels to prevent movement, and plastic sheeting was applied to cover the grout for curing (see Figure 11e). The panels were deemed ready for testing after the grout reached a strength of 4 ksi, at which point the sheeting and stabilizers were removed, completing the installation (see Figure 11f). The finished panels were flush with the existing pavement and properly aligned for testing.



Figure 11. Installation of the Directional Rumble Strip. a) Prepared holes for rumble strip panels, b) alignment of the rumble wells with vehicle, c) setting finished level, d) grouting panels, e) weighing down panels during curing, f) finished installed panels

### 2.2.3. Instrumentation

The experiment aimed to measure rider discomfort when traveling over the rumble strip in both right-way and wrong-way directions. Two indicators of discomfort were recorded: acceleration and noise levels. A four-door midsize sedan was chosen as the test vehicle. This vehicle, a 2023 Nissan Sentra, had a curb weight of 3084 lbs, 149 HP, and overall length of 183 in (15.25 ft) on a 106.6 in (8.88 ft) wheelbase. Data acquisition was performed using the HBM Quantum X1601B Piezoelectric Instrument, which enabled simultaneous collection from piezoelectric accelerometers and microphones. Data was recorded at a sampling rate of 300 Hz.

For acceleration measurements, PCB model 356A02 three-dimensional piezoelectric accelerometers, capable of measuring up to 500 g, were used. Five accelerometers were mounted on the vehicle: one above each wheel (indicated by red arrows in Figure 12a) and a fifth on the dashboard to measure interior acceleration (Figure 12c). Vertical accelerations were recorded at each wheel, while both vertical and linear accelerations were recorded by the dashboard accelerometer to monitor vehicle acceleration as well.



*Figure 12. Instrumentation used during the roadway test. a) Exterior positioning of accelerometers on the testing vehicle, b) Detail of the exterior accelerometers, c) position and orientation of the internal accelerometer, d) position of the passenger microphone on the interior of the vehicle.*

For noise level measurements, PCB 378B02 microphones were used. These are 0.5 in prepolarized free-field microphones with a frequency range of 3.75 Hz to 20 kHz. Two microphones were installed inside the vehicle, one above each of the driver and passenger doors (see Figure 12d), to capture sound levels near ear level, simulating what passengers would experience while crossing the rumble strip.

Additionally, a Photron high-speed camera was positioned perpendicular to the rumble strip (Figure 13) to record the vehicle's approach and passage. This footage was used to verify both the vehicle's alignment and its speed as it traveled over the rumble strip, ensuring accurate test conditions.



*Figure 13. High-Speed Camera Setup for High-Speed Testing*

#### 2.2.4. Right-Way and Wrong-way Testing

A testing scheme was developed to measure differences in acceleration and noise levels inside the test vehicle as it crossed the rumble strip in both right-way and wrong-way directions. Tests were conducted at speeds ranging from 5 to 40 mph, which reflect realistic speeds for vehicles approaching the end of highway exit ramps where such rumble strips might be installed. Readings were taken at 5 mph intervals to observe how acceleration and noise levels changed with speed.

For each test run in each direction, the peak values of acceleration and interior noise levels were recorded. These peak values helped assess the rumble strip's effectiveness in alerting wrong-way drivers while minimizing discomfort for right-way drivers. A higher ratio of wrong-way to right-way values would indicate better performance in signaling wrong-way travel.

During testing, the instrumented vehicle was accelerated to the specified speed, and data was recorded. Two personnel were inside the vehicle: one operating the vehicle and the other managing the data acquisition system and marking the time of impact with the rumble strip for precise data alignment. A third individual managed the high-speed camera and used a radar gun to verify the vehicle's speed. Data recording began prior to acceleration to capture the full linear acceleration profile, from stationary to rumble strip contact and beyond. Trials were repeated if the vehicle did not impact both rumble strips.

A total of 34 tests were conducted, with at least one run at each speed in both directions. This comprehensive approach provided a robust dataset to evaluate the rumble strip's performance across a range of speeds and travel orientations.

## 3. Results

### 3.1. Optimizing the Rumble Strip Geometry

During the parametric study of the rumble strip geometry, data was collected to maximize the ratio between wrong-way and right-way accelerations. This was achieved by measuring the peak accelerations of a simulated quarter-wheel assembly traveling over the rumble strip in both directions. The goal was to identify geometric configurations that would significantly increase accelerations in the wrong-way direction relative to the right-way direction, thereby enhancing the rumble strip's ability to alert wrong-way drivers.

Various geometric parameters of the rumble strip were tested, including the drop height ( $d$ ), which ranged from 0.5 to 2 in, the flat length ( $a$ ), which ranged from 0 to 7.5 in, and the curved length ( $b$ ), which ranged from 0 to 18 in. These variations allowed for an extensive examination of how different configurations impacted acceleration.

Figure 14 presents results from this parametric study, showing plots of right-way and wrong-way accelerations along with the resulting acceleration ratios across different vehicle speeds. The figure reveals that both right-way and wrong-way accelerations decrease as speed increases. Right-way accelerations exhibit a consistent, exponential decay, whereas wrong-way accelerations display a marked reduction at speeds exceeding 45 mph. This pattern causes the acceleration ratio to increase at lower speeds, peaking at around 45 mph before it begins to decline.

These findings indicate that certain geometric configurations are more effective at creating discomfort in wrong-way travel at moderate speeds, providing valuable insights for optimizing rumble strip design.

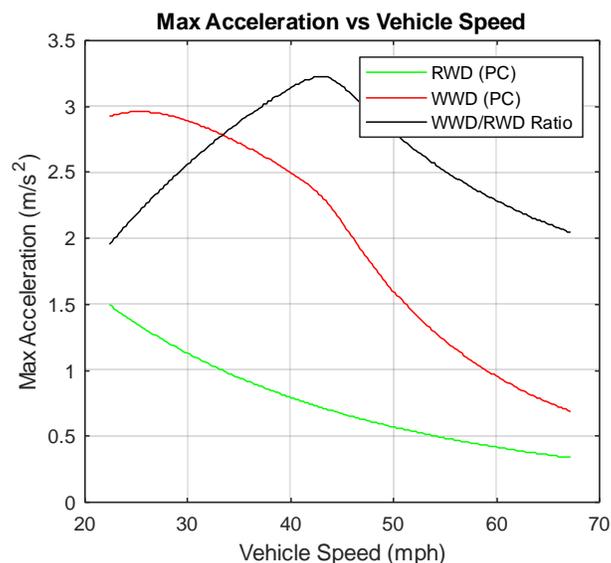


Figure 14. Accelerations and Acceleration Ratios vs. Vehicle Speed ( $a=2$  in,  $b=12$  in,  $d=0.75$  in)

Figure 15 illustrates the variation in the peak acceleration ratio between right-way and wrong-way travel as the geometry of the rumble strip changes. The shading of the data points represents the acceleration ratio for traversing the rumble strip, with darker shades indicating higher ratios. The plot shows that a

wide range of dimensions can achieve an acceleration ratio of over two, meaning that the acceleration in the wrong-way direction is more than twice that in the right-way direction. This suggests that the rumble strip's geometry can be somewhat flexible without losing effectiveness.

Based on the results from the numerical modeling, the final geometry was set with a drop ( $d$ ) of 2 in, a flat length ( $a$ ) of 2 in, and a curved length ( $b$ ) of 18 in. This configuration was found to produce a significant difference in accelerations experienced by a vehicle traveling over the rumble strip, enhancing its ability to alert wrong-way drivers effectively.

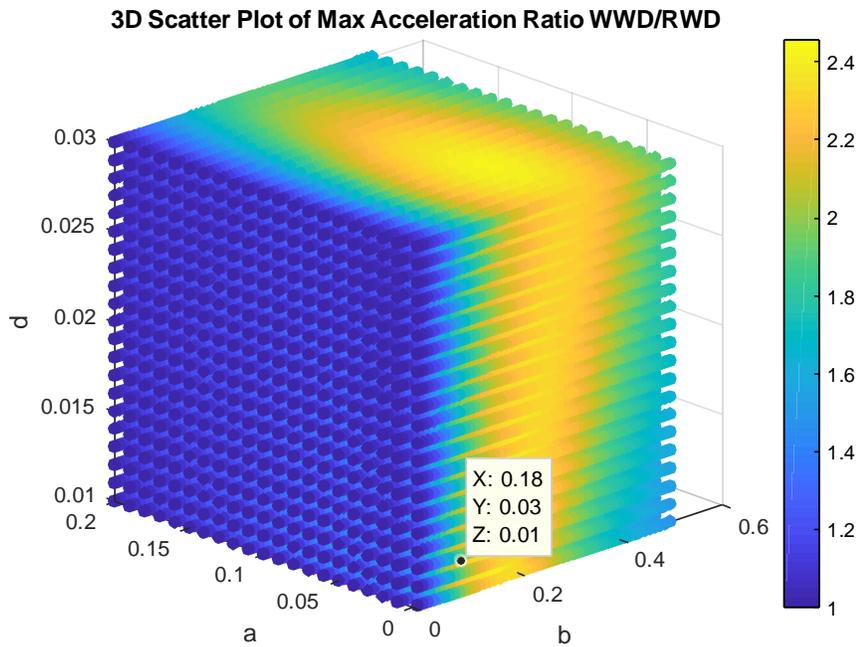


Figure 15. 4-D Plot of Acceleration Ratio vs. Geometric Factors for the Rumble Strip with Vehicle Speed of 30 mph

### 3.2. Roadway Testing Results

This section presents the results from the roadway testing, including the measured acceleration and noise levels inside the vehicle and the effect of vehicle speed on these values. A 2023 Nissan Sentra was used as the test vehicle, shown crossing the rumble strip in Figure 16. Data from each of the 34 test runs was processed in MATLAB.

To prepare the data for analysis, a bandpass filter between 1 and 100 Hz was applied to isolate relevant frequency ranges. Following filtering, the data was windowed according to the start and end times recorded by the passenger in the vehicle, ensuring that the peak acceleration and noise levels corresponded specifically to the vehicle's passage over the rumble strip.



*Figure 16. High Speed Camera Still of Test Vehicle Traveling a) Right-Way, and b) Wrong-way*

Figure 17 presents a sample of the data collected, with each dataset aligned so that the rumble strip impact occurs at time zero. The impacts of the rumble strip are visible in both the acceleration and microphone data. Distinct spikes in the data at approximately -0.3 seconds and 0.25 seconds correspond to the impacts of the front and rear tires, respectively, consistent with the vehicle's wheelbase and speed during the test.

The microphone data clearly shows spikes with each impact, indicating distinct noise responses to the rumble strip. However, the acceleration data shows less pronounced peaks compared to the microphone data. This is likely due to the rough road conditions surrounding the rumble strip, which may introduce additional accelerations. Such background noise could lead to larger acceleration values being recorded outside the rumble strip, potentially causing false readings if these values are mistaken for the peak acceleration associated with the rumble strip impact.

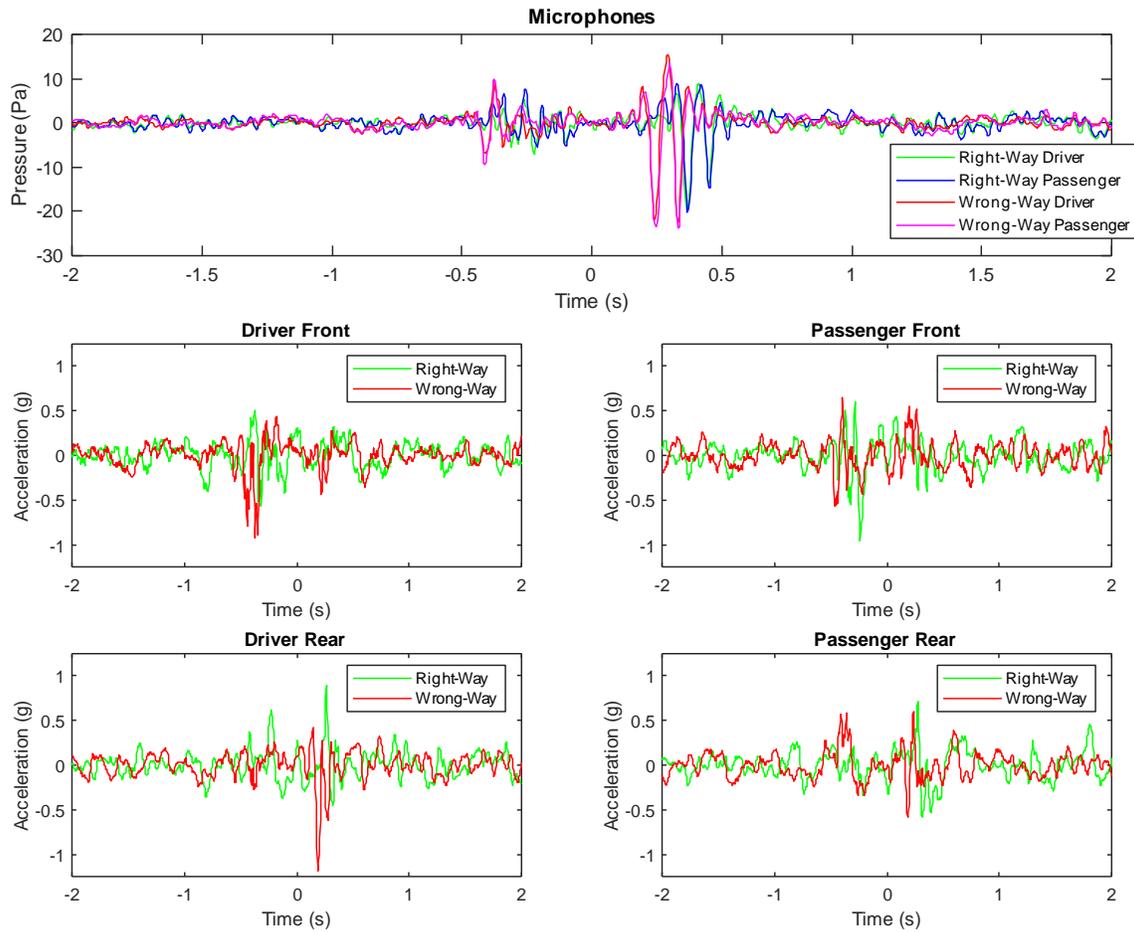


Figure 17. Sample of microphone and acceleration data acquired during testing, testing speed: 10mph

### 3.2.1. Acceleration Levels

Peak acceleration data from each of the 34 tests were plotted against vehicle speed, as shown in Figure 18. This plot reveals a relationship between peak acceleration and vehicle speed when crossing the rumble strip. Notably, there are some differences between the model's predicted accelerations and the observed data from roadway tests.

For the wrong-way direction, the accelerations measured during the roadway tests were lower than those predicted by the numerical model. The model predicted wrong-way accelerations between 3 and 2.5 g at speeds from 5 to 40 mph, whereas the roadway data showed accelerations between 0.75 and 1.25 g for the same speeds. In the right-way direction, measured accelerations were closer to the model's predictions, with model values ranging from 1.5 to 0.9 g and roadway values from 0.75 to 1.25 g across the tested speeds. Both right-way and wrong-way accelerations showed an increase of approximately 0.017 g per mph.

Although wrong-way accelerations were consistently higher than right-way values at each speed, the observed peak acceleration increased in both directions with vehicle speed in the roadway data,

contrary to the numerical model, which predicted a decrease. This discrepancy may be due to the rough conditions of the surrounding roadway affecting the vehicle's response. While wrong-way peak accelerations were, on average, higher than right-way values, they were only about 1.02 times greater in the roadway tests, compared to the model's prediction of a 2- to 3-fold difference for the tested speeds.

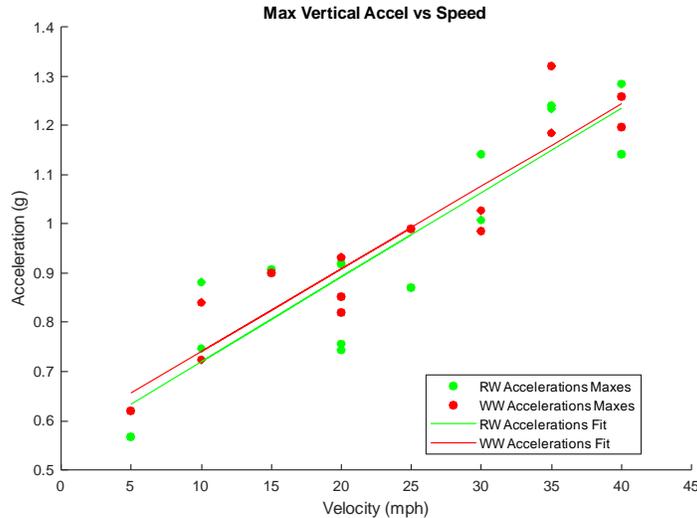


Figure 18. Max Vertical Acceleration vs Vehicle Speed

### 3.2.2. Acoustic Levels

Peak microphone output data from the 34 tests were plotted against vehicle speed, as shown in Figure 19. Unlike the acceleration data, no volume level predictions were made prior to testing. The data reveal a similar trend between volume level and vehicle speed as was observed with acceleration, with higher speeds corresponding to higher sound levels.

Right-way volume levels increased at a rate of 0.33 Pa per mph, while wrong-way volume levels increased at a rate of 0.19 Pa per mph. Both trends have an intercept of around 10 Pa, resulting in consistently higher volume levels for right-way travel compared to wrong-way travel. This outcome is not ideal, as it indicates that wrong-way travel provides a less noticeable acoustic signal than right-way travel. However, it does demonstrate that an asymmetric rumble strip design can produce varied acoustic responses based on the direction of travel.

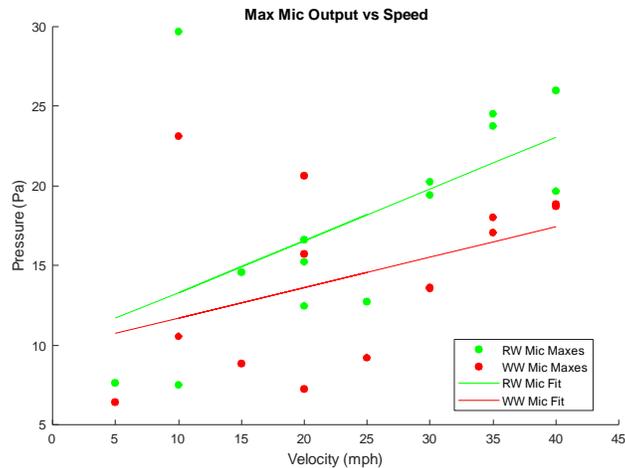


Figure 19. Max Microphone Output vs Vehicle Speed

## 4. Future Work

While the results of this study are promising, further work is necessary to develop an effective and implementable strategy to deter wrong-way driving. Several tasks could advance this research, including validating the numerical model, performing further roadway testing, and investigating other key aspects of the performance of the rumble strip.

### 4.1. Validating the Numerical Model

With a comprehensive set of acceleration data now available, the numerical model can be validated and refined. Initial predictions from the model indicated much higher accelerations than those recorded in testing, which may have led to a suboptimal rumble strip geometry. By adjusting parameters in the model—such as the stiffness values that represent the interaction between the tire and ground and between the tire and vehicle, as well as the suspension damping—the model’s accuracy can be improved.

Additionally, the tire’s trajectory over the rumble strip can be compared to high-speed video footage to verify the contact points identified in both the projectile and modified rigid roller models. Fine-tuning the model using these recorded data will enable more reliable predictions for subsequent tests, ultimately supporting the development of a more effective rumble strip design.

### 4.2. Second Round of Roadway Testing

Only one set of rumble strips were tested, and the testing revealed potential improvements to the roadway testing process:

#### 4.2.1. Improved Roadway Surface Conditions

The roadway used was isolated and posed no danger to pedestrians or other vehicles, however the roadway was in poor condition, with several areas of extensive cracking, loose pavement, and potholes. Having a smoother test track would provide better data.

### 4.2.2. Larger Specimen Size

The width of the rumble strips were kept small in order to reduce the volume of UHPC used in the trial and to keep the volume needed for testing to be within the capabilities of our mixer. However, this resulted in a specimen that was only 10 in wider than the testing vehicles tires, which made ensuring that both wheels hit the strip in the test difficult, especially at higher speeds. Wider specimens would be more reliably hit, and ensure that reliable data is collected.

### 4.2.3. Performance in Adverse Weather

The asymmetric recessed rumble strips will be installed on off ramps to deter wrong-way driving. These will be exposed to weather throughout the year and will be subject to maintenance. The performance of the rumble strip will have to be verified in adverse weather conditions, such as rain to ensure the water is removed and does not pose a safety risk. Their performance in snow should also be investigated, as ice could build up in the inverted section and cause not only a slick surface which poses a risk to drivers, or prove to be less effective. The buildup of roadway debris in the rumble strips should also be investigated to determine the frequency of cleaning that would be required.

## 4.3. More Extensive Testing

Only one design of rumble strip was tested. In order to draw more definitive conclusions, more testing will need to be done. This should include variations to the current design, as well as potential other asymmetric shapes investigated in the prior study, as well as any other shapes that can be determined from the validated numerical model. Currently only a single rumble strip design was tested with the goal of producing a single large acceleration or noise. Based on the results, the recessed design seemed more responsive to noise compared to acceleration, so investigating smaller repeating patterns that are intended to produce a more audible tone could prove effective.

The impact of heavier vehicles on the rumble strip should also be investigated. Heavier vehicles could result in excessive movement of the precast panel and cause debonding around the joint between the panel and the roadway. This should be investigated to determine if the inclusion of anchorage into the roadway is necessary.

## 5. Conclusions

### 5.1. Results

This work aimed to produce a preliminary proof of concept for a grooved, asymmetric directional rumble strip designed for regions where snow is common and extruded rumble strips would be vulnerable to snow plows. Numerical models were used to optimize the rumble strip geometry, with the objective of maximizing accelerations when traveling in one direction and minimizing them when traveling in the opposite direction. A novel quarter-vehicle suspension model, employing modified rigid roller and projectile modeling to determine the wheel path, was utilized, and a parametric study was performed on key dimensions of the rumble strip's geometry. This model predicted peak acceleration values for both right-way and wrong-way travel over the rumble strip. The results were normalized into a ratio of wrong-way to right-way accelerations, with the goal of maximizing this ratio to enhance the strip's effectiveness

in alerting wrong-way drivers. The numerical modeling indicated that an asymmetric rumble strip can indeed generate different acceleration levels depending on the travel direction. The final design had a drop of 2 in, a flat length of 2 in, and a curved length of 18 in.

After finalizing the design, formwork was created, and the rumble strip was installed and grouted into the roadway. Once the grout had set, 34 sets of acceleration and interior sound level data were recorded, with 17 runs in each direction. The acceleration data showed that, with this geometry, peak wrong-way accelerations were consistently higher than those for right-way travel. However, the difference between right-way and wrong-way peak accelerations was lower than predicted by the numerical model: wrong-way accelerations averaged 1.02 times those of right-way accelerations in the roadway tests, compared to an average of 2.5 times in the model. The sound level data similarly showed consistent differences between right-way and wrong-way travel, though wrong-way sound levels were unexpectedly lower than those for right-way travel.

## 5.2. Conclusion

In conclusion, the results of the testing have shown that the concept of an asymmetric recessed rumble strip is valid, but requires significant work before it is viable. While the concept is not currently ready for deployment, it has provided a solid concept for what could be done with this technology given further development. As it stands, further work is needed as the current roadway testing site has rather rough pavement and the current data, while showing that the concept works, does not currently provide a definitive difference between acceleration and interior volume levels associated right and wrong way of travel. While these differences are present, proving that the concept of directional recessed rumble strips is valid, they are not currently able to provide a reliable deterrent to wrong-way travel. With further work, this technology has the potential to drastically improve highway safety by providing a deterrent to wrong-way travel on the highway.

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