Design Directional Raised Rumble Aggregates and Strips for Awakening Wrong-Way Drivers

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ABSTRACT
Rumble Strips have been widely applied to shoulder, centerline or edgeline of roadways to warn or alarm drivers who could potentially run off the road to collide with fixed or moving objects. Wrong-way (WW) driving on freeways usually involved multi-vehicles traveling in the opposite directions and caused many severe injuries and/or fatalities. It is of practical engineering interest to stop a WW driver before the driver gets into freeways, namely, at the off-ramp exits or entries. Since the conventional rumble strips don’t discriminate the driving directions, it is very desirable to design a one-way rumble device that intends for awakening the WW drivers without frustrating the drivers getting off the freeways the right direction. In this article, we propose general designs for one-way or directional rumble aggregates and directional raised rumble strips by making use of the jerking or rumbling effect induced by these devices. The physical dimensions of these devices can be tailored to fit off-ramp width and sustain anticipated vehicle loads on these devices. These directional rumble devices, which should be implemented with other passive or active WW traffic signs for enhancing the prevention of WW driving, can be easily customized to generate the desired shaking effect for stopping potential WW drivers.

1. INTRODUCTION
Among various categories of roadway traffic accidents, a wrong-way (WW) collision on average causes larger number of fatalities and injuries per collision, drawing media, public, and politician attention. Most state agencies apply the WW prevention signs on state highways following the Manual on Uniform Traffic Control Devices (MUTCD) published by Federal Highway Administration [1]. Several states in US employ additional passive or active strategies to prevent WW collisions on freeways. For example, California and Texas Department of Transportation adopt a set of
countermeasures with a check list for subduing WW driving based on research and observational results [2–3]. Most traffic control devices that are installed for warning WW drivers are signs, markers, and pavement markings which are in compliance with the MUTCD. These devices, usually installed at the access points to freeways, such as the off-ramp terminals/exits, will be effective if a WW driver obeys the instructions on the devices.

It is known that approximately 90% of the WW drivers had been impaired with different degrees of intoxications [3], and an intoxicated driver’s response to a warning traffic device, such as traffic sign, pavement marking, and signal, remains largely unknown. No concrete evidences have shown that these warning traffic devices are effective on preventing an inebriated driver driving wrong way. It is also noticed that none of these devices would tactically stimulate the WW drivers, who may not respond to any visible traffic instructions. Under such circumstances, it seems necessary that these WW drivers should be physically jerked with a high intensity so that they would, if not heavily inebriated, be shaken up to recognize that their WW driving might lead to disastrous consequences. One way to awake a driver is jerking the driver by changing the direction of vertical acceleration experienced by the driver. It is known that this jerking technique has been a routine exercise for waking up a sleepy or asleep person. The jerking effect, also called rumbling effect induced by rumble strips, has been examined in details to understand the rumble strip spacing in design [4]. It has been further demonstrated in research that the jerk is the main dynamic quantity that a driver is sensitive to in a moving vehicle [5]. Since the rumbling effect is to be exerted on WW drivers but not on drivers moving in the right direction, it is very desirable to install a one-way/directional rumble device on off-ramps, where the WW drivers may access freeways. In order to create the desired jerking effect, installing disconnected pieces of a rumble strip on pavement may perform as well as a continuous raised strip. In this paper, the assembly of the pieces of a rumble strip is called one-way or directional rumble aggregates; when welding together top surfaces of a few aggregates to a small rectangular piece of steel, a boulder size aggregate can be made to perform higher jerking effect also; furthermore, when welding together all rumble aggregates to a long flat narrow piece of steel, a directional raised rumble strip is made. In practice, an engineer can mount one of these rumble devices on an off-ramp to prevent foreseeable WW driving.

2. DESIGN OF THE RUMBLE AGGREGATE

In the following discussions, structural steel, satisfying ASTM A-36 specification, with a yield strength of 280 MPa and an ultimate strength of 400 MPa, will be the steel material used for making the rumble devices. An oval-shape aggregate with the dimension of a few centimeters resting on a highway surface, can cause alarming vibration in a passenger vehicle upon running over it especially with a high speed since the jerk experienced by the driver is expected to be proportional to the cube of speed [4]. Instead of installing a raised rumble strip, one may place the one-way rumble aggregates across vehicle wheel paths to create a pronounced rumbling effect for waking up the WW drivers. Conceptually, these one-way rumble aggregates can be
horizontally locked onto a steel bar with a diameter ‘Φ’ of 32.3 mm (1.27”) or more but allowed to rotate around the bar for normal traffic and fix above the pavement surface for WW traffic.

The design of an assembly of rumble aggregates is schematically drawn in Figure 1 with a top view and a front view. This entire assembly, packaged with a steel box, has width of approximately 30.5 cm (1’), depth of 15.2 cm (6”) and a length between 91.4 cm (3’) and 152.4 cm (5’). Additionally, internal walls with a spacing ‘Λ’ of 30.5 cm are inserted inside the box for sustaining heavy truck loads. The thickness of the steel box, ‘Γ’, is chosen to be 7.62 mm, but can be made larger for supporting axle load of very heavy vehicles. In order to avoid potential conflict with edgeline rumble strip installation or not to provide large enough road side space where a WW driver might sneak through an off-ramp exit using the shoulders partially, this rumble aggregate box assembly is suggested to be mounted at least 30.5 cm but not more than 61 cm away from the travel way edges of the off-ramp. For an off-ramp of 427 cm width (14’), two 152 cm (5’) rumble aggregate assemblies would fit across the off-ramp, or four 3-ft assemblies may be installed across the off-ramp for shaking up WW drivers.

All the aggregates in the following discussions have flat elliptic shape with a thickness between 10.2 mm (0.4”) and 15.2 mm (0.6”) as shown Figure 1. The thickness should be increasing with the longer elliptic axis ‘b’ of the aggregate as shown in Figure 2. If the aggregate’s longer axis reaches the size of 10.2 cm (4”), the thickness of an aggregate should be chosen to be 1.52 cm (0.6”). The aspect (axis) ratio, ‘b/a’, is recommended to be in the neighborhood of ‘2’ to jerk a WW driver with a relatively

![Figure 1. Schematic plot of rumble aggregate assembly box](image-url)
high intensity without damaging the vehicle tires. Upon choosing aspect ratio to be 1, the aggregate would have a circular shape, and the rumbling effect is reduced to some extent. This aspect ratio can be tuned to control the desired rumbling magnitude.

3. ANALYSIS
Since an intoxicated driver’s reaction to a warning traffic device remains unknown and likely be ineffective, it is imperative that these drivers should also be physically jerked with a high enough intensity so that they would, if not very heavily inebriated, be shaken enough to recognize that their WW driving might cause a fatal traffic collision. The above assembly of rumble aggregates, designed to achieve this goal, will provide the sober WW drivers the freedom to back out from the wrong driving direction without damaging the vehicle as a traffic spike device does. This directional rumble aggregate device with a side view shown in Figure 2, will fold the aggregates into the assembly box upon contact with a vehicle tire moving the right direction. The speed of the moving vehicle tire is of little significance in this context of discussion.

One may question whether the steel box design is strong enough to support the axle load ‘P’ imposed on top of the box by a WW vehicle. The average vertical pressure ‘σ’ exerted on the holes supporting the bar would be given by [6]

\[
\sigma = \frac{P/2}{N\Phi \Gamma}
\]

(1)
Parameter ‘N’ is number of walls inside the assembly, e.g. a 3-ft steel box will have a total of 4 walls, 2 external and 2 internal walls, supporting the aggregate bar (see Fig. 1). Using an extreme case of 9.08 tons (20 kips) axle load due to an 18-wheeler truck, one finds that the pressure ‘σ’ on a 4-ft steel box is approximately 36 MPA, which is about 13% of the yield strength of the steel. A typical axle weight of a small size truck is around 1.5 tons, indicating that the pressure exerted on the wall holes supporting the steel bar very likely would not exceed 6 MPA, which is far below the yield strength of the steel.

The tensile stress at the bottom side of the steel bar should be checked because it is critical ensuring the bar stringing the rumble aggregates will not fail upon heavy loading. It is known that the loading distribution on top of the bar depend on the number of aggregate contacts with the tires crossing the assembly wrong way. Without getting into the details of load distribution but considering a uniform loading across the bar, the critical bending tensile stress $\sigma_b$ for an 18-wheeler truck can be estimated through the following equation

$$\sigma_b = \frac{PA}{\pi \Phi^2}$$

(2)

Thus, the critical bending tensile stress $\sigma_b$ for a 20-kip axle load with 4 wheels is approximately 260 MPa, which is below the yield strength of the steel. It is also noticed that the loading duration on top of aggregate is fleeting since it takes approximately 0.03 second for a truck with a speed of 32 kph (20 mph) to go over the rumble aggregates. With such a short loading duration, even the steel bar was loaded beyond the yield strength, the permanent deformation caused by this heavy loading would be very minimal. In addition, it is very unlikely for a fully loaded commercial truck to get on an off-ramp because large visible “WRONG WAY” and “DO NOT ENTER” signs are often made retro-reflective at the ramp exits, and truck drivers in general pay more attention to roadway signs and the driving environment upon making a turn. Using a steel bar with a diameter of 3.23 cm (1.27”) to lock together the aggregates in a box assembly should be sufficient for sustaining WW vehicle loads in practice. One may choose a slightly larger bar such as the #11 steel bar with a diameter of 3.58 cm if necessary.

4. DIRECTIONAL RUMBLE STRIPS

At this point, it is not hard to imagine that a directional raised rumble strip can be constructed by welded together the rumble aggregates onto a narrow flat steel strip. An additional open slit on the top surface of the assembly box will allow the right directional traffic folds the entire raised strip into the box assembly. Upon a WW entry, this directional rumble strip will lift up wheels and cause high jerking motion inside the vehicle after the vehicle has crossed the bar. The jerk magnitude can be fine-tuned with the height of the aggregate above the top surface of the assembly box as sketched in Figure 2. Furthermore, sets of directional rumble strips may be placed across the off-ramp at various locations, such as the exit/entrance spots, to enhance the prevention of
WW driving onto a freeway. For example, installing a set of two or three parallel
directional rumble strips with escalated aggregate heights spaced, say 9-m (30-ft) apart,
at an off-ramp exit/entry, can be potentially very effective on stopping at least a fraction
of WW drivers at off-ramp exits/entries.

5. CONCLUSION
Since majority of WW drivers on freeways are intoxicated at various levels, traffic signs
and/or warning devices may not be effective for preventing this type of WW drivers
from entering freeway through off-ramp exits, and these WW drivers may have been
driving subconsciously as if they are performing the act of noctambulism. Because the visual and directional senses of an inebriated WW driver are impaired at least partially
if not totally, interacting with the driver via strong tactile stimulation would be an active
tool to awaken a WW driver from his/her drunken state of mind. Within this context,
installing directional rumble strips emerges to be the right tactic for shaking up the WW
drivers. The detailed specification of this conceptual design can be ironed out to fit an
in-situ roadway layout. It is foreseeable that this directional rumble-strip design, which
can be tuned to meet different practice interests, would have the potential of being
widely used for preventing WW driving worldwide, including but not limited to
installing the directional rumble strips/aggregates when necessary at one-way streets,
unsignalized, and signalized intersections.

REFERENCES