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Developing a Framework to Combine the Different Protective Features of a Safe System

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16. Abstract

While the overarching objective of the transportation system is to provide mobility, transportation professionals dedicate significant resources to build a safe system. The aspirational objective is to establish a system on which no road user can suffer catastrophic outcomes. To accomplish such a safe system, it is necessary to effectively harness all the core protective opportunities provided by the system. Despite the increasing consensus that this needs to be thought of as a systems problem, the considerations for each of these layers of protection are siloed, and many of the protective features are evaluated in terms of potential lives saved due to a specific improvement. To address this, the research identifies kinetic energy as the appropriate common denominator that captures the overall protective characteristics of the system. The researchers concluded that it is not practical to aggregate the additive capability of the system's elements to control or contain kinetic energy. However, it is valuable to evaluate the cumulative kinetic energy of the entire system and the researchers propose a framework that can support researchers and practitioners in better understanding the safety mechanism and identifying strategies that may have been overlooked.

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Contents

Introduction

While the overarching objective of the transportation system is to provide mobility, transportation professionals dedicate significant resources to build a safe system. The aspirational objective is to establish a system on which no road user can suffer catastrophic outcomes. This is not only a moral imperative but also an economic one. The U.S. road safety toll in 2016 claimed the lives of 34,439 people. Of those victims, 23,714 were occupants or drivers of a motor vehicle; 5,987 were pedestrians; and 4,738 were motorcyclists, bicyclists, and other nonoccupants. The estimated economic cost of all motor vehicle traffic crashes in the United States in 2010 was $242 billion and is expected to be much higher today [1].

In the transportation safety realm, catastrophic outcomes are commonly considered fatal and severe crashes [2,3,4]. This is supported by initiatives by various national and international organizations [5,6,7,8], and by an increasing number of endorsements by cities, states, and countries [9,10]. These concepts represent a shift in the way we think about traffic safety by acknowledging that even compliant road users will misjudge road conditions. This, in turn, calls for a safe system that does not distinguish between road injury factors and can be conceptualized as a transport system that is inherently safe for human users [10].

However, despite the intentional effort to establish this new set of safety priorities there is still no framework that can provide consistent traction for action. The actual implementation efforts depend heavily on institutional opportunities across different jurisdictions and less on prescribed best practices. The result is that the current system has major structural shortcomings that can lead to catastrophic outcomes because of human misjudgment and error.

To accomplish such a safe system, it is necessary to effectively harness all the core protective opportunities provided by the system. For example, if we're looking at bicycle safety, we would want alert and compliant cyclists and other road users, to make trips using safe bicycles and safe vehicles, on safe streets designed with adequate separation from motorized traffic, all of which are governed by safe speeds, and supported by effective cyclist protection and the emergency medical system when needed. Similarity, if we're looking at pedestrian safety, we would want alert and compliant pedestrians, to make trips on safe streets, with adequate separation from safe motorized vehicles, operated by alert and compliant users, all of which are governed by safe speeds, and supported by effective pedestrian protection and the emergency medical system, when needed.

Despite the increasing consensus that this needs to be thought of as a systems problem, the considerations for each of these layers of protection are siloed, and many of the protective features are evaluated in terms of potential lives saved due to a specific improvement. In other words, discrete injury factors are systematically identified and countermeasures to these factors are implemented. The goal of this research is to examine what happens when we no longer assume each of the individual components holds a desirable level of protection for a certain circumstance, but that they contribute to a larger joint entity (i.e., the system) that can exhibit the required characteristics or traits (i.e., safe). The premise here is that there is a set of protective features that can jointly fulfill the promise of a safe system. In other words, the street design, the vehicle design, and the rest of the system's components create a package that delivers safe travel.

A challenge of the proposed approach is related to the fact that the protective opportunities seem inherently different. Some countermeasures separate road users over space, while others separate users over time. Some encourage desirable behavior, while others protect from injury. To address this, the research identifies the appropriate common denominator as kinetic energy that captures the overall protective characteristics of the system. Assuming energy is indeed valuable, it would enhance our initial conjecture to also require that the set of protective features would provide a safe and structured dispersion of kinetic energy for all street users.

An additional challenge is due to variation in the levels of kinetic energy that road users carry and that they are exposed to. When vehicles travel freely on highways, they carry much more energy than when they travel in urban areas. Similarly, pedestrians carry much less kinetic energy than they are exposed to. Considering this, there is a necessity to specify the level of kinetic energy that the system would need to contain for different types of travel. By incorporating these considerations, we can establish an overarching goal to be the development of a framework to quantify the capability of sets of protective features to jointly provide a safe and structured dispersion of kinetic energy for road users, given a predetermined threshold.

Motivation

This research considers the magnitude of a safety event as the core peril at hand. Since most trips don't result in a safety event, the corresponding safety magnitude is usually close to zero. However, when a hazardous situation occurs, the magnitude rises significantly and represents the level of potential harm that the system needs to contain, if no action is taken. Again, if we assume the magnitude can be approximated by kinetic energy, the problem reduces to a set of system components that should, in series or in parallel, dissipate or redirect as much energy as possible before it reaches a road user. Ideally, the level of kinetic energy should be reduced such that the road user is not exposed to magnitudes that exceed what the human body can sustain. For illustration purposes, we consider an example of lane drifting by a distracted driver which would lead to a head-on collision with an oncoming vehicle. In this case, the components of the system need to provide enough buffers to protect the road users. These buffers can include brakes which can directly reduce the magnitude, a shoulder lane which can modify the crash angle and reduce the impact (a wide paved shoulder can also redirect the energy so that the vehicles don't collide), followed by the vehicle's capability to absorb energy, and finally the occupant protection systems which help manage the eventual bodily impact. The expectation is that, jointly, these components would protect the road users from such perils that typically arise due to human misjudgment.

The Safe System Approach

The Safe System approach to road safety is a holistic approach that seeks to reduce the harm caused by road traffic collisions by designing roads, vehicles, and speed limits in such a way as to protect road users from serious injury or death. This approach recognizes that mistakes and collisions are inevitable, so the focus is on minimizing the consequences of these incidents. This is achieved by implementing a range of measures, including separating different types of road users, providing safe infrastructure for pedestrians and cyclists, and ensuring that vehicles are designed to minimize the risk of injury to occupants and other road users in the event of a collision.

Safety Approaches in Other Disciplines

To better understand the opportunities to fuse together different elements of risk, the research team is exploring literature in other disciplines. The added value of this is to evaluate whether there is a generic mechanism to combine various aspects of safety.

Types of Risks

Risks can be classified into three main categories: scene-based risks, location-based risks, and action-based risks. These types of risks are clearly outlined in the construction industry. Scene-based risks, also referred to as unsafe conditions, are those related to the static conditions of the construction site. These risks include the absence of hard hat requirements and the presence of fall hazards. Construction sites also involve location-based risks related to the interaction between the static environment and different movements, such as workers not being alerted to moving vehicles that could collide with them. A failure resulting from such a risk is not due to unsafe actions, but to failure to consider certain interactions between different elements of the job site [12]. Action-based risks, also referred to as unsafe actions, are introduced when certain actions which defy the safety rules are taken. This type of risky behavior at construction sites includes carrying heavy items or operating equipment while maintaining improper posture [13].

These types of failures are also conveyed in the healthcare field as performance obstacles. Scene-based risks are portrayed by tool performance obstacles when the required tools for proper functioning are absent. Location-based risks are portrayed through physical environment performance obstacles, such as a poorly designed hospital space that impedes easy movement of hospital staff, meetings for medical personnel, or the comfort of patient rooms. Action-based risks in the healthcare field involve organization-based performance obstacles such as delays in ordering medication [14].

In the transportation field, risk-inducing conditions can also be classified into these categories. Scene-based risks in the transportation field include poorly designed transportation facilities such as inadequately illuminated roadways [15] or poor geometric road design [16]. In addition, severe weather conditions can be identified as location-based risks since nonrisky behavior may interact with other conditions related to poor weather, such as slippery road conditions [17]. Action-based risks, which are based on human behavior, are a quite common reason for failure in the transportation field. These risks include speeding and driving under the influence of alcohol [18].

Classifying risks into scene-, location-, and action-based categories is useful in understanding the reasons behind system failures. While the identification of the several types of risks are important, the next step is determining how to identify risk-inducing conditions beyond the constraints of these classifications to increase system safety.

Identification of Risk-Inducing Conditions

To solve a problem, one must know that it exists. Risk-inducing conditions are certain aspects of a system that are deemed unsafe and can potentially cause future failure. In the healthcare industry, great attention is focused on reducing risk. Patients and hospital staff are encouraged to report health and safety concerns. Recurring risk factors lead to safety checks to better understand and address reported problems [19]. Many hospitals follow a safety procedure during surgery that obliges the operating team to follow up on any health and safety concerns reported during the operation, such as lost sponges or tools that might have been left inside the patient [20]. In addition, safety-driven innovations have helped streamline and improve risk identification in hospitals [21]. These innovations include computerized decision support tools that contain patient information and could help prevent errors when prescribing new medication or allergic reactions to certain treatments. For example, a computerized decision support system was helpful in preventing the prescription of iodine, required for magnetic resonance imaging (MRI) scans, to patients who were allergic to it [20].

This principle is also applied in the construction and electronics fields. Safety inspections are required at many construction sites. These inspections require the identification of safety concerns or risk-inducing conditions, including fall hazards in the form of unsecured holes or unfixed railings [22]. In addition, with the advent of building information models, designers are now able to check the model and schedules for safety concerns [23]. In the electronics field, some components are equipped with self-checking capabilities that can identify when they have failed. Self-checking enables the replacement of the failed components before further and potentially more severe failures occur [24].

In the transportation field, the identification of risk-inducing conditions is also given importance. As in the healthcare field, different stakeholders are encouraged to identify these conditions so they can be addressed. Currently, road accidents and crash-related injuries, which are indicators of risk-inducing conditions, are primarily reported by the police. However, this reactive approach sometimes leads to underreporting in the number of incidents [25]. Other proactive approaches are recommended to better identify safety concerns. Designers are urged to voice safety concerns to their superiors during the design process [26]. Road users are also encouraged to report road safety concerns using crowd-sourcing mobile applications [27]. Similarly, in the construction field, building information models have integrated tools for roadway safety inspection, such as those for sight distance [23]. In the field, some instrumented intersections are equipped with risk identification features through the installation of laser scanners, cameras, and infrastructure-to-vehicle communication devices, which have all been proven to significantly decrease crash rates [27]. In addition, assisted driving systems, which fall under safety-driven innovations, act as features that help identify risky conditions that could lead to failure. These features, which include lane departure warnings and high-speed alerts, alert the driver, and could help in avoiding these risk-inducing conditions [28,29].

In the transportation field, as in other fields, the identification of risk-inducing conditions plays a key role in the proactive prevention of future failures. It is evident that encouraging various stakeholders to report safety concerns and integrating safety driven innovations into the transportation system are along the path towards a safe system.

Principles in Safe Systems

After introducing different types of risks and how to identify risk-inducing conditions, the following sections will introduce three major principles to be followed toward achieving a safe system: redundancy, designing around vulnerable users, and inherent fail-safety.

Redundancy

Redundancy ensures the system's availability even in case of a failure. This principle has been explored extensively in the electronics field. A common approach to the problem of the lack of system availability is the replication of the building blocks of the system or its components. There are two main types of replications: active replication and passive replication [30]. Active replication, also referred to as providing a composite fail-safe system, involves having identical components working at the same time while the output from only one primary component is used. If the primary component fails, its identical counterpart becomes the primary component in the system. Passive replication, also called providing a reactive fail-safe system, involves having one functional primary component and an identical nonactive backup component. If the primary component fails, the backup component starts functioning and acts as the primary component [30,31]. In both types of replications, the system itself must be able to identify a failure to shift the primary role from one component to the other through a process called self-checking [31, 22]. In active replication, this process is conducted directly through the acceptance of the output of the secondary component; however, passive replication requires a swift reaction time on the part of the operator to detect the failure and activate the backup component [22].

In the construction industry, redundant systems are used in critical activities. One example is redundant braking systems in cranes. Cranes used in certain situations, particularly in nuclear plants, are required to have redundant braking systems that activate the backup brakes in case the primary brakes fail [21]. The healthcare industry also relies on redundancy to prevent specific health-related failures. Active replication is applied through requiring workers to wear two sets of gloves while handling antineoplastic drugs to prevent exposure [22,23]. Some hospitals employ passive replication in their patient oxygen-delivery systems. These systems incorporate two separate oxygen sources and pipe systems, and the second system is used only if the primary system becomes contaminated [24]. In addition, although hospitals are generally connected to the main power grid, they are required to have a backup power source to avoid serious failures in the event of power outages [25]. Redundancy has been proven to be particularly efficient in preventing blood transfusion errors via the requirement of two sign-offs at every stage of the transfusion process [8]. In the transportation field, redundancy has been implemented in numerous situations. Civil aircrafts incorporate redundancy principles in their critical systems, such as hydraulics and electrical wiring to augment system reliability [26]. Another example of an active redundancy feature is brake-by-wire systems in vehicles using brake pedal sensors. This redundancy feature works by installing two sensors in the brake pedal which work in parallel to prevent braking failure due to lack of sensor responsiveness [27]. Another example of redundancy employed in the transportation field is lane separation by both lines and reflective studs; if a driver fails to see the lines, the reflective studs act as an active redundant measure which serves as a secondary lane departure warning [28].

As illustrated in these examples, redundancy can be applied toward achieving safe systems in many different fields. It should be noted that such systems are expensive [29]; however, integrating redundancy in vehicles and infrastructure to prevent crashes resulting from failure scenarios is crucial.

Vulnerability

Another important principle that could be utilized in achieving a safe system is the concept of designing around vulnerable users. Vulnerable system users may be either at an increased risk of being exposed to failure or at an increased risk of being injured in the case of a failure [30,31,32]. In the healthcare field this principle is applied when considering vulnerable patients and populations. Vulnerable patients in the healthcare field include newly admitted patients who are severely ill, and patients who have just undergone surgery. It is recommended that various functional aspects of hospital design should be oriented around these patients' needs since they are more susceptible to medical failure. Examples of such designs include the proper location of patient-only elevators and corridors to ease patient movement; patient transfer procedures to ensure proper information transfer; the size of toilet facilities to accommodate limited mobility of patients; and visibility-maximizing measures such as windows to allow nurses to check on patients without disturbing them [33]. Another group discussed in the literature is vulnerable populations which include low-income individuals and ethnic minorities. These population groups are considered vulnerable because they have reduced access to social support and healthcare, and thus are less likely to be screened for certain types of cancer and other diseases. It has been recommended that programs be established to conduct screenings for this vulnerable group [30].

In the construction industry, regulations to protect workers exposed to occupational health and safety risks are recommended. The Department of Health and Human Services suggests that young immigrant workers in the construction field are at increased vulnerability and that this disparity should be addressed [32]. In the electronics field, some aspects of design are driven by vulnerable system components. For example, some industry standards have been changed to protect electronic components that are vulnerable to electrostatic discharge [34], while certain microelectromechanical applications have been developed to protect vulnerable electrical components from exploitation through reverse engineering [35].

The transportation field employs this principle by considering vulnerable road users in numerous aspects of design. Vulnerable road users such as pedestrians and cyclists are at greater risk of injury because of traffic crashes. The needs of these vulnerable users, of reducing crash risk and reducing the effects of a crash, are considered in the design of various elements of the transportation network. Bike lanes have been shown to significantly decrease the risk of crash exposure [31]. In addition, while helmet usage has not been shown to reduce biker crash risk, it has been shown to reduce the effect of a collision [36]. In addition, the rise of new technologies in the intelligent transportation systems sector has offered new opportunities to protect vulnerable road users, such as vehicle-to-pedestrian communication technologies to enable smart vehicles to better manage interactions with pedestrians [37].

The principle of designing around vulnerable users of a system has been demonstrated in the healthcare, construction, electronics, and transportation fields through the consideration of vulnerable groups (patients and populations), workers, electrical components, and road users, respectively, in the design process. Further exploration of the characteristics of vulnerable road users and how the transportation system can better accommodate them to achieve a safe system is crucial.

Inherently Fail-Safe Systems

Inherent fail-safety is another principle that could be employed in working toward achieving a safe system. An inherently fail-safe system takes into account the effects of possible failures and enters a default safe state in the case of failure. This principle is of particular focus in the electronics domain, where there is no tolerance for catastrophic effects or loss of system safety due to a single component failure. One method for achieving inherent fail-safety is ensuring that different elements of the system are separate and independent of each other's failures [20]. Both passive and active redundancy measures can be applied to achieve inherent fail-safety [19,27]. In addition, the concept of "0/1 fail-safe output" is used in the electronics field to highlight the importance of the default output of the system in case of failure. One way a "0 fail-safe output" can be established is by enforcing system shutdown in case of a catastrophic failure. The "0 fail-safe output" concept can be applied to the electronic elements used in the transportation field. It is suggested that when the motor control system of a vehicle fails, the engine should turn off by default. It is also suggested that a failed traffic signal shouldn't provide a red or a green light if its system has failed since that might lead to accidents; instead, the suggested "0 fail-safe output" is a flashing yellow light [38]. Another example of inherent fail-safe systems in vehicle electronics is the call-in center procedure for automated Nissan vehicles—if a Nissan self-driving car encounters problems while driving, operators in call-in centers take control of the car and steer it until the vehicle is able to make safe decisions again [39]. The application of inherent fail-safety in transportation is not limited to the electronic components of the transportation system. For example, the addition of guardrails along roads minimizes the negative effects of failures characterized by vehicles leaving their lanes [3].

While the principle of inherent fail-safety has been thoroughly explored in the electronics field, it also has some application in the construction and healthcare industries. In the construction field, emergency action plans act as inherent fail-safe measures by considering possible failures such as worker injuries and determining how to address them in an efficient manner to prevent catastrophic results such as permanent disability [40]. In the healthcare industry, the principle of “designing around precarious events” as a safety design principle involves designing various aspects of hospitals while considering repeated failures to avoid the occurrence of such failures. To reduce inpatient suicides, some patient rooms are designed with features to prevent suicide. In addition, standardizing operating rooms and tube connectors in patient rooms help to reduce medical errors [33].

These examples illustrate the application of inherent fail-safety in designing safe systems. While this concept has already been implemented in various electronic and infrastructure elements of the transportation system, additional integration of inherent fail-safety design principles would further increase the safety of the transportation system.

Kinetic Energy in the Transportation System

Kinetic energy is a form of energy that an object possesses due to its motion. It is the energy that an object has because of its motion or movement. Kinetic energy is important because it is a fundamental concept in many fields, including physics, engineering, and mechanics. In physics, kinetic energy is a measure of the energy that an object has due to its motion and is a fundamental concept in the study of the motion of objects. In engineering, kinetic energy is important because it is a measure of the potential for work that an object has due to its motion. In mechanics, kinetic energy is important because it can be used to predict the behavior of moving objects, and to calculate the forces that act on them.

The source of the energy absorbed by road users during a crash is the car’s impact kinetic energy. When the transferred kinetic energy exceeds the human body's protective capacity, road users will be injured. The higher the amount of conveyed energy, the more severe the injuries may be [54]. The car’s impact kinetic energy can be calculated using the equation $E = \frac{1}{2} m {v_1}^2$.

Where:

E: The impact kinetic energy of the car (Unit: J).

m: The mass of the car (Unit: kg).

v_1: The impact speed of the car (Unit: m/s).

Therefore, in order to better protect road users, the energy transferred from vehicles should be reduced as much as possible. Note that here the conveyed energy should not just be cut down to the level that the human body can accept. The reason is that some extra error tolerance ought to always exist in case some extreme conditions happen. In addition, due to the fact that fatalities or severe injuries can occur at various energy levels, it is plausible not to target specific energy reduction criteria.

The reduction can be achieved by two methods generally: First, reduce the total impact kinetic energy that the vehicles possess. Second, make sure that the vehicle itself absorbs the kinetic energy as much as possible via designs such as crumple zones. During the pre-crash phase, only the first countermeasure can be achieved, as the collision does not occur throughout this time interval. Thus, the problem of protecting the road users can be converted to how to reduce the vehicle's kinetic energy to the maximum extent.

The vehicle's kinetic energy dissipation during the pre-crash process can be obtained by calculating the difference of the car's initial kinetic energy and the impact kinetic energy. In order to quantify the amount of energy dissipation during the pre-crash phase, the following equation can be used:

$$\alpha = \frac{\Delta E_k}{E_0} = \frac{E_0 - E_1}{E_0} = \frac{\Delta \frac{1}{2} m v^2}{\frac{1}{2} m v_0^2} = \frac{\frac{1}{2} m v_0^2 - \frac{1}{2} m v_1^2}{\frac{1}{2} m v_0^2} = 1 - \frac{\frac{1}{2} m v_1^2}{\frac{1}{2} m v_0^2} = 1 - \frac{v_1^2}{v_0^2}$$

Where:

α: The proportion of the vehicle's kinetic energy dissipation during pre-crash compared to the initial kinetic energy.

ΔE_k: The dissipated kinetic energy during the pre-crash process.

E_0: The initial kinetic energy of a vehicle.

E_1: The impact of kinetic energy of a vehicle.

v_0: The initial speed of a vehicle.

v_1: The impact speed of a vehicle.

The following case is an example of the application of this equation.

Crashworthiness Data System (CDS) and Kinetic Energy

This crash case is documented in the National Automotive Sampling System - Crashworthiness Data System (NASS CDS) with the case ID 149006672. Here is the brief crash description: Vehicle 1, a 2001 Honda Odyssey was traveling south on a four lane, two-way undivided roadway. Vehicle 2, a 1998 Toyota Sienna was traveling north on the same roadway. Vehicle 2 started to make a left turn in front of Vehicle 1, and the front of Vehicle 2 contacted the front of Vehicle 1. Both vehicles rotated and side slapped, with the left side of Vehicle 1 contacting the right side of Vehicle 2. The weather was clear, and the roadway was dry. It was daylight at the time of the crash. The scene diagram is shown in Figure 1 below.

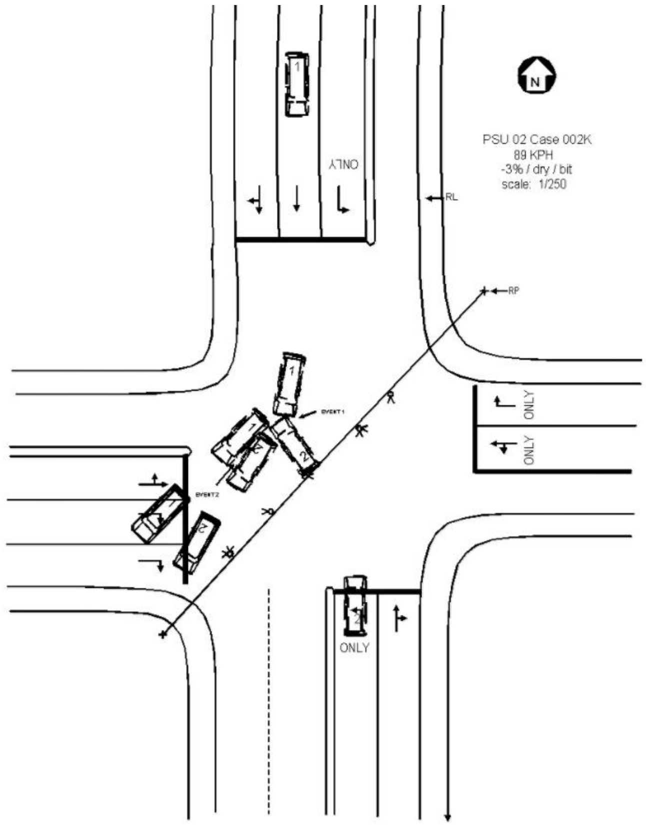


Figure 1. Crash (case ID 149006672) illustration

Using the equation above, the proportion of kinetic energy dissipation of both cars can be calculated.

For vehicle 1:

$$\alpha = 1 - \frac{v_1^2}{v_0^2} = 1 - \frac{45^2}{69^2} = 0.5747$$

For vehicle 2:

$$\alpha = 1 - \frac{v_1^2}{v_0^2} = 1 - \frac{31^2}{68^2} = 0.7922$$

After analyzing several real-life cases (case IDs 760012655, 149006673, 149006711, 149006733, 149006791, 149006811, 149006831, 149006851) from NASS CDS, the results show that kinetic energy reduction during the pre-crash process is pretty significant with α ranging from 60% to 90%. The energy dissipation accounts for a large amount for the vehicle's initial kinetic energy.

As E_0, the initial kinetic energy, is constant for a specific traffic scenario and the impact kinetic energy, E_1, is the main source of the absorbed energy by the road users, in order to minimize E_1 with the aim of better protecting road users, the energy dissipation during the pre-crash process needs to be maximized.

During the pre-crash process, the vehicle's kinetic energy dissipation is mainly due to the energy loss caused by braking. A vehicle's braking, in general, results in two different kinds of friction: friction between the vehicle's brake pad and the rotor of the wheels, and friction between the vehicle's tires and the ground.

Additionally, other kinds of friction account for the vehicle's kinetic energy dissipation during the pre-crash process. For example, air resistance and mechanical resistance inside the vehicle can both lead to the energy loss of the vehicle.

However, these kinds of friction remain effective not specifically during the pre-crash phase but the whole process while the vehicle is in operation. Furthermore, vehicle manufacturers always want to minimize these kinds of friction in order to improve the efficiency of the vehicles. For instance, the improvement of the aerodynamics of car shapes, more precisely the reduction of their drag coefficient, is one of the main topics of automotive research centers [55].

Therefore, the main focus here is how to maximize the kinetic energy dissipation during the pre-crash phase caused by the friction between the vehicle's brake pad and the rotor of the wheels and the friction between the vehicle's tires and the ground.

The pre-crash energy dissipation maximization objective function is stated as follows:

$$\max\ E_b = F_p * d_p + F_R * d_R$$

Where:

E_b: The dissipated kinetic energy caused by the friction between the brake pad and the rotor of the wheels and the friction between the wheels and the ground during the braking process.

F_p: The friction force between the cars' brake pad and the rotor of the wheels.

d_p: The relative displacement between the cars' brake pad and the rotor of the wheels.

F_R: The friction between the car's tire and the road.

d_R: The distance that the center of the wheel travels on the road during the braking process.

Friction between brake pad and rotor

There exist several aspects that can be improved in order to maximize E_b.

First of all, it can be done by maximizing F_p, the friction force between the car's brake pad and the rotor of the wheels. The function of F_p is:

$$F_p = f(M_p, T_d)$$

Where:

M_p: The material of the brake pad.

T_d: The type of vehicle's brake disc.

M_p plays an important part in determining F_p. The friction materials of the brake pad are supposed to have high and stable friction coefficient, great thermal conductivity, excellent heat and wear resistances, and weak absorbability of water, oil, or brake fluid [56].

Depending on the matrix material [57], M_p can be divided into three basic categories: metallic, semimetallic, and nonmetallic matrix material. For metallic matrix materials, a significant advantage is that they have very high conductivities resulting in being able to remove heat from the frictional surfaces very quickly. On the other hand, they will rust, especially if the vehicle has an extended rest period [56]. Another drawback of using metallic matrix materials is that they might cause excessive wear of the brake disc. Steel has also been shown to increase friction coefficient fluctuations [58], likely because it abrades the transfer film between braking surfaces, which is responsible for friction coefficient stabilization.

As for the semimetallic matrix friction material, it has great heat resistance, high power absorption, and excellent tribological properties. However, it also has some shortcomings such as low frequency noise, easy rusting, and long-term serious damage to the brake disk. Nowadays, semimetallic matrix friction material is widely applied in automobiles, motorcycles, and other light vehicles.

There are a series of nonmetallic matrix friction materials, among which the ceramic matrix composite friction materials have extremely excellent tribological properties. In the field of ceramic matrix composites, carbon/carbon materials (C/C) have been in use for friction applications in airplanes and Formula One race cars for several decades [57-60]. The C-C composite friction material has high strength and toughness, superior thermal stability, and favorable wear resistance. At present, the C-C composite friction material is mainly used in planes and race cars. However, C/C shows some drawbacks, in terms of their low coefficient of friction at low temperatures and high humidity conditions. Therefore, this material is not suitable for lifetime brakes in passenger cars. Only at temperatures above 400° C are carbon/carbon brakes favorable and show very promising performance. For passenger cars, during normal street use brake disks and pads won't see temperatures climb past 200° C [61].

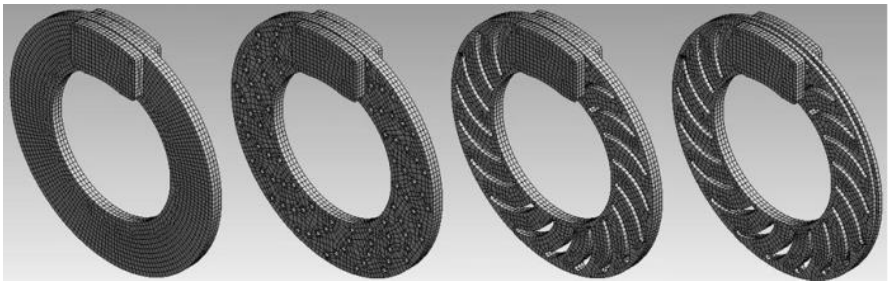
Based on these drawbacks and the time and cost consuming fabrication process, C/C brakes are not suitable for service brake applications. When replacing the carbon matrix by SiC, the obtained C/SiC composites show a significantly enhanced wear and oxidation resistance compared to C/C. Furthermore, the tribological performance of the material is improved as well [62].

As a result, because of the shortcomings of metallic, semimetallic, and C/C materials, in order to maximize the energy dissipation, the C/SiC composite friction materials should be used to produce brake pads.

The type of vehicle brake disc, T_d also has a huge influence on the friction force between the car's brake pad and the rotor of the wheels. During the braking process, part of the vehicle's kinetic energy is converted to heat. Around 90% of this energy is absorbed by the brake disc and then transferred to ambient air. One of the most common problems related to brake discs is overheating, which negatively affects braking performance especially under the continuous braking conditions of vehicles [63].

Ventilated brake discs generally exhibit convective heat transfer coefficients approximately twice as large as those associated with solid discs [64].

There are three typical different ventilated disc designs: cross-drilled (CD), cross-slotted (CS), and cross-slotted with side groove (CS-SG) discs.



(a) SL disc (b) CD disc (c) CS disc (d) CS-SG disc

Figure 2. Solid (a) and three typical disc designs (b)-(d)

After using the finite element analysis method to determine the thermal behaviors of ventilated brake discs using three different configurations at continuous brake conditions in terms of heat generation and thermal stresses, heat generation on the solid brake disc surfaces is reduced to a maximum of 24% by ventilation applications. The experimental study verifies the finite element temperature analysis results in a range between 1.13% and 10.87%. This result shows that ventilated brake discs will positively affect braking performance by maintaining the friction coefficient between the pad and the disc surface and by stabilizing the wear rate of the pad surface, especially under continuous braking conditions.

One shortcoming is that the thermal stress formations are higher with ventilated brake discs (CD, CS, and CS-SG discs) in comparison to those with solid discs. However, maximum stress formation is reduced to 11% and 19% for the CS-SG disc configuration in comparison to other ventilated disc designs (CD and CS). In other words, CS-SG discs can more effectively reduce heat generation and thermal stresses among ventilated brake discs. Therefore, this disc configuration should be used to produce brake discs. Other than M_p, T_d, some other factors, such as the material of the brake disc and the type of brake (drum or disc), are also worth improving. For instance, the analysis of the material for the brake disc is like that of the brake pad and the disc brake has more stopping power than the drum disc. These factors are also worth looking into, but they are out of the scope for this research.

Friction between tires and road

Secondly, pre-crash energy dissipation can be maximized by maximizing F_R, the friction between the car's tire and the road. The function for F_R is:

$$F_R = h(M_t, T_R)$$

Where:

M_t: The material of the tires.

T_R: The texture of the road.

As the material for making the tire is mainly rubber, the properties of rubber friction on the road surface are of great importance. Rubber friction depends on the history of the sliding motion (memory effects), which is found to be crucial for an accurate description of rubber friction. For rubber sliding on a hard rough substrate, the historical dependence of the friction is due to frictional heating in the rubber-substrate contact regions. It is also called flash temperature, illustrating that the temperature in the rubber-road asperity contact regions at time t depends on the sliding history for all earlier times $t' < t$. This effect is demonstrated in the following figure concerning a rubber tread block sliding on an asphalt road surface [65].

This effect is illustrated in Figure 3 for a rubber tread block sliding on an asphalt road surface. The (calculated) kinetic friction coefficient for stationary sliding without (blue curve) and including the flash temperature (red curve) is showed as a function of the velocity v of the bottom surface of the rubber block. The black curves show the effective friction during nonstationary sliding experienced by a rubber tread block during braking at various slips (slip values from 0.005 to 0.09). Because some finite sliding distance is necessary to fully develop the flash temperature, the friction acting on the tread block initially follows the blue curve corresponding to “cold rubber” (neglecting flash temperature). Thus, it is not possible to accurately describe rubber friction with just a static and a kinetic friction coefficient or even with a function $\mu(v)$ which depends on the instantaneous sliding velocity $v(t)$. Instead, the friction depends on $v(t')$ for all times $t' \leq t$.

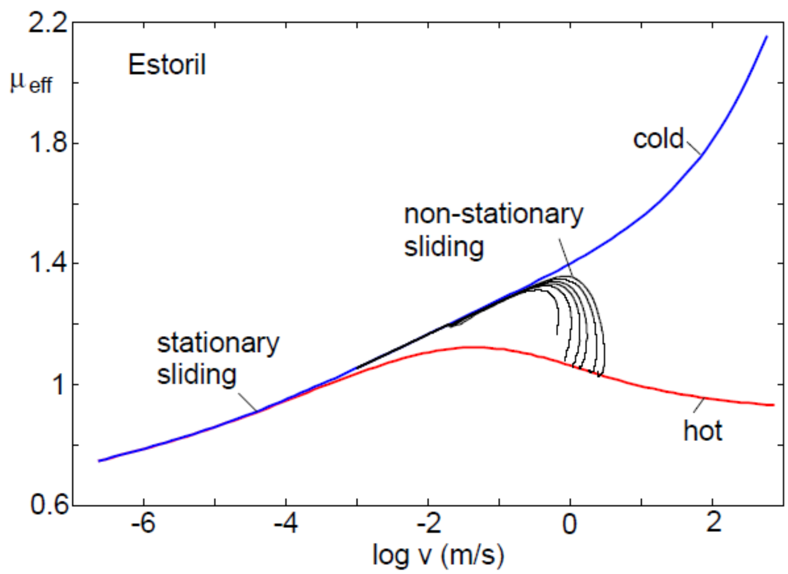


Figure 3. Kinetic friction coefficient for a rubber tread block sliding on an asphalt road surface.

At exceptionally low sliding velocity, the temperature increase is negligible because of heat diffusion, but for velocities of order 0.01 m/s the local heating may become especially important [66 page 7790]. Therefore, to alleviate the negative impacts caused by flash temperature, low heat buildup materials should be incorporated to produce the tires. For example, polybutadiene is often used in combination with other rubbers because of its low heat buildup properties. Silica, used together with carbon black in high-performance tires as a low heat buildup reinforcement, is another kind of enhancer that can be effective.

In addition to the materials of the tires, the tread pattern and pressure (which affects the contact area between the tire and road) are other attributes of the tires that can affect F_R. These factors are also worth studying but they are not the focus for this research.

T_R: The texture of the road also has a major influence on F_R. Pavement texture is defined by the American Association of State Highway and Transportation Officials' *Guide for Pavement Friction* as "the deviations of the pavement surface from a true planar surface" [67]. To classify the characteristics of these deviations and their impact on pavement surface performance, the Permanent International Association of Road Congresses has defined a scale based on the wavelength of the deviations [68].

Tire pavement friction is dominated by the texture, or roughness, of the surface, with different texture components making different contributions. Of fundamental importance on both wet and dry roads is the microtexture, that is, the fine-scale texture (below about 0.5 mm) on the surface of the coarse aggregate in asphalt or the sand in cement concrete that interacts directly with the tire rubber on a molecular scale and provides adhesion. This component of the texture is especially important at low speeds but needs to be present at any speed.

On wet pavement, as speed increases skid resistance decreases and the extent to which this occurs depends on the macrotexture, typically formed by the shape and size of the aggregate particles in the surface. Surfaces with greater macrotexture have better friction at high speeds [69].

Therefore, pavement friction design involves utilizing proper materials and construction techniques to achieve a high level of microtexture and macrotexture in the pavement surface. The type of aggregates used in the surface mix directly affects the microtexture, while gradation and size of aggregates governs the macrotexture properties of the pavement surface. The wear characteristics of aggregates are also important in maintaining proper friction level. Aggregates' mineralogy and hardiness directly affect the durability and polish ability of the aggregates. It is generally better to have aggregates with different sizes and wear characteristics in the mix so they can constantly renew the surface [70].

Braking distances

Third, the maximization of the pre-crash energy dissipation can also be done by maximizing d_p and d_R. In order to achieve it, the relationship between d_p and d_R should first be calculated. The assumed relationship between them is as follows:

$$d_p = (0.7 \sim 0.9) * d_R$$

When considering cars with an antilock braking system, during the braking process the actual friction between the car's tire and road consists of both static friction and dynamic friction. The maximum friction is achieved at the endpoint of static friction changing into dynamic friction. This is because the friction coefficient between the car's tires and the ground is the largest at this endpoint. The fraction of the slippage is approximately 10-30% [71]. This is illustrated in Figure 4 below.

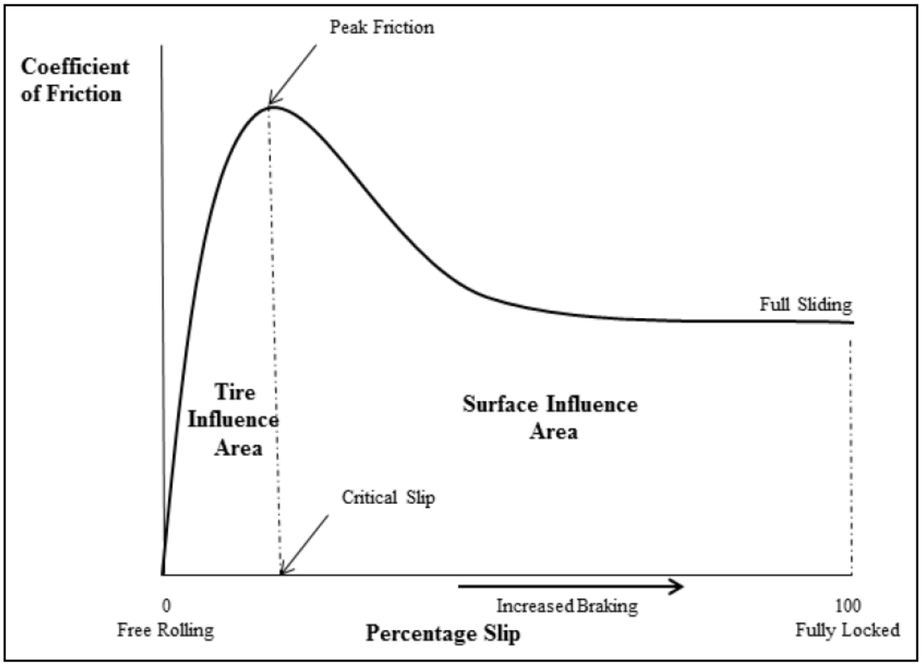


Figure 4. Friction versus slip [18]

During the slippage, the friction between the ground and the tires is the dynamic friction, which results in the relative displacement between the brake pad and the rotor being zero. Thus, d_p is around 70% to 90% to

d_R.

Thus, the problem for maximizing d_p and d_R can be transformed to maximize d_R. The following relationships need to be considered.

$$d_l = d_r + d_R$$

$$d_r = v_0 * R_t$$

Where:

d_l: The total line distance. It is defined as the line distance between the car and the hazard the instant the driver has eye contact with it. In other words, it is the line distance between the car and the hazard exactly before the reaction time starts.

d_r: The distance that the center of the wheel travels during the reaction time.

v_0: The speed of the vehicle the instant the driver has eye contact with the hazard.

R_t: The reaction time of the driver.

Thus, maximizing d_R can be achieved by minimizing d_r, which is a function of R_t *and* v_0. Another factor that needs to be considered is the extra maneuverability the road can provide. For example, if the shoulders of the road are wide enough, the driver can have a longer time to perform braking, which will result in the increase in d_R. The relationship can be described as follows:

$$d_R = g(d_r(R_t, v_0), M_R)$$

Where:

M_R: The maneuverability that the road can provide. For example, during the pre-crash phase, if the shoulder of the road is wider than the limit, the driver will be able to steer the vehicle properly in order to increase d_R and eventually increase the kinetic energy dissipation. A wider lane can also be effective.

The factors that affect reaction time is illustrated in the equation below:

$$R_t = k(U, CL, SRC, PRP, A, G, NOS, V, RC)$$

Where:

U: The urgency of the driver. People brake faster when there is greater urgency when the time to collision is briefer.

CL: The cognitive load of the driver. When other driving or nondriving matters consume the driver's attention, then braking time becomes longer.

SRC: The stimulus-response compatibility of the action. Humans have some highly built-in connections between percepts and responses. Pairings with high stimulus-response compatibility tend to be made extremely fast, with little need for thinking and with low error.

PRP: The psychological refractory period of the driver. Following a response, people exhibit a psychological refractory period. During this period, new responses are made more slowly than if there had been no previous behavior.

A: The age of the driver. Most basic research finds that older people respond more slowly than younger ones.

G: The gender of the driver. Although the data is not clear, it seems likely that females respond slightly more slowly than males.

NOS: The nature of the signal. Some braking cues are subtler and more difficult to detect, causing slower braking times.

V: The visibility of the environment. Reaction time increases in poor visibility (low contrast, peripheral viewing, bad weather, etc.).

RC: The response complexity of the action. More complex muscular responses take longer.

Implications of Pre-Crash Kinetic Energy Analysis

Despite significant efforts, it is notable that adding up the different components of kinetic energy is not a practical way to establish an estimation of the kinetic energy that can be contained by the system. As a result, a different approach was pursued.

An Aggregate Framework

To develop an alternative framework, it was necessary to step back from the additive perspective and approach the objective from an aggregate direction. This is done recognizing that kinetic energy is indeed the focal variable of interest. When observing values of kinetic energy in the transportation system, it is not only the magnitude of the kinetic energy that matters. For example, the amount of kinetic energy carried by an airplane is very high but that does not immediately translate to a higher risk. Another example is walking on ice, which carries a limited amount of kinetic energy but does not immediately translate to lower risk. In other words, the direction of bigger kinetic energy does not always translate to a bigger problem. Another way to think about it is that different levels of kinetic energy, but not indicated of safety.

When we talk about kinetic energy, we want to keep in mind this relationship. With every safety action, we want to determine whether we are increasing capability or decreasing kinetic energy of a typical trip. Both are attributes of the system. We have some empirical evidence that this is reasonable. During COVID no real change in the system's capability to control or contain kinetic energy was implemented. However, the rate of fatal and severe crashes went up. This is possibly due to an increase in the amount of kinetic energy carried by users during a trip due to higher speeds and less congestion. This provides a direction where we compare the amount of kinetic energy carried by users to the capability of the system to control it. The takeaway here is that we want a framework to understand how we can change the system attributes.

Protective Layers of Any Safety System

To provide holistic coverage of the Safe System approach, all the protective layers of the system were identified for any safety-critical system. This includes the design of public space, which considers changes to the built environment that would make the public space safer. It includes public space operations, which are guidelines that dictate how we move through space safely. In includes individual actions to maintain a safe environment around each of us (labelled here as individual behavior). It includes an early warning, which can provide a warning about the level of risk. It covers personal protection elements that can protect you or others from a hazard given exposure. And it also includes medical treatment to reduce symptoms and reduce the probability of death given impact.

Protective Layer	Purpose	Transportation
Public space design	Changes to the built environment that would make the public space safer	Street design

Public space operations	Guidelines that dictate how we move through space safely	Street operations
Individual behavior	Individual actions to maintain a safe environment around each of us	Street-user behavior
Early warning	Warning about the level of risk	Street-user warning
Personal protection	Elements that can protect you or others from a hazard given exposure	Street-user protection
Medical treatment	Reduce symptoms and reduce the probability of death given impact	Emergency medical services

Each of the components of the system are listed in the table below and provide an example for what it would include in the transportation domain. For example, public space design would translate to street design in the transportation system. Road signage and traffic signals are an example of public space operations. Street user behavior covers the individual behavior category. Within the transportation context we can organize the elements in an ordinal manner. This goes from street design to street operations, street user behavior, street user warning, and when all else fails it leaves it to the emergency medical system.

Transportation	Purpose	Example
Street design	Changes to the built environment that would make the public space safer	Shoulder lane
Street operations	Guidelines that dictate how we move through space safely	Speed limit
Street-user behavior	Individual actions to maintain a safe environment around each of us	BAC limit
Street-user warning	Warning about the level of risk	Lane departure warning
Street-user protection	Elements that can protect you or others from a hazard given exposure	Airbag
Emergency medical services	Reduce symptoms and reduce the probability of death given impact	EMS

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