Ultralight Vehicles
Non-Linear Correlations Between Weight And Safety

K Chan-Lizardo*, A B Lovins**, L Schewel, and M Simpson

*Rocky Mountain Institute, 1820 Folsom Street, Boulder, Colorado 80302 USA
**Office of the Chief Scientist, Rocky Mountain Institute, 2317 Snowmass Creek Road, Snowmass, Colorado 81654 USA

Abstract

Development of dramatically lightweight and fuel-efficient vehicles has been slowed by perceptions that lighter vehicles are less safe. Highly safe lightweight vehicles may seem counterintuitive. Yet, size need not determine the weight of a vehicle and vehicle safety is primarily a function of design.

RMI virtually modeled an ultralight concept vehicle that met NHTSA safety requirements in crash simulations. It also performed well in side impact testing and had a low likelihood of rollovers.

In car-to-car crash simulations, the concept vehicle performed below that of a production Ford Edge. Minor design changes improved its test performance significantly, demonstrating the potential for dramatic safety improvements in a production-intent design.

The ultralight concept was also less "aggressive," indicating that a 100 percent lightweight fleet would increase overall safety. First lightweighting the heaviest vehicles in today's fleet would accelerate progress towards "Triple Safety"—protection from climate change, drivers themselves, and other road users.

Keywords: lightweight vehicles, safety, fuel efficiency

INTRODUCTION: LIGHTWEIGHT VEHICLES CONSERVE FUEL, BUT IGNITE SAFETY CONCERNS

In 2007, more than 41,000 people were killed in motor vehicle crashes in the United States and 2.5 million were injured. Vehicles endanger not only drivers: of those affected by accidents in 2007, more than one in every twenty were outside a vehicle.[1] Automobiles' effect on human health and welfare includes not only crashes but climate change and air pollution. In a previous publication,[2] RMI identified lightweight vehicles as a solution to all three of these problems—climate, drivers, and other road users—simultaneously, without compromise.

Lightweight vehicles enhance the first component of Triple Safety, the environment, through fuel efficiency: lightweight vehicles with comparable performance and utility consume less fuel.[3] However, many Americans believe that lighter vehicles are necessarily smaller and more dangerous. This conflation of weight and size—which starts in the design room and continues all the way to the showroom—is a barrier to Triple Safety.[4]

RMI believes that sophisticated design using alternative materials can produce lightweight vehicles that meet and exceed today's safety standards. We based this research project on two notions:

1. size need not definitively determine the weight of a vehicle for a given acceleration requirement, and
2. vehicle safety is a function of design and can be achieved with diverse lightweight materials.

Platform fitness

Corporate average fuel economy (CAFE) standards remained relatively constant during the past two decades while the average vehicle's weight increased nearly 20 percent due to more powerful but more efficient engines. Yet today's internal combustion engine automobile uses less than 1 percent of the energy in its fuel to actually move the occupant.

Improving energy efficiency (i.e., "platform fitness") offers significant fuel savings and enables cost savings across many automotive subsystems.[5] For example, platform fitness can reduce the cost of vehicle electrification by reducing total power demand and thus reducing the size and cost of the batteries required for a given vehicle range.

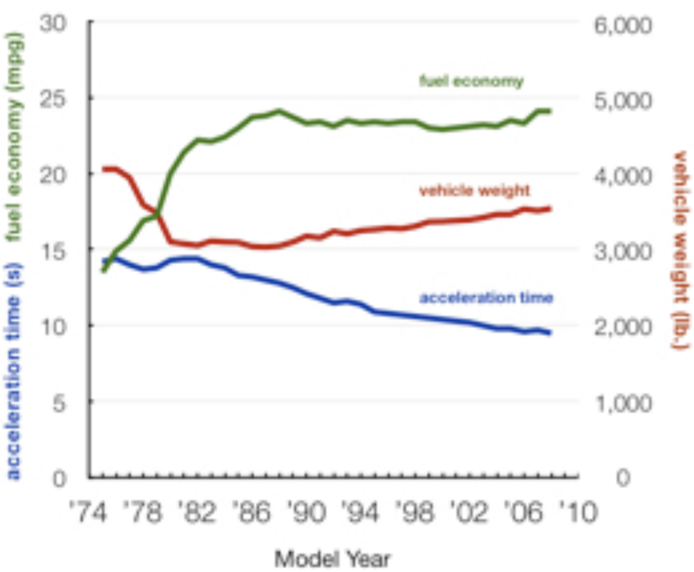

Figure 1: Light-duty vehicle performance and weight (U.S. EPA; 3-year moving average)

Previous literature

The fuel-saving benefits of lightweighting are not new to the automotive design world, and several studies have been published about the safety implications of lightweight vehicles. While the most recent studies agree that lightweighting can maintain or improve safety, experts continue to debate how much.

Table 1: Recent lightweight automotive safety studies reviewed by RMI

Year	Author	Description	Conclusion
1989	Crandall and Graham	Used regression model to predict traffic fatalities based on vehicle weight.	Increased weight leads to fewer fatalities, CAFE would increase fatalities 14–28%.
1992 1994 2004	Evans	Focused on momentum of collision partners and safety risk.	Fatality likelihood increases as mass ratio (ratio of collision partner's weight) increases.
1997 2003 2004	Kahane	NHTSA[a] study, regression analysis of fatalities per billion miles. Included vehicle type and mass, driver age and gender, and crash location and type. Ignored coupes and certain vehicle dimensions, ie. assumed mass and size were equivalent.	Fatality rates increase with weight decrease (100 lb. reduction in vehicles leads to over 1100 more fatalities in 1999, from 258 to 1555).
2001 2002	Wenzel and Ross	Separated collision data by driver, make, and model; analyzed size and weight independently. Ignored driver behavior and crash location.	Found similar safety for drivers in all vehicle classes, but increased danger to others by SUVs. Pickups are least safe. Determined that mass alone does not explain variations in safety/risk.
2002 2003 2004 2005	Van Auken and Zellner	Commissioned by Honda, reanalyzed Kahane's six types of crashes plus many configurations/orientations of vehicles using statistical analysis of NASS data. Accounted for track width and wheelbase.	Found that a weight reduction would have no statistically significant effect on fatalities in 1999 (different trends in different sizes/weights of vehicles). Size, not weight, connected to safety.
2004	Kebschull, Kelly, Van Auken, and Zellner	Modeled a Ford Explorer, a lightweight (aluminum-intensive) Explorer, and lengthened (increased crush space) Explorer in NASS[b] crashes.	Found 15% Equivalent Life Unit (ELU) reduction in the lightweight Explorer, 26% reduction in the long Explorer.
2006	Robertson	Investigated NHTSA's Fatality Analysis Reporting System for relationships between collision fatality and vehicle size, stability, and weight.	Vehicles with the same wheelbase vary widely in weights and safety ratings. If all vehicles were the lightest in their wheelbase class, fatalities would decrease 28% (16% less fuel consumption).

a *National Highway Traffic Safety Administration*
b *National Automotive Sampling System*

Early studies by Evans and by Crandall and Graham claimed heavier vehicles are generally safer, but conflated the effects of size and weight. Charles Kahane (NHTSA) published a study that linked decreases in car weight to increases in traffic fatalities. This research represented the start of quantitative lightweight vehicle assessment. Several subsequent studies criticized his lack of differentiation between weight and size. Even when he revisited the issue later, he used only historical regressions, which could accurately depict traditionally designed vehicles, and he continued to muddle the effects of size and weight.[6] Further analyses by his early critics disentangled these two variables and drew opposite conclusions from the same database.

In the previous studies, researchers explored only historical regressions and the effects of incremental lightweighting—substituting materials in heavy components with lightweight alternatives while maintaining component geometry.[7,8] Because RMI believes that integration between vehicle systems could exploit new opportunities in geometry and in the unique performance characteristics of advanced materials, this study looks at *ultralight* vehicles—i.e., vehicles weighing 50 percent less than comparable traditional cars.

SOLUTION: DEMONSTRATE THAT AN ULTRALIGHT VEHICLE CAN BE DESIGNED SAFE

Drawing from RMI's literature review and theories developed while researching *Winning the Oil Endgame*,[9] RMI hypothesized that an ultralight vehicle that is large and designed for safety can be as crashworthy as—or more crashworthy than—a similarly sized heavy vehicle. According to the International Council on Clean Transportation (ICCT):

> "The many technologies available to improve vehicle fuel economy (particularly those that do not involve weight reduction) have no impact on vehicle safety. Those approaches that strategically reduce vehicle weight (using new lightweight materials to reduce weight while holding vehicle size constant and reducing the weight of the heaviest trucks and SUVs to make them less aggressive) also improve fuel economy while maintaining, and perhaps even improving, vehicle safety."[10]

Making a light and safe vehicle relies heavily on utilizing lighter, stronger materials.[11] Designing for passive safety on par with current NHTSA five-star ratings means not only using lightweight materials, but also designing components and the spaces between them to perform as energy-absorbing crush zones and incorporating advanced active safety features, such as curtain airbags and collision prevention systems.

Methods of comparison

RMI tested its hypotheses by simulating the crash behavior of a virtually designed ultralight[12] vehicle, referred to as the UltraLight, in front and side impact configurations and hundreds of real-world collision scenarios.[13] Three different crash simulations were used:

- Frontal barrier (a mandatory NHTSA test)
- Side impact (a NHTSA protocol, voluntary)
- Real-world collision scenarios (simulations based on field-data from crashes nationwide)

Safety was evaluated in terms of equivalent life units (ELUs). Probabilities of injuries to the head, chest, abdomen, femurs, knees, and tibias are factors in this "normalized injury cost." NHTSA defines a single ELU as corresponding "to one fatality or 20 injuries requiring overnight hospitalization."[14]

The UltraLight model leverages RMI's previous automobile design experience[15] and is the result of many efforts spanning nearly ten years and three phases (Figure 2).[16] For this study, a model from 2000, the Revolution, was modified as much as budget allowed to enable "apple-to-apple" comparisons to a baseline vehicle of similar gross geometry, cargo capacity, and acceleration time.

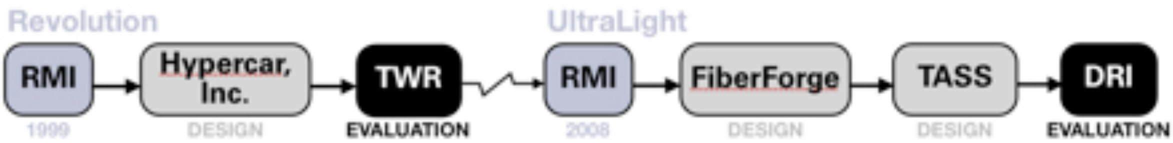

Figure 2: UltraLight design and evaluation history

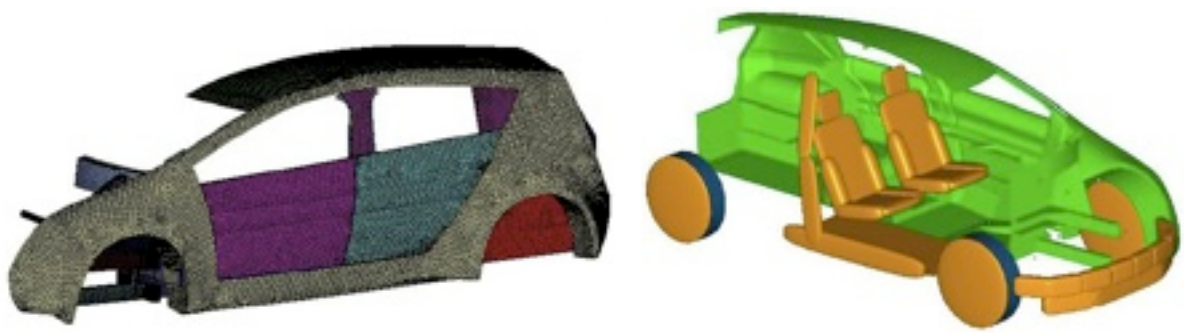

Figure 3: UltraLight Finite-element model, left, and ellipsoid multi-body model in orange, right (TASS)

The UltraLight represents an aerodynamic 900-kg five-passenger midsize SUV with rigid composite enclosures. It is over 50% lighter than the selected comparison vehicle, a 2007 production Ford Edge, but equivalent in size (see Table 2). However, unlike the Ford Edge, it is an early-stage concept vehicle which has not been physically crash-tested (Figure 4). RMI compared the safety of the two vehicles without normalizing for design maturity.

Figure 4: Automotive design phases (RMI analysis)

Table 2: Gross comparison of the 2007 Ford Edge SUV and the RMI UltraLight architecture [17]

Specification	Ford Edge	UltraLight		Difference
Wheelbase	111.2	131.1	in.	18%
Length	185.7	202.8	in.	9%
Height	67.0	68.8	in.	3%
Width	75.8	81.3	in.	7%
Track	65.0	69.8	in.	7%
Ground Clearance	8.0	8.8	in.	10%
Cargo Volume [seats down]	69.6	69.0	ft^3	-1%
Curb Weight	4073.0	1883.2	lb.	-54%
Acceleration Time (0 - 60 mph)	8.1	8.3	s	2%

CRASH PERFORMANCE

Front barrier crash

Results from the original Revolution frontal barrier crash simulation, done by TWR Engineering in 1999, were compared to physical crash results of the Ford Edge, which has a five-star NCAP rating in frontal barrier crashes.

TWR calculated a peak acceleration of the Revolution's architecture of 57 *g* during the simulated 35-mph impact. Table 3 outlines the crush distance, peak acceleration, and average acceleration of the physical Ford Edge crash test and the UltraLight crash simulation. Greater acceleration of the vehicles typically means greater acceleration/impact of the occupants, resulting in greater injury and damage.

Table 3: Crash test measurements of the Ford Edge and UltraLight, respectively

	Ford Edge	UltraLight	Unit
Crush Distance	432	600	mm
Peak Vehicle Acceleration	52	57	*g*
Average Acceleration	22	28	*g*

The crash simulation report[18] indicated that the front crush structure of the Revolution was not optimized for offset collisions and that components inside the engine compartment occupy significant crush space. TWR noted:

> "The aluminium subframe, composite front upper sidemember, and composite nose can absorb sufficient energy to stop the vehicle, acceptably for occupant safety, without damage to the composite body in the 35-mph [frontal] rigid barrier impact.
>
> The composite body analysed performs acceptably in providing a structurally secure compartment for occupant safety. However it suffers damage ... due to local details.
>
> The steering motors and mounting to subframe cause an early lockup between the front wheels and the dash. This causes higher values than intended in the peak and average vehicle deceleration."

These vehicle characteristics were responsible for high peaks in the crash pulse (rapid changes in acceleration) and shortened deceleration time. Behind the firewall, the Revolution's cabin structure protected occupants and deformed very little, as shown in Figure 5 below.

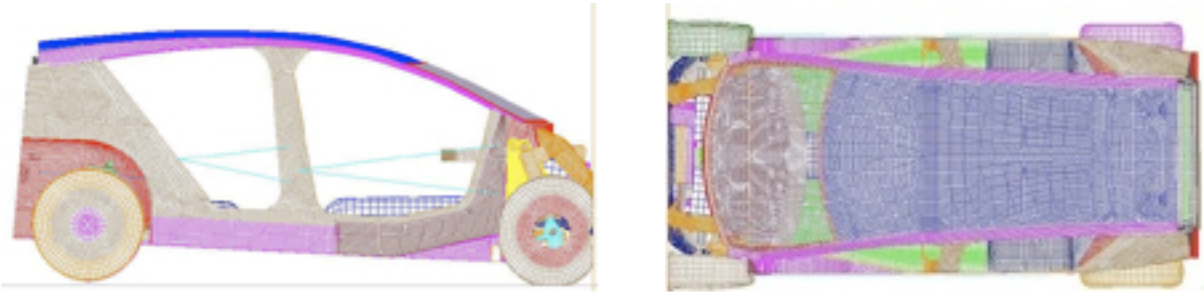

Figure 5: Revolution frontal-impact simulation during maximum crush at 54 milliseconds (TWR Engineering)

Side impact testing

NHTSA awarded the Ford Edge a five-star side impact rating based on side impact test results, presented in Table 4 and pictured in Figure 6.

RMI hired TNO Automotive Safety Solutions (TASS) to simulate the same crash conditions with the UltraLight. With the addition of curtain air bags and pelvic-thoracic side air bags, little weight was added, yet the UltraLight's safety greatly improved. Table 4 displays the results of the Ford Edge testing and UltraLight simulation, and shows that the head injury criterion of the UltraLight is much lower than that of the Ford Edge, despite higher accelerations within the body. The higher rates of acceleration in the UltraLight stem from its stiffer structure.

Figure 6: 2007 Ford Edge after side impact crash test (NHTSA)

Table 4: Side impact measurements of the Ford Edge and UltraLight, respectively

	Ford Edge	UltraLight	Unit
Head Injury Criterion (36 ms)	122.0	82.4	-
Upper Rib Acceleration	28.2	50.4	*g*
Lower Rib Acceleration	30.2	53.1	*g*
Lower Spine Acceleration	29.4	45.0	*g*
Pelvis Acceleration	51.0	41.7	*g*
Thoracic Trauma Index	30.0	49.1	*g*

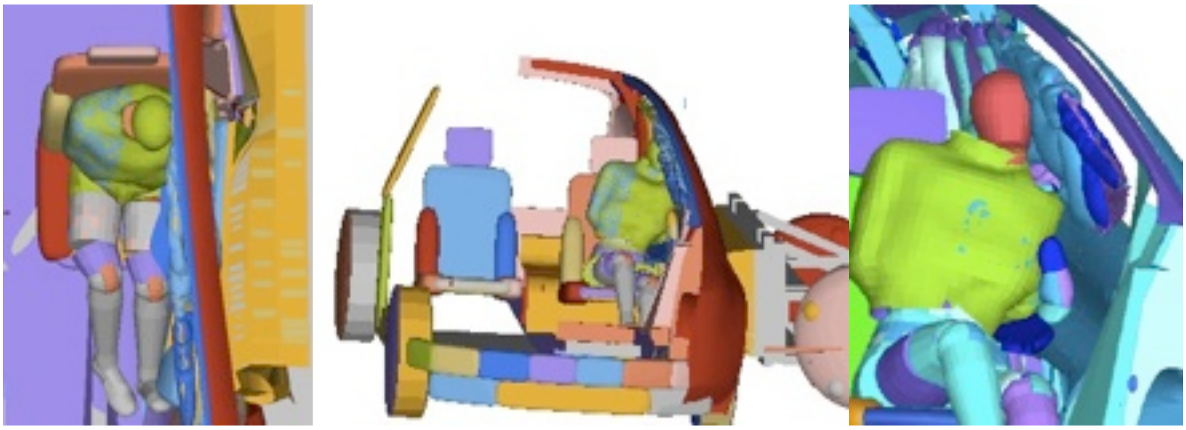

Figure 7: UltraLight side impact simulation at 20 milliseconds (TASS)

Real-world collision scenarios (field-data simulations)

For evaluating safety during car-to-car and car-to-object collisions, RMI worked with Dynamic Research Inc. (DRI) to quantitatively compare the crashworthiness of the UltraLight and Ford Edge. DRI ran the vehicle models through simulations that mimicked real-world accidents, using injury likelihood data from a variety of crash case studies. Each simulation was built on specific road conditions, types of vehicles involved, victims' experiences, and the resultant damage to both the vehicles and their occupants as logged in the National Automotive Sampling System Crashworthiness Data System (NASS CDS).[19] Each simulation was weighted to represent its probability during 500 total collisions. A second and third set of these same crash configurations were then run with the vehicles traveling at a slightly higher speed and a slightly lower speed (+2 mph and –2 mph, respectively) to create a statistical database.

DRI initially modeled the UltraLight with a subjectively positioned interior. After reviewing the first round of simulations, RMI and DRI made minor modifications and tested several hypotheses about weaknesses in this initial design.

Phase 1: Initial design assessment

The crash simulations were grouped into four categories. Two collision categories, rollovers and collisions with a stationary object, were based on crash scenarios involving a single vehicle. The other two collision categories included vehicle-to-vehicle collisions. In these vehicle-to-vehicle scenarios, ELUs were calculated for the drivers in the primary vehicles and the partner vehicles, either a Honda Accord or a Ford Edge. ELUs represent the relative total cost of a given combination of injuries, based on bio-economic data—the higher the number, the greater the severity of the injuries. The initial UltraLight in Phase 1 was less protective than the Ford Edge, and had a 59 percent greater potential for injury according to crash statistics. The simulation results are shown in Table 5.

Table 5: Phase 1 simulation results for real-world collision scenarios

	Collision Category	Number of Cases	Ford Edge as Primary (ELU)	UltraLight as Primary (ELU)	ELU Ratio (UltraLight/Edge)
Primary Vehicle	Rollover	75	0.08	0.75	9.38
	Hits Stationary Object	180	0.26	0.94	3.62
	Hits Honda Accord	750	4.06	15.21	3.75
	Hits Ford Edge	495	12.37	32.21	2.60
Partner Vehicle	Driver in Honda Accord	750	7.21	0.29	0.04
	Driver in Ford Edge	495	7.54	0.78	0.10
Total		2,745	31.52	50.18	1.59

In rollovers, the UltraLight had 9.38 times the number of ELUs of the Ford Edge, caused primarily by head trauma, but it is important to note that the UltraLight's greater stability reduces its probability of rollover by 31 percent.[20]

In the category of collisions with stationary objects (tree, wall, pole), UltraLight drivers suffered almost six times as many injuries as Ford Edge drivers, primarily as a result of head trauma.

In collisions with other vehicles, the UltraLight experienced higher ELUs than the Ford Edge, mostly due to the head and femur injuries, as shown in Figure 8.

In the vehicle-to-vehicle crash simulations, 93 percent fewer injuries occurred in partner vehicles colliding with the UltraLight than partner vehicles colliding with the Ford Edge.

Figure 9 includes a relative comparison of injury by collision category.

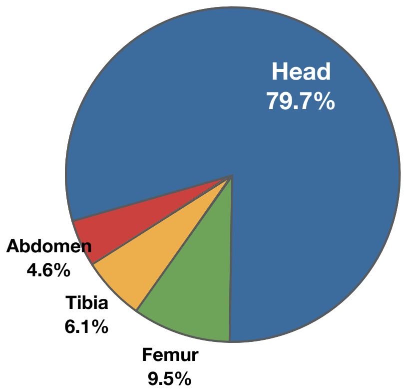

Figure 8: Frequency of greatest injury severity occurrences in the head, abdomen, tibia, or femur with the UltraLight

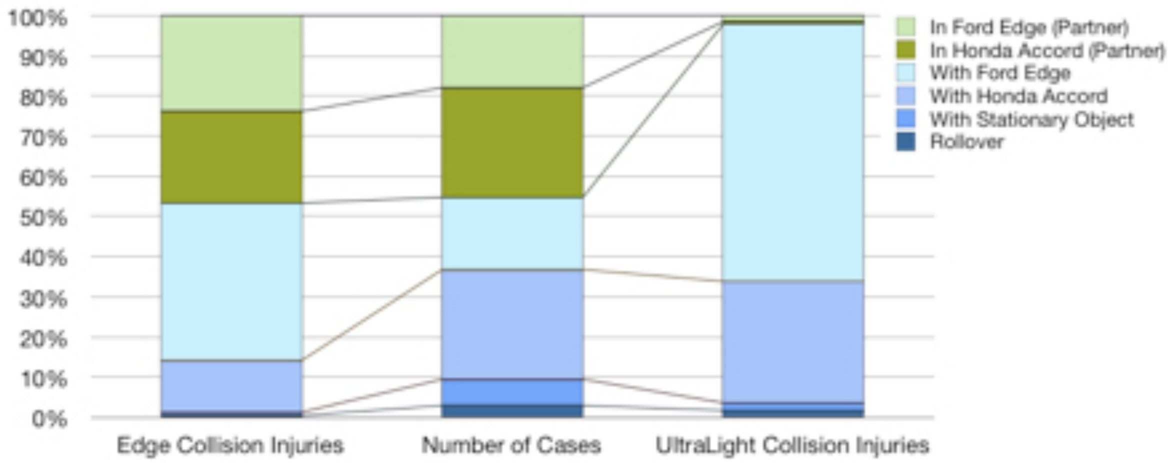

Figure 9: Relative injury distribution by configuration from Phase 1

To gain greater detail on the severity of injuries, RMI converted the Phase 1 results (in ELUs) to the Abbreviated Injury Scale (AIS; see Table 6).[21] The AIS underscores the high frequency of inexpensive/less-severe injuries. Unfortunately, the Phase 1 UltraLight protects the driver significantly less during impacts with the Ford Edge, as seen with the number of maximum AIS (MAIS) 5 and fatal (F) injuries.

Table 6: AIS summary of collision simulation injuries

		MAIS						
Ford Edge	**Collision Category**	**1**	**2**	**3**	**4**	**5**	**F**	**Total**
Primary Vehicle	Rollover	78	6	0	0	0	0	84
	HIts Stationary Object	166	5	0	0	0	0	171
	HIts Honda Accord	723	2	0	25	0	0	750
	HIts Ford Edge	397	22	2	71	3	0	495
Partner Vehicle	Driver in Honda Accord	671	27	34	12	5	1	750
	Driver in Ford Edge	420	29	4	39	3	0	495
Total		2,455	91	40	147	11	1	2,745

		MAIS						
UltraLight	**Collision Category**	**1**	**2**	**3**	**4**	**5**	**F**	**Total**
Primary Vehicle	Rollover	70	9	0	5	0	0	84
	Hits Stationary Object	151	17	0	1	2	0	171
	Hits Honda Accord	619	30	39	42	20	0	750
	Hits Ford Edge	328	16	57	46	38	10	495
Partner Vehicle	Driver in Honda Accord	745	4	1	0	0	0	750
	Driver in Ford Edge	478	13	0	4	0	0	495
Total		2,391	89	97	98	60	10	2,745

Phase 2: UltraLight model changes

The high proportion of ELUs related to head injuries prompted investigation of simple UltraLight design changes without alterations to the vehicle structure or mass.[22] RMI discovered three primary oversights in the Phase 1 model:

1. Because of the seating and dash placement, the driver was perfectly aligned (laterally) with the B pillar. There was a greater potential for the occupant's head to strike this hard surface during side impacts.
   - DRI repositioned the seat, dash, and thus the occupant, three inches forward.
2. The front seat headrests, designed in 2000, lacked the forward positioning of NHTSA's 2004 mandate.[23] The resulting gap between the occupant's head and the headrest increased the risk of whiplash in rear impacts.
   - DRI rotated the headrest forward, closing the gap between the head and the headrest to approximately one inch.
3. DRI originally modeled the airbag deployment based on field data from the CDS—i.e., matching the deployment timing of airbags to those in the real accident. But since airbag deployment is typically based upon acceleration rates, airbags would have triggered more often in the UltraLight than in the CDS cases.

- In Phase 2 simulations, airbags were modeled to deploy during all crashes in both vehicles. This change is conservative and unrealistic, but normalizes the benefit of airbag protection between the Ford Edge and UltraLight models.

These design decisions—requiring no structural modifications and zero weight gain—were responsible for comparatively large reductions in the number of injuries. The majority of reductions occurred during single-vehicle and midsize-sedan partner-vehicle collision simulations. On average, the UltraLight's ELUs dropped by 20 percent. The effects of these changes to the vehicles' safety are shown in Table 7 and Figure 10. The percentages (in *red*, **green**, and gray) represent the change in ELUs with these seating and airbag modifications.

Table 7: Phase 2 simulation results for real-world collision scenarios [24]

	Collision Category	Number of Cases	Ford Edge as Primary (ELU)		UltraLight as Primary (ELU)		ELU Ratio (UltraLight/Edge)
Primary Vehicle	Rollover	75	0.08	*1%*	0.34	**-55%**	4.25
	Hits Stationary Object	180	0.09	*2%*	0.41	**-57%**	4.56
	Hits Honda Accord	750	4.07	0%	8.86	**-42%**	2.18
	Hits Ford Edge	495	12.22	**-1%**	29.60	**-8%**	2.42
Partner Vehicle	Driver in Honda Accord	750	7.20	0%	0.18	**-39%**	0.03
	Driver in Ford Edge	495	7.54	0%	0.77	**-2%**	0.10
Total		2745	31.20	0%	40.16	**-20%**	1.29

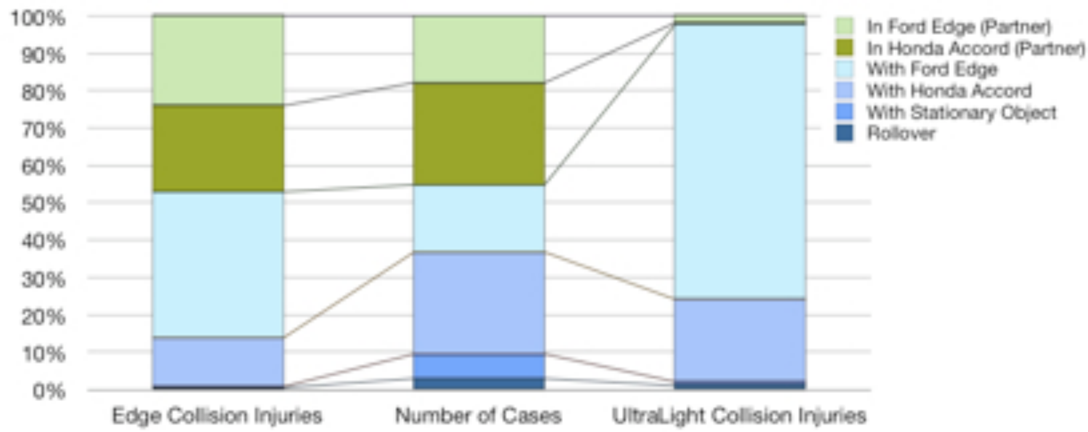

Figure 10: Relative injury distribution by configuration from Phase 2

Similarly, the MAIS results for the Phase 2 UltraLight improved significantly (Table 8) and the difference between MAIS frequency distributions of the baseline (Ford Edge) and subject (UltraLight) vehicles decreased (see Figure 11).

Table 8: Phase 2 AIS summary of collision simulation injuries

		MAIS						
Ford Edge	**Collision Category**	**1**	**2**	**3**	**4**	**5**	**F**	**Total**
Primary Vehicle	Rollover	78	6	0	0	0	0	84
	Hits Stationary Object	165	6	0	0	0	0	171
	Hits Honda Accord	723	2	0	25	0	0	750
	Hits Ford Edge	398	22	2	70	3	0	495
Partner Vehicle	Driver in Honda Accord	663	36	33	12	5	1	750
	Driver in Ford Edge	420	29	4	39	3	0	495
Total		2,447	101	39	146	11	1	2,745

		MAIS						
UltraLight	**Collision Category**	**1**	**2**	**3**	**4**	**5**	**F**	**Total**
Primary Vehicle	Rollover	78	3	3	0	0	0	84
	Hits Stationary Object	150	21	0	0	0	0	171
	Hits Honda Accord	653	41	20	27	9	0	750
	Hits Ford Edge	333	32	51	31	39	9	495
Partner Vehicle	Driver in Honda Accord	747	3	0	0	0	0	750
	Driver in Ford Edge	477	14	0	4	0	0	495
Total		2,438	114	74	62	48	9	2,745

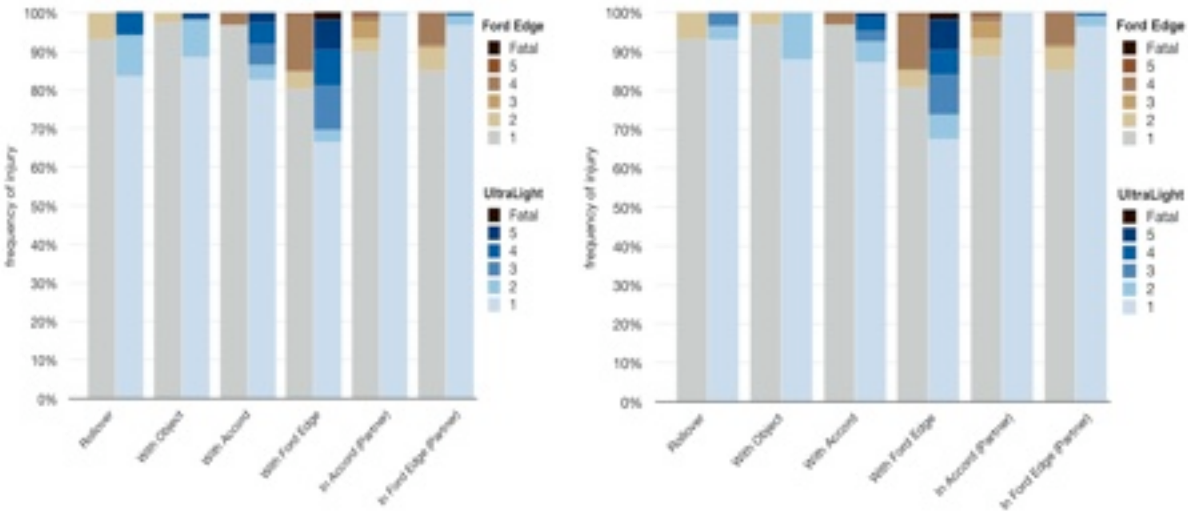

Figure 11: Proportional representation of relative frequency of injuries by MAIS severity, Phase 1 (left) and Phase 2 (right)

Future lightweight fleet implications

The current UltraLight model would be at a disadvantage in today's fleet: during the transition to a lighter fleet, the UltraLight would not be as safe as comparably sized, conventional-weight vehicles. This reflects in part, and perhaps entirely, the two vehicles' different levels of refinement in safety design.

However, DRI found interesting results when simulating the same collision scenarios replacing all Ford Edges with UltraLights. In simulations, this hypothetical, homogeneous future fleet experienced 29 percent fewer injuries overall—14.1 ELUs—than a fleet of all Ford Edges (see Table 9).

Table 9: Comparison of relative safety in today's automotive fleet to that of an entirely ultralight fleet

Fleet	Primary Vehicle ELU		Partner Vehicle ELU		Total	ELU Ratio
	Ford Edge	UltraLight	Ford Edge	UltraLight		
100% Heavy Fleet	12.2	-	7.5	-	19.8	1.6
Transition Fleet	-	29.6	0.8	-	30.4	38.4
100% Lightweight Fleet	-	7.7	-	6.4	14.1	1.2

CONCLUSIONS

The TWR and TASS crash simulations together with the DRI multi-scenario crash simulations offer a broad view of ultralight vehicle safety that helps predict real-world performance. Realistically, one concept car and a pile of simulation data do not prove or disprove a theory; this study illustrates the complexity of vehicle design and safety. Engineering decisions that affect neither size nor weight can make vast differences to occupant safety. The myth that small equals lightweight equals dangerous is just that—a myth.

This study led RMI to three primary conclusions about the design of ultralight vehicles:[25]

1. This study confirms the trend noted in DRI's previous research for the Aluminum Association[26]—that lightweight vehicles are much less aggressive than heavier vehicles. There were 93 percent fewer injuries in partner vehicles during collisions with the UltraLight than with the Ford Edge.

   UltraLight vs. UltraLight collisions had 29 percent fewer ELUs than Edge vs. Edge crashes, and 57 percent fewer ELUs than UltraLight vs. Edge crashes. This indicates that the total number of ELUs may decrease in a fleet of properly designed lightweight vehicles.

   These trends suggest that groups interested in societal safety (e.g., insurance and government) should pursue additional research into the benefits of a lightweight national fleet, and policies that can gradually reduce the fleet's average mass and its mass dispersion.

2. Despite being less aggressive, the UltraLight model, in both its original form (without safety optimization) and after one round of simple improvements, offered less protection to its driver than the Ford Edge. This suggests a need for more iterations focused on passive and active safety design. Multi-scenario simulations would enable rapid iterations. Dedicated research and design would help protect early adopters of lightweight vehicles during the transition to a safer, lighter fleet. A strategy involving the initial lightweighting of only the heaviest vehicles in the fleet will create the fewest incompatibilities while significantly enhancing Triple Safety.

3. Important information concerning the crash physics of ultralight vehicles designed with rigid, lightweight materials was gained.

   - Vehicles with high rigidity relative to mass (e.g., the UltraLight) offer little resistance to the motion of a heavy partner vehicle, and can actually move with the partner vehicle in collisions. This helps prevent intrusion during side impacts where there is little space for deceleration. TASS hypothesized that this may have reduced the number of harmful impacts to the UltraLight occupants during the side impact simulation. As result of these crash dynamics, the occupants of the rigid vehicle experienced greater accelerations. These effects can be mitigated by airbags, seat-belts, and interior fascia.

- The UltraLight's lightweight structure has less mass near the roof, lowering its center of gravity. The stability from this low center of gravity makes it 31 percent less likely to roll over than the Ford Edge.[27]

Lessons Learned

The simulations in this study used models built upon legacy concepts because of limitations design time, process, and budget. This limited the degree to which RMI's safety hypothesis could be tested. Future research should focus on developing subject and baseline vehicles of similar design maturity. Future research projects should incorporate significant iteration time to explore structural modifications that exploit all possible synergies between systems—the only way to achieve an optimized design regardless of material and historical relevance. A more refined production-intent simulation model will more accurately demonstrate the potential for Triple Safety. A production design might produce a 30–40 percent lighter vehicle (rather than an ultralight vehicle), and could certainly include the full active and passive safety optimization omitted by this study.

Most importantly, this study shows the importance of design iterations to capture the full safety potential of ultralight materials. One round of basic design changes to the UltraLight showed its safety potential. According to Dr. Tom Hollowell, the previous director of the Office of Applied Vehicle Safety Research at NHTSA:[28]

> "We should be able to redesign [the UltraLight] to maintain the same level safety [as today's fleet]. Under the current [UltraLight] model, the crash pulses were shortened, but it is possible to increase the time duration of the crash pulse so that the outcomes won't be quite as severe and could even be better."

RMI concludes that these results should help further decouple automobile safety and weight, shedding light on the complex non-linear correlation between these two vehicle attributes throughout the design process. Highly safe lightweight vehicles may seem counterintuitive, yet automakers can implement light and safe design through careful, intelligent choices.[29]

Additional Questions Generated by this Study

RMI recommends continued research on designs and policy that protect occupants in ultralight vehicles as the nation transitions to a lighter fleet. This study highlighted a wide array of nuances in our hypothesis that warrant further exploration. Our remaining questions include:

1. Can injuries in ultralight vehicles be fully eliminated by safety technologies and more careful design?
    - What design innovations can best address a large weight mismatch between two colliding vehicles?
2. Can conventional design lead to an ultralight vehicle with comparable or superior safety performance to that of a conventional vehicle about twice its weight—even when they collide?
    - Advanced materials such as high-strength steels and aluminum alloys offer significant weight savings without quantum leaps in design methodologies. Can innovative interior design (seats, insulation, etc.) help keep occupants safe and comfortable without adding significant mass?
3. Can we model safety features and advanced materials more accurately in computer simulations?
    - Does a model of an anisotropic composite structure (e.g., the UltraLight) calibrated with only two crash pulses capture enough detail to accurately

simulate collisions from all angles? Could optimal anisotropic design further improve safety with even less mass?

4. What evidence regarding vehicle safety does the public require to demand and adopt ultralight vehicles?

Answers to these questions will require automotive engineering and manufacturing expertise applied to design exploration and, eventually, real-world testing.

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APPENDIX A

Platform Fitness

The first step in addressing concerns about energy consumption and emissions is to focus on end-use efficiency. The end use of energy is personal mobility. Only three primary forces, known as "tractive loads," resist the motion of a conventional automobile: aerodynamic drag, rolling resistance induced by surface friction and tire-wall flex, and mass.

Nearly 86 percent of the original energy in gasoline (on average) becomes relatively useless noise and heat; only the remaining 14.6 percent (on average) reaches the wheels and becomes work acting against the three tractive loads. Wasting less energy in the downstream "services" of a car—that is, moving its occupants—affects all energy losses up the chain and magnifies energy savings.[30] With a conventional powertrain, a reduction in each end-use unit of energy is equal to saving nearly eight times the input energy, or three to five times the input energy with a hybrid powertrain.

The figure below shows how the energy is used as a vehicle converts fuel into forward movement. Green bars indicate the portion of energy that is used by the vehicle or passed on to the next major sub-system.

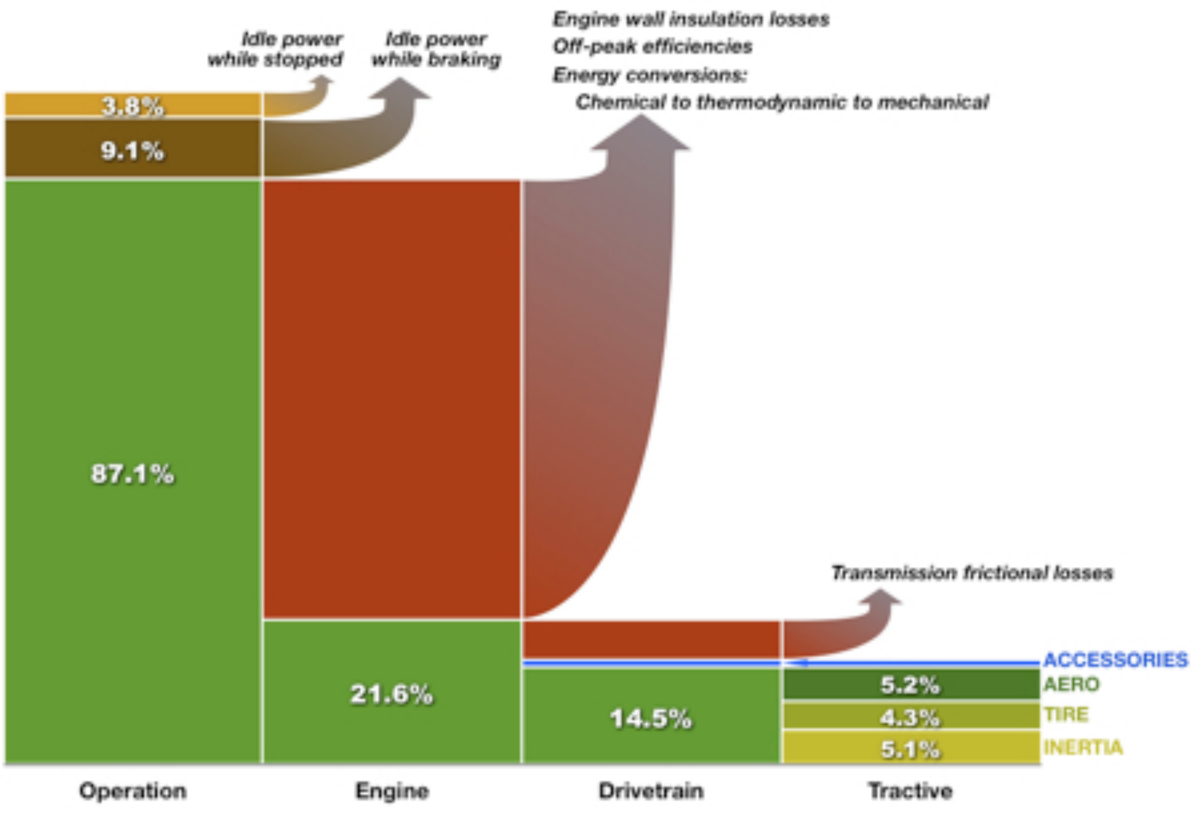

Figure 12: Energy use in a modern internal-combustion engine automobile (RMI analysis)

Mass-related losses occur in the brakes and tires, resulting from acceleration and rolling resistance. Roughly two-thirds of the energy that goes into a typical vehicle is used to overcome inertia; the driver represents roughly 5 percent of the total mass (approximately 85 kg of 1600 kg). In a conventional midsize sedan, this means that only 0.5 percent of the fuel energy moves the driver.[31] A 50 percent reduction in mass translates directly to a 50 percent reduction of energy losses in brakes and tires, or a roughly one-third reduction of total tractive load. Thus, a 50 percent lighter vehicle requires only two-thirds of the shaft power needed by a conventional-weight vehicle.

The conventional engine and driveline use 8.71 gallons of fuel energy converting 10 gallons of fuel energy to the equivalent of 1.56 gallons of useful power (1.45 gallons of kinetic energy plus 0.11

gallons to run auxiliary components) for an 18 percent efficiency. A typical engine also uses 1.29 gallons (of that original 10) to keep the engine idling.

If the vehicle instead requires only 0.96 gallons kinetic energy (the aerodynamic traction load consuming 0.46 gallons, plus half of the weight-dependent traction load—0.5 times 0.99 gallons), the total useful energy requirement drops to 1.06 gallons. At 18 percent efficiency, the engine and drivetrain will lose only 5.95 gallons to useless energy states. The total energy consumed is then: 5.95 + 1.29 (idle) = 7.24 gallons, saving 17 percent of the original fuel to travel the same distance. This increases fuel economy by 20 percent.[32]

This calculation is, of course, unrealistically conservative: a typical 2009 OEM engine of 18 percent efficiency would accelerate an ultralight vehicle far faster than consumer expectations, and potentially pose a danger to vehicle occupants. On the assumption that the average consumer does not require additional acceleration (beyond 2009 expectations), the designer may choose to downsize the engine, saving weight, cost, and losses. This calculation also omits major weight savings as components don't just shrink, but disappear altogether.

With the inherent weight savings, structural weight may now decrease as the engine mounts and auxiliary components are downsized. This design integration during multiple iterations can lead to transformative designs, such as the Hypercar Revolution, the Toyota 1/x, and the Volkswagen One-Liter,[33] whose concept designs are estimated to achieve 67, 90, and 170 mpg, respectively.

Designs that reduce drag and rolling resistance and simultaneously achieve lightweighting exemplify platform fitness. Each improvement yields more efficiency when implemented in concert with the others, ultimately enabling powertrain reductions. Recent industry analyses suggest that this synergistic whole-system approach can pay for much of the new design and lightweight materials needed.

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3 Power—thus energy consumption—required to move an object is proportional to mass. A lighter vehicle will accelerate at the same rate as, and will have less rolling resistance (friction) than, a heavier vehicle with the same powertrain while consuming fuel at a lower rate.

4 Harris Interactive conducted a survey for RMI of over 2000 people of varying demographics between 16 and 18 September 2008. Results can be found at www.move.rmi.org/features/safety-implications-of-lightweight-autos.html .

5 See Appendix A.

6 Kahane, Charles J, Ph.D., *Vehicle Weight, Fatality Risk and Crash Compatibility of Model Year 1991–99 Passenger Cars and Light Trucks*, NHTSA DOT, DOT HS 809 662, 2003. Using the same design principles and materials as heavier vehicles, the density remains relatively constant, so traditionally-designed lightweight vehicles were also smaller.

7 Kebschull *et al*., *An Analysis of the Effects of SUV Weight and Length on SUV Crashworthiness and Compatibility Using Systems Modeling and Risk-Benefit Analysis*, DRI-TR-04-04-2, July 2004

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9 Lovins, Amory B. *et al.*; *Winning the Oil Endgame*, Rocky Mountain Institute, 2004, http://www.rmi.org/rmi/Winning+the+Oil+Endgame.

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11 Schewel, 2008 (see ref. 2).

12 In this paper, we use “lightweight” as a generic adjective. It refers to vehicles that have been designed to be at least 50 percent lighter. When we refer to RMI’s test model for this analysis, we use “UltraLight” as a proper noun.

13 Cramer, David. Taggart, David. Hypercar, Inc.; “Design and Manufacture of an Affordable Advanced-Composite Automotive Body Structure”, The 19th International Battery, Hybrid, and Fuel Cell Electric Vehicle Symposium & Exhibition, EVS-19, 2002, www.rmi.org/rmi/Library/T02-10_AdvancedCompositeAutomotiveBody .

14 Kahane, Charles; “An Evaluation of Federal Motor Vehicle Safety Standards for Passenger Car Steering Assemblies”, NHTSA DOT HS 805 705, Jan 1981

15 Cramer, Taggart, 2002 (see ref. 26); Cramer, David R. & Lovins, Amory B., “Hypercars, Hydrogen, and the Automotive Transition,” *Intl. J. Veh. Design* 35(1/2):50–85 (2004), www.rmi.org/rmi/Library/T04-01_HypercarsHydrogenAutomotiveTransition

16 In 2000, Hypercar, Inc. contracted TWR Engineering to conduct a 35-mph frontal-impact finite-element analysis (FEA) simulation, deriving a frontal crash pulse for their Revolution model. No additional design iterations followed. The original Revolution design lacked detailed closure definition and pre-dated research on side-airbag benefits. RMI hired Fiberforge (Hypercar’s successor) at the start of this project to design vehicle closure panels and add side-impact safety measures. Fiberforge modeled composite laminates mimicking steel closure strength. Then, TNO Automotive Safety Solutions (TASS) meshed the driver side of the updated 3-D model and evaluated the vehicle in two side-crash simulations (FMVSS 214 and SINCAP), adding eight airbags and testing the need for an intrusion bar. Lastly, RMI hired Dynamic Research Inc. (DRI) to create an articulated total body (ATB) version of the model based on the original frontal crash pulse from TWR. This is the RMI UltraLight model. ATB models include boundary conditions similar to those used in FEA but contain larger model elements of averaged specifications. DRI added seat belts, pedals, a steering column, and other interior components similar to those in conventional vehicles to achieve a direct “apples-to-apples” comparison, though the gross geometry remained unchanged.

17 Edge data from Edmunds Inc., *2009 Ford Edge Test Drive on Edmunds.com*, www.edmunds.com/ford/edge/2009/testdrive.html, 2009, Accessed: 7/2009.

18 Taggart, David et. al, *P218 Concept Frontal Impact Analysis*, TWR Engineering, TWRER1967, Aug 11, 2000.

19 NHTSA, *NCSA NASS CDS*, www.nhtsa.dot.gov/people/ncsa/nass_cds.html, Accessed: 7/2009. Investigators from the National Automotive Sampling System (NASS) examine motor vehicle collisions throughout the U.S. and continuously update the CDS with their findings.

20 Based on static stability factor (SSF), which is the ratio of half the vehicle track width to the height of the vehicle’s center of gravity, RMI estimates that the UltraLight would be involved in 31 percent fewer rollovers than the Edge. The Ford Edge’s SSF is 1.35, while the UltraLight achieves an SSF of 1.5. A logarithmic regression of rollover likelihood over SSF corresponds to 0.126 rollover incidents per single vehicle crash for the Edge, 0.087 for the UltraLight. Accounting for rollover probability would reduce the ELU lost in UltraLight rollovers to 0.52.

21 The AIS is an anatomically based system that classifies individual injuries by body region on a six-point ordinal scale of risk to life. The AIS does not assess the combined effects of multiple injuries. The maximum AIS (MAIS) is the highest single AIS code for an occupant with multiple injuries.

22 Resource constraints prevented major structural redesign as the expense of creating CAD and FEA models is comparatively large.

23 NHTSA, *NHTSA Announces Upgraded Rule for Head Restraints in Vehicles*, 49 CFR Part 571, 2004, www.nhtsa.dot.gov/cars/rules/rulings/HeadRest/update/202FinalRule.html, Accessed: 7/2009.

24 As mentioned in ref. 20, the UltraLight has 69 percent of the probability of rollover as the Edge. The final rollover results are actually 0.23 ELU.

25 Dynamic Research, Inc. conducted analyses which formed the basis of some of the findings herein. The opinions, findings, and conclusions expressed in this publication are not necessarily those of Dynamic Research, Inc.

26 Kebschull, 2004 (see ref. 7).

27 See ref 20.

28 RMI Interview with Dr. Hollowell, 18 September 2009.

29 Incremental solutions corresponding to lighter *and* safer designs include Honda Advanced Compatibility Engineering (ACE), the Tridion safety cage in the Smart ForTwo, the BMW X1, the Lotus Elise, and the 2004 Jaguar XJ8.

30 RMI analysis of: Sovran, Gino; Blaser, Dwight; *A Contribution to Understanding Automotive Fuel Economy and Its Limits*, 2003-01-2070, SAE International, 12-14 May 2003, updated to 2007 EPA fuel economy standards.

31 Over 35 percent of the tractive load is aerodynamic drag. Its contribution to productive fuel consumption is real but unclear. A human on a recumbent bike (most similar to the seating position in a car) has a drag coefficient area (C_DA) of approximately 0.27 m^2, but an automobile is typically closer to 0.7 m^2. Thus about 39 percent of the drag comes from the person (or 14 percent of the tractive load). However, most car designs incorporate side-by-side seating, increasing the C_DA. Additionally, designers can tweak the streamlines of vehicles to optimize flow of even the largest vehicles, decreasing the C_DA. These effects are difficult to quantify.

32 All numbers here represent current EPA drive schedules and average automobile performance.

33 The Volkswagen One-Liter car prototype weighs 838 pounds, has a drag coefficient of 0.195, and has a fuel economy of 170 miles per gallon. Most two-seat cars weigh nearly 2500 pounds, with drag coefficients of 0.35 or greater, and achieve 30 miles per gallon in optimal conditions: Volkswagen, *Volkswagen Revamps One-Liter L1 Concept; 170 MPG, On Roads in 2013?*, MotorTrend, http://wot.motortrend.com/6554269/concept-cars/volkswagen-revamps-one-liter-l1-concept-170-mpg-on-roads-in-2013/index.html, 14 Sept 2009, Accessed: 9/2009.