Executive Summary

The 2020 Steel Industry Technology Roadmap for Automotive provides an overview of long-term technology developments necessary to support future automotive material selection decisions. The steel industry continues to provide a broad spectrum of steel grades, including third generation advanced high-strength steels (AHSS)*, which are used by automakers to develop mass efficient and cost-effective body and chassis designs that meet or exceed safety and performance expectations. The roadmap covers persistent challenges facing the automotive and steel industries and identifies technical gaps needing attention to facilitate the application of advanced steel products. These gaps constitute areas of research and development – both ongoing and needed – at steel producers, automakers, academia, national laboratories and industry consortia which will support rapid deployment of current and emerging automotive AHSS grades.

While this roadmap provides a comprehensive overview of the state of the industry, it is intended to open the door to more healthy collaboration across all parties aimed at ensuring the sustainability of the automotive and steel industries globally.

The primary technical areas of interest on the roadmap include material modeling and characterization, computer aided engineering (CAE), forming processes and joining technologies. Additional technology areas such as corrosion, paint, repairability, recyclability and life cycle assessment are presented as areas requiring coordinated future research activities across multiple disciplines and industries.

The roadmap specifically highlights the automakers’ shift toward virtual performance assessments, which drives a renewed emphasis on enhancing modeling and simulation by addressing accurate material data, new element formulations and enhanced analyses techniques. Meanwhile, increased automaker interest in mechanical joining techniques, such as adhesive bonding and self-piercing rivets, is also reflected on the roadmap as viable and robust alternatives to resistance spot welding. They offer automakers the flexibility of joining different grades and stack-ups with increased confidence without wholesale changes to existing body shop equipment and practices.

* In this Roadmap, AHSS refers to all steel products with a tensile strength equal to or greater than 590 MPa including those UHSS products with a tensile strength at or above 1000 MPa.
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Introduction

The steel industry has a longstanding record of collaborating with automakers globally to introduce new automotive steel products, manufacturing processes and design solutions. Numerous research projects at the Auto/Steel Partnership (A/SP) and WorldAutoSteel, as well as detailed structural design demonstrators, have proven steel to be both innovative and a high value proposition for automakers seeking to lightweight their body and chassis designs cost-effectively without compromising safety or structural performance. High-strength steel (HSS) and AHSS grades have been the dominant materials of choice for automakers over the past three decades, yet the steel industry continues to innovate, as shown below, by introducing new grades and manufacturing processes in support of future mobility. This innovation promises to revolutionize the transportation industry through the proliferation of electrified, connected and shared autonomous vehicles. The steel industry remains determined and committed to face these future challenges through a broad partnership with the automakers and the supply base.

Benefits of Steel

A key part of the steel industry’s future focus is to continue to offer the automotive industry unique advantages not attainable with other materials, such as:

- Exceptional strength and ductility combinations to maintain the integrity of the vehicle body and chassis systems, ensure occupant safety and protect vehicle
components without compromising interior spaciousness and exterior contemporary styling themes;

- Solutions that require only incremental changes to the existing manufacturing infrastructure thus avoiding major capital expenditure;
- A constantly modernizing and expanding supply chain infrastructure;
- The most environmentally responsible material;
- Cost-effective mass reduction solutions for improved fuel economy and electric vehicle range; and,
- Enhanced cost of ownership to the consumer, including cost of purchase and repair.

Applications

In the past 20 years, new steel innovations helped automakers reduce vehicle weight. See figure 1 (a) below:

*Source: worldautosteel.org
However, with increasing safety and crashworthiness requirements driven by government regulations, consumer advocacy groups and the insurance industry, as well as increased stricter global greenhouse gas (GHG) emissions standards, the emphasis within the automotive industry has shifted towards more balanced vehicle solutions. In addition to safety, weight reduction remains a key imperative but is no longer the primary or sole design driver. Strength, durability, structural rigidity, and total lifecycle GHG emissions are becoming equally important for any successful vehicle program. It is evident from recent executions, as seen in figure 1 (b),* that steel is the material of choice to meet such a challenge. This trend is expected to continue especially with the advent of electrified autonomous vehicles.

**Figure 1 (b): Enhanced Performance at lower weight in New Vehicles enabled by AHSS**

*Sources:  
[www.worldautosteel.org](http://www.worldautosteel.org)  
[www.steel.org/steel-markets/automotive/gdis](http://www.steel.org/steel-markets/automotive/gdis)

## Automotive Challenges

To develop a sustainable automotive steel technology roadmap, one must first understand the perennial challenges facing the global automotive sector and the driving forces behind this highly competitive industry. The automotive industry is facing mounting pressures worldwide to increase fuel economy and reduce CO₂ emissions, and global safety and crashworthiness requirements are becoming more stringent and consumer tests more severe. Additionally, customer facing technologies and creature
comfort features are becoming common across all segments. To secure a competitive position, automakers are required to balance these challenges cost-effectively within the constraints of their existing manufacturing infrastructure while conserving much needed capital to sustain their product portfolios.

**Challenge #1: Fuel Economy and Emissions**

The conventional Corporate Average Fuel Economy (CAFE) standards have been evolving over the last three decades to more environmentally conscious requirements. While the standards correlate to fuel economy, they are intended to have a farther-reaching impact than merely depletion of global fossil fuel resources.

Figure 2 below shows a progressive reduction in vehicle CO₂ emissions by year through 2030 for various countries that are enacting air quality standards. It depicts the most recent passenger car CO₂ emissions and fuel consumption projected values normalized to the New European Driving Cycle (NEDC). By 2025, the standards fall in a narrow range, 80 to 120 grams of CO₂ per kilometer. The chart illustrates how aggressive the European Union (EU) and Japan targets become leading up to 2030, with China and Canada close behind. Meanwhile the U.S. tracks higher by 2030 (closer to 115 g/km). It should be noted, however, the chart does not take into account any credits provided (such as eco-innovations), nor any differences in real-world enforcement.

![Passenger car CO₂ emission and fuel consumption values, normalized to NEDC](https://theicct.org/chart-library-passenger-vehicle-fuel-economy)

*Source: The International Council on Clean Transportation (ICCT), May 2020*

While emission standards may vary globally based on regional market drivers and vehicle size mix, one thing is certain: automakers will have to meet the mandates everywhere they wish to sell vehicles, and therefore they must develop an appropriate set of cost-effective and efficient solutions that allow them to do so. Automakers are already looking toward vehicle electrification as a means of meeting emissions targets. They are currently implementing various strategies to electrify their offerings to achieve CO₂ emissions targets at fleet levels by increasingly investing in dedicated battery electric vehicle (BEV) platforms while ramping up Plug-in Hybrid Electric Vehicles (PHEVs) and Mild-hybrid Electric Vehicles (MHEVs) for mainstream demand.

Increasing vehicle range is a key design objective for BEVs. This drives the need for adequate onboard energy and lightweight designs. With battery energy density increasing and the cost of batteries decreasing over the next decade, automakers will look to combine the most cost-effective lightweight vehicle design with an appropriately sized battery pack to produce affordable electric vehicles with competitive range capabilities.

On the other hand, the proliferation of BEVs will also drive stringent, globally harmonized crash requirements over and above the existing standards to minimize intrusion into the battery pack, maintain pack structural integrity and ensure occupant safety. Steel is the better positioned material to enable the global automotive industry to achieve these goals. By combining the fundamentals of efficient design with the broad spectrum of available steel grades, automakers will be able to produce the most cost-effective lightweight electric vehicles while ensuring exceptional safety and crashworthiness.

**Challenge #2: Increased Vehicle Safety Requirements**

Global vehicle safety and crashworthiness requirements can be categorized as follows:

1. Government regulations which are the basic requirement for passenger protection in vehicle crash and all vehicles must meet these standards. Figures 3 (a) and 3 (b) are examples of the U.S. Federal Motor Vehicle Safety Standards (FMVSS). Similar regulations exist in Europe and in other countries such as China, Japan, Australia, South Korea and India.
The New Car Assessment Program (NCAP) represents a higher protection level targeted by most car manufacturers today. Under NCAP, vehicles tested are selected at random and the results are publicly accessible (www.safercar.org for U.S. vehicles). NCAP is completely optional to the OEMs but is targeted at the buying public. The performance ratings (star ratings) are widely publicized. These safety ratings are gathered during controlled crash and rollover tests conducted at research facilities such as the National Highway Traffic Safety Administration (NHTSA) in the U.S. It should be noted that the U.S., Europe and China use similar test and rating systems. Figures 4 (a) and 4 (b) show examples of NCAP tests in the U.S., Europe and China. The new Euro NCAP Moving Progressive Deformable Barrier test (MPDB), where both vehicle and
trolley are moving at 50 km/hr (31.1 mph), is a new addition to the NCAP suite which continues to increase in severity.

![Figure 4 (a). NCAP Example: Frontal Impact Tests](image)

![Figure 4 (b). NCAP Example: Side Impact Tests](image)

3. Consumer testing is represented by additional independent vehicle safety tests performed by independent organizations such as the Insurance Institute for Highway Safety (IIHS) in the U.S. These tests tend to rank vehicles according to their performance.

They are completely optional to the automakers, but are targeted at the buying public as a way of comparing vehicles to more real-world crash levels. Ratings are widely publicized. Similar to NCAP testing, not every vehicle is tested but any manufacturer with a new vehicle in the market that is noticeably different from the competition is likely to be selected for testing.
Examples of IHSS test includes:

- **Frontal 40% Offset Deformable Barrier Impact**
  - 64 km/hr (40 mph) is higher speed than U.S. NCAP or FMVSS

- **Frontal 25% Small Overlap Rigid Barrier (SORB)**
  - Driver side testing started in 2012
  - 64 km/hr (40 mph) test speed is the most severe test currently in the U.S. or Europe testing matrices
  - Passenger side testing adopted in 2017

- **Side 90º Movable Deformable Barrier Impact**
  - 50 km/hr (31.1 mph) and is higher than U.S. NCAP or FMVSS
  - 1500 kg sled is heavier than U.S. NCAP or FMVSS

- **Roof Crush**
  - 4 times vehicle weight (higher than the FMVSS 1.5 times)

Figure 5 illustrates the progression of U.S. safety test standards. Although the figure is truncated at 2015, it is clear based on the above data that the standards will continue to become more stringent over time. Some examples include NHTSA’s Oblique Offset Moving Deformable Barrier Impact Test and Euro NCAP Mobile Progressive Deformable Barrier Test. Additionally, with worldwide proliferation of electric vehicles, more specific tests will be introduced to ensure the safety of the occupants, protection of the battery pack, and integrity of the cells and associated electronics and thermal management systems. The arrival of autonomous vehicles will further extend vehicle protection to include the multitude of sensors and control modules critical to maintaining a vehicle’s safe operation.
Challenge #3: Life Cycle Assessment

Life cycle assessment (LCA) is a more rigorous and disciplined approach to evaluating GHG emissions throughout the entire life of a vehicle is critical to ensure that automakers take the appropriate and adequate steps to help reduce emissions and slow global climate change.

For example, focusing only on the driving phase and tailpipe emissions of vehicles has long misrepresented the real environmental impact. This approach forces automakers to select high cost alternate materials for body and chassis designs in an effort to reduce vehicle mass and therefore driving phase emissions.

By contrast, a total life cycle assessment approach includes both production and recycling phases. By accounting for the emissions associated with material production, this approach affirms that lightweighting with steel is the more environmentally sound solution, and selecting alternate materials can have a long-lasting adverse effect on the environment. In fact, there is a move to have automakers in Europe report lifecycle CO₂ emissions of all new cars based on a harmonized methodology by 2025. This trend is likely to be adopted globally. Over the last two decades, automakers have been learning
more about the impact of material selection decisions on overall vehicle emissions and the importance of full LCAs.

Figure 6 illustrates the three phases of a steel vehicle’s life cycle: production, use (driving) and end of life disposal (recycling). As illustrated, material production has a considerable share of the product manufacturing phase emissions.

![Figure 6. The Life Cycle of Steel](image)

Material production alone can account for up to 30 percent of the total GHG emissions in Internal Combustion Engine powered vehicles (ICEs) and Hybrid Electric Vehicles (HEVs) and as much as 47 percent in BEVs. As automotive fleet fuel economy improves and the share of alternate powertrain vehicles, such as BEVs, increases in material production emissions become even more important.

**Challenge #4: Manufacturing Infrastructure and Capital Investment**

The leading forming process in the automotive industry is currently stamping and the dominant joining technology remains fusion welding. These two processes have matured over the years and remain the most cost-effective means of mass producing automotive body, chassis structures and closures. While automakers have been introducing new forming technologies (e.g., roll-forming) and new joining technologies (e.g., adhesive bonding), their manufacturing infrastructure within the automotive industry remains largely dominated by stamping and fusion welding. This presents automakers with the challenge of introducing innovative architectures with only incremental updates to existing processes. Steel has the ability to help automakers realize both evolutionary and revolutionary approaches.
Steel’s Role in Addressing Automotive Challenges

Lightweight efficient designs

The steel industry’s approach to meeting the automakers’ challenges has been holistic and comprehensive. The industry continues to develop a diverse pallet of grades – high-strength, advanced high-strength and ultra-high-strength (UHSS) – along with the key application enablers to allow lightweight vehicle designs with exceptional strength and stiffness to meet safety, crash, ride and handling, and noise, vibration and harshness (NVH) performance targets without compromising spaciousness or contemporary exterior design cues.

As vehicle lightweighting became a critical imperative for automakers, steel companies worked collaboratively with the auto industry, and through organizations such as WorldAutoSteel, AISI and the A/SP, to demonstrate cost-effective weight reduction opportunities using a portfolio of grades developed specifically to enable mass reduction and enhance vehicle structural performance on all fronts. Figure 7 and the links listed are a collection of full-scale projects undertaken by WorldAutoSteel over the past two decades to ensure automakers have access to options commensurate with their product portfolio strategy and manufacturing infrastructure.

Links:
UltraLight Steel Auto Body (ULSAB);
UltraLight Steel Auto Suspensions (ULSAS);
UltraLight Steel Auto Closures (ULSAC);
UltraLight Steel Auto Body-Advanced Vehicle Concepts (ULSAB-AVC);
FutureSteelVehicle (FSV).
Additional projects completed at A/SP in the same timeframe with automaker participation were a lightweight front-end structure (LWFES) and future generation passenger compartment (FGPC). These projects focused primarily on vehicle structures, closures, suspensions and sub-frames as these subsystems collectively represent around 60 percent of the vehicle weight, as seen in figure 8.

![Figure 8. Typical Vehicle Mass Breakdown by Major Component Areas](image)

Detailed analyses of energy losses in a typical internal combustion sedan (shown in figure 9), reveal that while vehicle mass is a contributing factor, engine and transmission efficiencies as well as aerodynamics combine to account for almost 70 percent of total losses. Consequently, a cost-effective lightweighting strategy using steel is a more sensible approach for automakers as they can avoid using more expensive alternate materials and, instead, use the savings to fund powertrain improvements and efficient aero technologies.

![Figure 9. Typical Distribution of Sedan Energy Losses](image)
In the case of battery electric vehicles, the cost saved by implementing efficient steel architectures is better utilized by adding onboard energy in the form of more batteries. Such a trade-off will become self-evident as battery system costs decrease over the next decade. Figure 10* projects that when battery system costs drop below $100, steel intensive designs will be almost always the preferred approach.

![Figure 10. Battery system cost vs. cost of lightweighting](image)

*Source: Nucor presentation at BEVA conference, Sep. 2018

**LCA**

As mentioned previously, vehicle mass reduction contributes to improvements in fuel economy and reductions in emissions. As a result, automakers continue to feel pressure to use more costly alternate materials to achieve maximum mass reduction to meet fuel economy and tailpipe emissions targets and reduce the industry’s carbon footprint. Unfortunately, by ignoring the material production phase, this approach can have unintended consequences.

For example, producing primary aluminum ingot in North America currently generates at least four times the emissions from producing steel, (1.9 ton of CO₂e /ton of steel vs. 8.94 ton of CO₂e /ton of aluminum). This comparison utilizes the aluminum industry’s assertion that aluminum smelters in North America operate using 75 percent
hydropower. Power accounting methods using regional grid information and/or recognizing imported aluminum ingots would skew production emissions even higher. Production emissions of other lightweighting materials (e.g., magnesium and carbon fiber reinforced composites) are also considerably higher than steel emissions. Figure 11 illustrates material production GHG emissions for steel in comparison to other automotive lightweighting materials, factoring in the lightweighting potential of each material. Even with more conservative CO₂e values for material production (e.g., 8.97 kg CO₂e per kg aluminum), lightweighting with AHSS offers significant environmental advantages over any other material.

<table>
<thead>
<tr>
<th>Material</th>
<th>kg CO₂e/kg</th>
<th>Estimated Part Weight (kg)</th>
<th>kg CO₂e</th>
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</thead>
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<tr>
<td>Mild Steel</td>
<td>1.9</td>
<td>100</td>
<td>190</td>
</tr>
<tr>
<td>AHSS</td>
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<td>75</td>
<td>143</td>
</tr>
<tr>
<td>Aluminum</td>
<td>8.9</td>
<td>67</td>
<td>596</td>
</tr>
<tr>
<td>Magnesium</td>
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<td>50</td>
<td>1525</td>
</tr>
<tr>
<td>CFRP</td>
<td>22</td>
<td>45</td>
<td>990</td>
</tr>
</tbody>
</table>

**Figure 11. Material Production GHG Emissions for Common Body Structure and Closure Materials Accounting for Estimated Part Mass Reduction**

These emissions result in a substantial environmental impact before a vehicle is even driven, yet they are not accounted for in any current fuel economy regulations or factored into most automotive design practices. Once emitted, GHGs immediately absorb energy from the sun leading to warming of the atmosphere. Major GHGs can remain in the atmosphere from seconds (e.g., 10 to 100 seconds for methane) to years (e.g., CO₂) after being released. Therefore, timing of the emissions is also an important consideration. The steel industry conducted a considerable amount of peer-reviewed research in this area and has openly shared the findings. As mentioned earlier, there are clear indications that a total LCA approach which includes material production phase emissions will be mandated in Europe first, and eventually globally, as a means of reducing future environmental impact.

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1 https://www.worldautosteel.org/life-cycle-thinking/Consequential Life Cycle Greenhouse Gas Study of Automotive Lightweighting with Advanced High Strength Steel (AHSS) and Aluminum
Vehicle safety

The extensive portfolio of steel grades developed in the last few decades has consistently delivered efficient vehicle designs that possess the desired strength and energy management characteristics to meet safety and crash test requirements that have consistently evolved in terms of configuration and severity. Improved energy management in front and rear structures, as well as enhanced occupant protection and intrusion prevention, have benefitted greatly from the use of AHSS and UHSS grades in automotive body structures.

For example, figure 12 below highlights crash simulations from the WorldAutoSteel FutureSteelVehicle (FSV) project which focused on mass reduction in a steel-intensive vehicle with multiple powertrain designs. The FSV design utilized a wide range of HSS, AHSS, and UHSS grades that existed at the time of the project and others that were still in the process of being developed by the steel industry. It leveraged state-of-the-art optimization techniques to develop a highly efficient Five-Star vehicle (front, rear, side and roll over). The project presented automakers with credible optimized geometry, grade and gage solutions used to draw upon for designs and are manifested in vehicles on the road today.

In addition to supporting WorldAutoSteel detailed vehicle engineering studies, the steel industry also dedicates considerable effort to stimulating a productive dialogue with automakers to understand their current and future challenges, through:

- A/SP pre-competitive enabling projects;
- AISI Automotive Program sponsored one on one design projects; and
- AISI sponsored university programs.

Figure 12. FSV 5-Star Crash Simulations for Side, Rear and Front Load Paths Made Possible Lightweight AHSS Design
Steel grade development

The need for innovative grades and possible applications is well documented and typically discussed in forums such as A/SP and the U.S. Automotive Materials Partnership LLC (U.S. AMP). While actual grade developments are left to the individual producers, the industry at large often seizes the opportunity to participate in pre-competitive research with academic institutions and national research laboratories to advance the state of the art in material modeling from the atomic scale through engineering design and testing. One such project, Integrated Computational Materials Engineering (ICME) (see figure 13), was concluded in 2017. Two grades were successfully developed within that project. Both showed promise of outstanding strength and ductility and provide an excellent path toward future emerging grades.

Figure 13. The Multi-Scale Nature of Steel Alloys and Linkage with Alloy Design for Performance

Manufacturing

While the introduction of new steel grades is intended to enhance structural performance and enable mass reduction, it needs to be accompanied by the appropriate upgrades to the existing manufacturing infrastructure to ensure successful deployment. In that context, the steel industry works collaboratively with automakers and part manufacturers to enhance existing manufacturing practices and equipment, while also

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working to support promising technologies that enable cost-effective quality parts and assemblies using the emerging grades. Figure 14 lists a range of forming processes available to automakers that may enable them to achieve optimized and complex designs with future AHSS grades.

<table>
<thead>
<tr>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Stamping</td>
</tr>
<tr>
<td>Laser Welded Blanks</td>
</tr>
<tr>
<td>Roll Stamping</td>
</tr>
<tr>
<td>Sheet Hydroforming</td>
</tr>
<tr>
<td>Tailor Rolled Blank</td>
</tr>
<tr>
<td>Induction Welded Hydroformed Tubes</td>
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<tr>
<td>Laser Welded Hydroformed Tubes</td>
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<tr>
<td>Tailor Rolled Hydroformed Tubes</td>
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<td>Hot Gas Blow Form</td>
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<tr>
<td>Hot Stamping (Direct and Indirect)</td>
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<td>Laser Welded Blank Quench Steel</td>
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<td>Tailor Rolled Blank Quench Steel</td>
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<td>Roll Forming</td>
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<td>Laser Welded Coil Roll-formed</td>
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<tr>
<td>Tailor Rolled Blank Roll-formed</td>
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<tr>
<td>Roll Form with Quench</td>
</tr>
<tr>
<td>Multi-walled Hydroformed Tubes</td>
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<tr>
<td>Multi-walled Tubes</td>
</tr>
<tr>
<td>Laser Welded Finalized Tubes</td>
</tr>
<tr>
<td>Laser Welded Tube Profiled Sections</td>
</tr>
</tbody>
</table>

Figure 14: Improved Manufacturing Processes to Support New AHSS Grades
Steel Industry Technology Roadmap and Challenges

The steel industry seeks to address the automotive industry challenges with a constantly evolving technology roadmap that is also aligned with global megatrends such as: Industry 4.0, Sustainability and Standardization.

Perhaps the most efficient and meaningful way to discuss the steel industry’s technology roadmap and identified challenges is through the lens of organizations like WorldAutoSteel and A/SP. WorldAutoSteel is a consortium of global steel producers which continuously monitors and evaluates the state of the industry worldwide and launches focus projects to address rising concerns and future trends. A/SP, on the other hand, is an American consortium of steel producers and automakers that identifies ongoing and future issues associated with the application of existing and upcoming steel grades in an effort to resolve concerns collaboratively with automaker participation and promote the use of steel as the material of choice. Thus, the roadmap will not elaborate on any proprietary information and will only focus on precompetitive technical areas of research and development.

The Steel Strength-Ductility Diagram, figure 15, highlights at a high level the wide variety of steel grade classifications by their relative strength and ductility. The diagram shows the wide collection of grades (combination of chemical composition and thermo-mechanical processing) that the steel industry has developed, and some that are currently in development. As grade developments are company specific and proprietary, they will be excluded from the current discussion unless it is a focal project similar to or an extension of the ICME project.
Technology Roadmap

Steel continues to introduce newer grades and manufacturing processes to support vehicle mass reduction, which presents the steel industry with new challenges. The following sections introduce a proposed industrywide technology roadmap that helps describe the technical developments needed to respond to these challenges which may be categorized in the following major areas:

- Materials
- Modeling - computer aided engineering (CAE), modeling and simulation
- Forming technologies and enablers
- Joining technologies and enablers
- Other relevant technical areas

Identifying and addressing technical gaps within each of these areas will allow automakers to adapt quickly and seamlessly to newer AHSS grades with minimal disruption to their existing engineering and manufacturing infrastructure. This is an ongoing effort that needs periodic updates to adapt to the changing nature of the automotive industry.

**Materials**

Higher strength, increased ductility and reduced gage will be central to future automotive steel innovations. The steel industry is focused on ensuring the appropriate manufacturing infrastructure will be in place to support the production of such grades. Relevant key initiatives within this area can be summarized as follows:

- **Global grade harmonization** – As advances in microstructure refinement and thermo-mechanical processing become increasingly specialized, same grade consistency across the steel industry and global availability of such grades may be impacted. This is contrary to the automotive manufacturers’ desire to maintain sufficient flexibility to use the same grade for the same part globally with increased confidence. A workable initiative, including standardizing OEM specifications, is needed to better align the global needs of steel producers and automakers alike.
• **Modulus of Elasticity** – This key material property plays a very important role in automotive design, engineering and forming. As newer steel grades evolve, it is important to:

  o Standardize testing methods to accurately measure this property and assess the effects of anisotropy directionally on its measurement.

  o Model changes in the elastic modulus for an AHSS material in a typical tension-compression-tension cycle, which is not easy for materials exhibiting phase structure change. However, it is essential in part forming and performance characterization.

  o Investigate means of potentially increasing the elastic modulus to compensate for gage reduction and avoid loss of part or panel stiffness.

• **Plasticity modeling fundamentals** – Successful modeling of polycrystalline behavior would benefit the understanding and application of new steel grade plasticity properties. Modeling the effect of the microstructure and the various damage/strengthening mechanisms during deformation will enhance the understanding of grade-specific formability and energy management characteristics.

• **Material fracture prediction** – The ability to accurately model and predict material fracture in large deformation regimes will enhance forming and crash simulation capabilities. The industry is working collaboratively to:

  o Determine fracture failure mechanisms of AHSS under complex and high strain rate loading conditions;

  o Better understand the effects of deformation mode on shear fracture including the influence of microstructure to help refine AHSS products and processing; and

  o Standardize testing to measure shear fracture and edge-stretching capability.

• **Local formability** – Standardized material test methods are needed to provide the appropriate material data required to support modeling and prediction of local flow stresses incorporating anisotropy. A standardized test for shear fracture and edge stretchability would advance AHSS application opportunities by establishing the appropriate criteria for component and structural designs.
• **Delayed fracture and hydrogen embrittlement** – Standardized reproducible test methods are needed to reflect real service environmental conditions. This is specifically important for coated steels.

**CAE Modeling and Simulation**

Advances in finite element formulations, enhanced modeling, analyses and post-processing techniques have significantly improved the fidelity and speed of simulations and allowed automakers to quickly iterate on their designs to achieve an optimum balance of performance, mass and cost without compromising safety as their primary objective. The ability to reliably predict formability, crashworthiness, durability and NVH ahead of hardware builds and physical testing can have a significant impact on development cost and program timing.

The steel industry supports major initiatives within this area, such as:

- Improving the accuracy and robustness of the material data generated and provided as inputs to the CAE models;
- Standardizing the material card testing and simulation practices;
- Understanding the effect of non-linear strain paths on forming and crash simulation;
- Development of a true multi-disciplinary optimization (MDO) simulation methodology that not only seeks to optimize performance and mass of a design, but also incorporates manufacturability, process based technical cost, and LCA modeling. This simulation approach will allow OEMs to balance their designs appropriately across multiple disciplines early in the vehicle program; and
- Understanding the role of steel in future automotive technological advances such as shared and autonomous vehicles.

The above calls for a collaborative effort between steel manufacturers, automakers and finite element code developers to ensure that virtual vehicle simulations have the sufficient accuracy and predictive capability.
Forming Technologies

While newer steel grades offer opportunities for improved performance, they can also present additional forming challenges that need to be addressed to ensure application of these grades with reduced risk. Mainstream forming technologies and the major challenges associated with each are outlined below:

- **Conventional Stamping** – Stamping is the most dominant production process for steel. Process capability and improvement are critical to expanding the future application of AHSS/UHSS. Arrival of higher-strength, more ductile, thinner-gage steel grades open up a number of technical gaps such as:
  
  o Accurate material data to promote proper forming predictions;
  
  o Correlated and validated forming simulation techniques;
  
  o Validated material failure models to support forming simulations and improve the analytical predictive capability prior to hardware builds;
  
  o Springback prediction and control;
  
  o Phase transformation induced non-linear springback modeling and reduction;
  
  o General forming guidelines, thinning control and springback compensation, including specific part and die design concessions necessary to ensure first time/high-quality parts;
  
  o Material handling and blanking techniques (tooling, equipment, volumes);
  
  o Updated trim and pierce techniques; and
  
  o Enhanced blank holder design and press feedback control systems to enable stamping thinner gage AHSS.

An important contributor to the success of these initiatives will be the education and training of OEM product design and manufacturing engineers as well as tiered stampers.

- **Hot Stamping Process** – Hot stamping offered a unique opportunity for automakers to produce components with fairly complex shapes and high
dimensional accuracy. This technology can be direct or indirect and be further refined for softening, hardening and hybrid processing. As the technology continues to mature, there is a need to address technical gaps pertaining to cycle time improvement and production rate increase. For example:

- Reducing the time of controlled blank pre-heating through equipment improvements to speed up the direct hot stamping process;
- Shortening the in-die cooling phase to reduce overall cycle time of the direct hot stamping process;
- Exploring surface treatments to improve heat transfer and result in reducing the cycle times of direct hot stamping;
- Reducing the heating and cooling cycle times for indirect hot stamping; and
- Advancing post hot stamping heat treatment practices and equipment (e.g., laser processing or focused induction processing) to tailor component properties and performance characteristics locally within the part.

**Hydroforming and Roll Forming** – Hydroforming and roll forming processes are mature steel forming technologies widely used within the automotive industry to produce open and closed structural sections. As in the case of stamping, higher-strength, more ductile, thinner-gage AHSS grades create technical gaps requiring attention to ensure successful automotive applications. For example:

- Validated forming simulation techniques and the necessary material properties required to conduct the analyses;
- Updated hydroforming pressure requirements and end seal design;
- General forming guidelines, thinning control and springback compensation, including specific part and die design concessions necessary to ensure first time/high-quality parts;
- Updated trim and pierce techniques;
- 3D roll forming;
Production equipment requirements and updates to existing infrastructure; and

Roll size sequencing to best avoid the possibility of deformed edge micro-cracking.

**Other Forming Innovations** – The preceding forming technologies are the most common within the automotive industry. Less common forming processes include: additive manufacturing; thin wall steel castings; brake forming; spinning, electromagnetic forming, electro-hydraulic forming, incremental stamping and explosive forming. Many of these processes are still under development or limited to lower volumes, however they cannot be totally dismissed in light of the advent of new automotive body architectures that will accommodate full electrification and autonomous driving.

**Tooling Technologies** – Irrespective of the selected forming process, adequacy and capability of forming tools and existing equipment needs to be revisited in order to meet production requirements of current and emerging AHSS grades and achieve part quality at the desired production rates. Technical focus areas include:

- Enhanced die modeling, design and optimization methods;
- Accurate press tonnage prediction;
- Die materials for improved tool life, longer production runs, less maintenance and reduce tooling costs;
- Die heat treatment to prevent die surface damage and improve impact and wear resistance;
- Die surface treatment to reduce friction, tool wear and permit operating at higher-surface temperatures for conventional cold forming and potentially improve die heat transfer characteristics in the case of hot stamping;
- Die lubricant technologies to improve their performance at higher operating pressures and temperatures with stability, improve the cleaning ability with no residue and corrosion protection; and
- Press equipment technologies to address higher-tonnage capacity and potentially permit design of AHSS components with fewer hits.
Joining Technologies

Perhaps one of the most critical considerations in body and chassis design is joining. Engineering lightweight vehicles using stronger, more ductile, thin gage steel needs to be complemented with repeatable and robust joining methods to ensure that actual structural performance in the field is consistent with analytical predictions with no surprises. The continuing evolution of AHSS grades demands considerable effort to update existing joining methods and joint simulation techniques to realize the full mass reduction benefits enabled by these grades without compromising structural safety, strength or stiffness. Additionally, automakers are expressing strong interest in joining steel grades to other automotive grade materials as they continue to be pressured to reduce mass in body and chassis subsystems – which calls for proven mixed material joining technologies. Automotive joining processes can be categorized as:

- **Welding** – Joining processes requiring heat input (or generation) to join the parts with or without filler materials. Examples include: resistance spot welding (RSW), laser welding, gas metal arc welding (GMAW), metal inert gas (MIG), tungsten inert gas (TIG), hot wire welding (HWW), and friction stir welding (FSW).

- **Mechanical Joining** – Joining processes that do not need heat application during joining. Examples include: riveting (both self-piercing and blind), threaded fasteners, flow drill screws (FDS), clinching, hemming, impact riveting and adhesive bonding.

Challenges associated with each of these processes represents opportunities on the steel technology roadmap.

- **Welding** – Weld strength and durability in automotive body and chassis subsystems are key considerations in material grade selection at the design stage. Proliferation of current and emerging AHSS/UHSS grades in future automotive applications is contingent on increasing automaker confidence in:
  
  o Predicting analytically, weld durability as well as weld failure or separation during high-strain rate events;

  o Ensuring process repeatability and robustness; and

  o Understanding and counteracting Liquid Metal Embrittlement (LME).

This generates a number of opportunities on the roadmap such as:
Developing and validating weld fracture/separation models to be used in structural optimization studies and full vehicle simulations;

Developing enhanced smart software to guide design and manufacturing engineers through the process of defining weld content and weld parameters as a function of grade and gage combinations, joint performance requirements and steel surface conditions (i.e., coated versus bare); and

Developing AHSS/UHSS welding best practices defining optimized weld cycles, heat input, clamping pressures and cooling rates for different material grade and gage combinations and stack-ups in order to: improve joint fatigue performance, ensure more uniform and repeatable weld nugget size and composition, minimize heat-affected zones (HAZ), minimize micro-cracking in weld zones, reduce area subject to intergranular coating diffusion in coated AHSS/UHSS, address potential post-welding corrosion concerns, enhance and update weld quality assurance practices to reduce variability and increase confidence and develop non-destructive weld inspection techniques to minimize teardown inspections in body shops.

Mechanical Joining - Mechanical joining is more versatile since it is independent of the material and grade combinations being joined and somewhat independent of the gages. It also has the significant advantage of not altering the microstructure of the joined materials as in the case of welding. Threaded fasteners have been in use within the automotive industry since its inception and guidelines governing their specifications, use and quality assurance are well established. Therefore, these do not need to be included in a steel-specific technology roadmap.

Other mechanical joining methods requiring either piercing or deformation (or both) of the joined steel components such as, riveting, flow drill screws, clinching, hemming and impact riveting will require considerable development especially as automakers start using the newer higher-strength, thinner gage, more ductile AHSS/UHSS grades.

The use of structural adhesives as a primary or secondary joining method is continuing to gain considerable acceptance within the industry as a means of achieving continuous joints without the significant heat input from continuous welding which has unwanted consequences. It is viewed as the most efficient method to transfer shear loads. However, since adhesives are typically poor in
peel, they are often accompanied by another mechanical joining method – depending on the dominant loading condition – to act as a joint peel stopper.

For mechanical joining a number of opportunities exist, such as:

- Developing robust and validated failure models for all joining methods above (including proven adhesive finite element modeling techniques) to be used in structure optimization studies and full vehicle simulations;

- Developing SPR, FDS and impact riveting technologies compatible with emerging higher strength AHSS/UHSS grades and suitable for a range of grade and gage combinations and joint stack-ups;

- Developing best practices to govern the proper arrangement and sequence of AHSS/UHSS grades within a given joint relative to the driving direction of the self-piercing rivets, flow drill screws and impact riveting;

- Developing adhesive best practices defining optimized adhesive bead size and placement within a joint for optimum coverage in order to improve joint stiffness and durability;

- Developing robust, non-destructive methods to detect adhesive presence and appropriate wet-out conditions within a joint; and

- Investigating structural adhesives compatibility with and sensitivity to existing surface coating technologies to recommend best practices and development of new coating chemistries.

Other relevant technical areas

It is important to capture other technical areas where the steel industry interfaces heavily with other automotive related industries and need to remain on the overall steel technology roadmap, such as:
• **Corrosion** – Increasing standards within the automotive industry drive the need for a fundamental understanding of different corrosion mechanisms and their interaction with microstructures, surface treatments and surface coatings. This is especially critical as automakers migrate towards thinner-gage steels for mass efficiency.

• **Paint** – The ability to leverage stronger and thinner HSS and AHSS grades in exposed painted areas of a vehicle body without affecting appearance or perceived quality can further contribute to mass reduction and enhance performance.

• **Repairability** – Ease of repair is one of the advantages of steel, when compared to other materials. Introduction of stronger, thinner AHSS and UHSS grades requires a fresh look at repair procedures for body and chassis components to ensure that repairs remain cost-effective and robust and do not compromise part performance or function.

• **Recyclability** – As new grades with increased alloying emerge, it is important to track end-of-life recycling and investigate the potential consequences to develop the appropriate action plans in advance of disposal vehicles with these new grades.

• **LCA** – The development of robust, easy-to-use LCA tools will be needed to allow automakers to assess the environmental impact of material selection decisions early in the vehicle development program. The steel industry will continue to use vetted data to inform automakers and regulatory bodies about the importance of including production and end-of-life (recycling/disposal) phases in the overall vehicle emissions assessment. Focusing the regulations only on tailpipe emissions (use/driving phase) does not capture the true vehicle emissions impact on the environment and can have long lasting unintended consequences.
Appendix A
Auto/Steel Partnership Roadmap

Figure A1 below is a snapshot of the 2021 A/SP technology roadmap. The roadmap reflects input from A/SP member steel companies and participating automakers. While it is an evolving document, the major areas of concentration are expected to remain the same and consistent with the steel industry roadmap. Meanwhile, the initiatives within each area highlight specific projects that are either, ongoing and need to continue or are projects identified by the consortium for short, mid-term- or long-term implementation.

The overarching themes of Industry 4.0, Sustainability and Standardization will help ensure alignment with more global megatrends.

Figure A1: Auto/Steel Partnership Roadmap 2021