Mechanistic Design Framework for Concrete Crosstie and Fastening System

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Mechanistic Design Framework Outline

- Overview of Mechanistic Design
- Design Process

1. **Define Load Inputs**
    - Vertical Load
    - Lateral Load
    - Longitudinal Load
    - Load Distribution
2. **Define Design Thresholds**
    - Material
    - Geometric
    - Assembly
3. **Component Design Process**
4. **System Level Verification**

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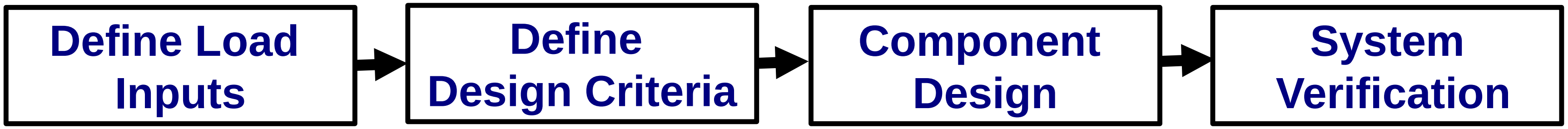
Overview of Mechanistic Design

- Design approach utilizing forces measured in track structure and properties of materials that will withstand or transfer them
- Uses responses (e.g. contact pressure, relative displacement) to optimize component geometry and materials requirements
- Based on measured and predicted response to load inputs that can be supplemented with practical experience
- Requires thorough understanding of load path and distribution
- Allows load factors to be used to include variability due to location and traffic composition
- Used in other engineering industries (e.g. pavement design, structural steel design, geotechnical)

Design Process Sequence

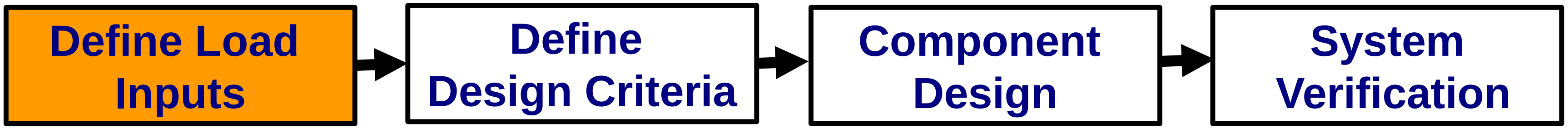
- Design process consists of four stages
- To facilitate understanding of where each stage fits into the design process, the following graphic will be utilized

1. **Define Load Inputs**
   - Vertical
   - Lateral
   - Longitudinal
   - Distribution
2. **Define Design Criteria**
   - Material
   - Geometric
   - Assembly
3. **Component Design**
   - Material
   - Geometric
   - Assembly
4. **System Verification**



Load Characterization

- Load magnitude will vary according to:
    - Traffic type
    - Train speed
    - Track geometry
    - Vehicle and track health
- Each component of the input load must be considered
    - Vertical
    - Lateral
    - Longitudinal
- A complete understanding of the input loads can lead to optimized component and system designs
    - (e.g. as load magnitude and frequency change the design of the crosstie and fastening system should change)

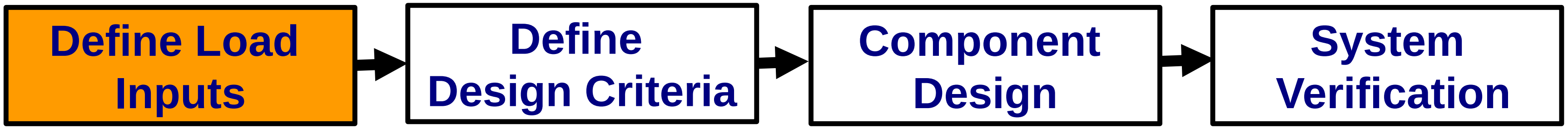


Define Load Inputs → **Define Design Criteria** → **Component Design** → **System Verification**

Load Threshold Approach

- Design thresholds must be determined
  - Low thresholds could yield greater loads exceeding the design value which could result in accelerated wear and/or component failure
- Load distributions can be analyzed to better understand thresholds
  - 99.5% would be a threshold that is only exceeded by 0.5% of all wheels
- Engineers can set this threshold based on their economic model
  - Optimize between initial capital costs and operating costs

Threshold Level	**Conservative**	→	**Less Conservative**
Percentile Load (%)	99.5	97.5	95



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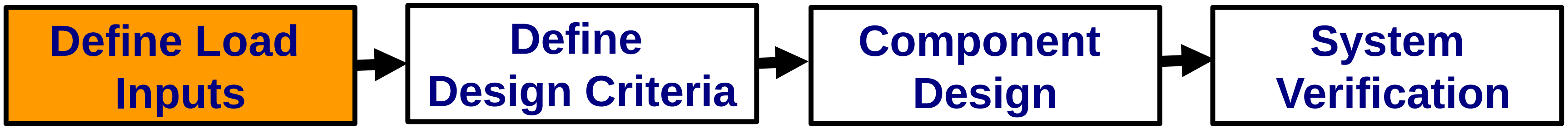
Vertical Load Characterization

- Vertical loads can be characterized using data from WILD sites
  - Provide average load and peak load for each wheel at each site
- WILD sites only provide a measure for well maintained track
- Useful for determining overall magnitude and variability according to car type
- Causes of vertical load variation could include, but are not limited to:
  - Speed
  - Temperature
  - Location (geographic)
  - Position Within the Train
  - Track Geometry
  - Vehicle Characteristics
  - Curvature
  - Grade
- Additional causes in load variation due to other conditions can likely be accounted for using a safety factor



Vertical Wheel Load Tables

Nominal Load (kips)

Car Type	**Mean**	**95%**	**97.5%**	**99.5%**	**100%**
Unloaded Freight Car[1]	6.6	9.6	11.0	13.6	15.0
Loaded Freight Car[1]	33.4	**39.5**	**40.2**	**41.4**	45.5
Intermodal Freight Car[1]	20.5	35.3	36.8	39.8	50.6
Freight Locomotive[1]	33.6	36.6	37.2	38.5	43.5
Passenger Locomotive[2]	27.0	35.8	37.2	39.3	42.6
Passenger Coach[2]	15.0	18.3	19.0	20.1	45.4

Peak Load (kips)

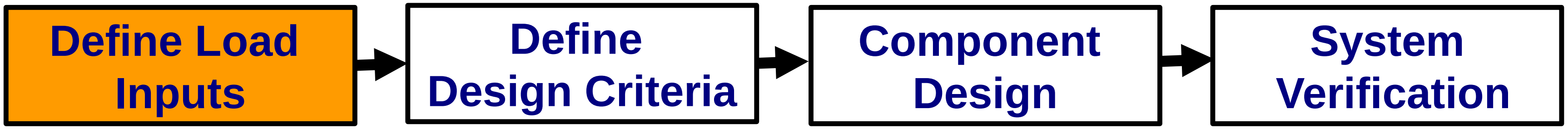
Car Type	**Mean**	**95%**	**97.5%**	**99.5%**	**100%**
Unloaded Freight Car[1]	10.8	20.5	26.4	39.7	100.8
Loaded Freight Car[1]	42.3	**56.2**	**65.3**	**84.7**	156.6
Intermodal Freight Car[1]	27.5	46.8	54.3	74.8	141.9
Freight Locomotive[1]	42.8	53.9	57.5	68.8	109.6
Passenger Locomotive[2]	38.1	50.0	53.6	63.4	94.0
Passenger Coach[2]	23.2	35.3	42.9	58.5	108.8

[1] Source of data: Union Pacific Railroad; Gothenburg, Nebraska; January 2010

[2] Source of data: Amtrak; Edgewood, Maryland, Hook, Pennsylvania, and Mansfield, Massachusetts; November 2010

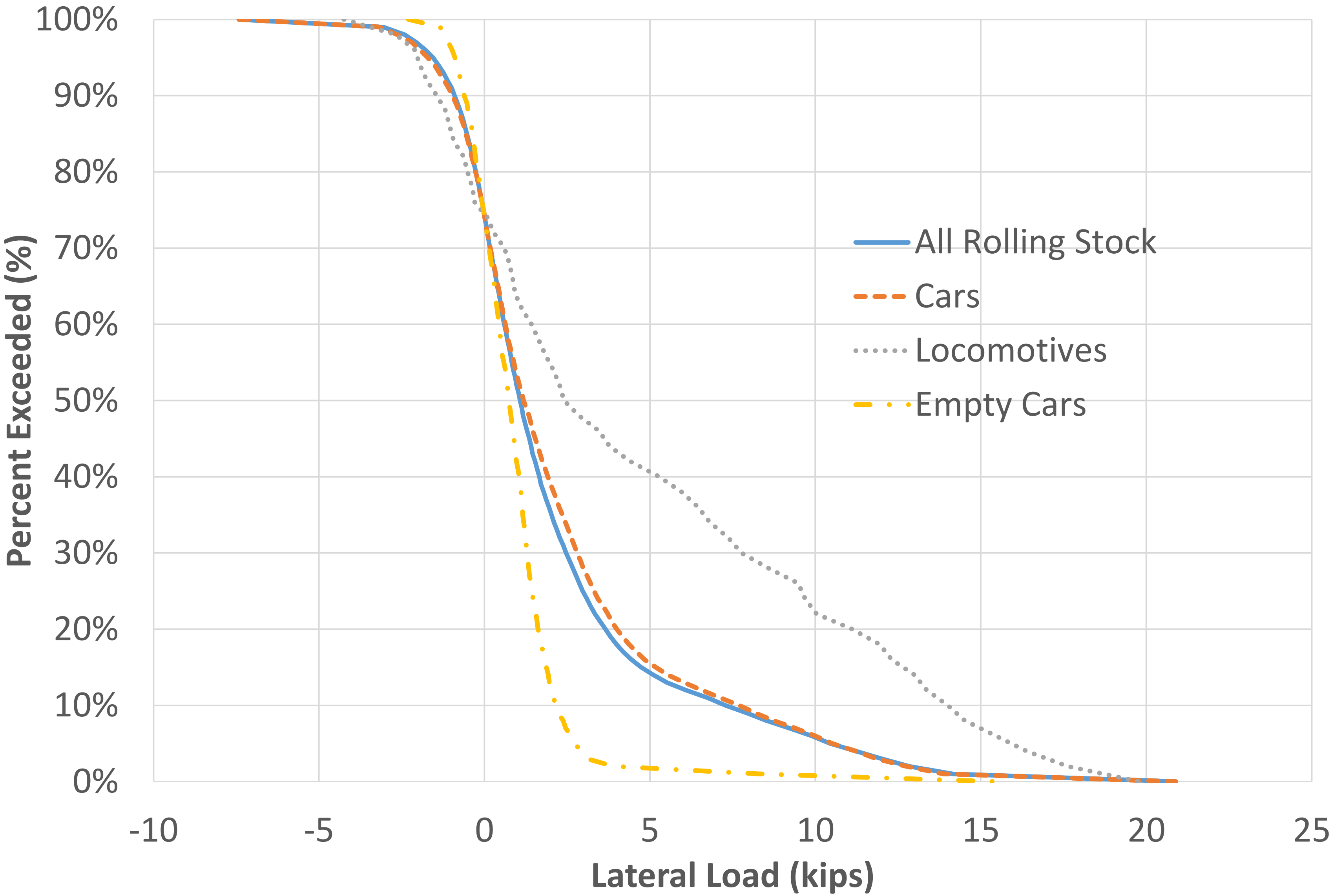
Lateral Load Characterization

- Lateral loads in curves can be characterized through the use of truck performance detectors (TPDs) and/or instrumented wheel sets (IWS)
  - TPDs are similar to WILD sites, but found in curves
- Lateral loads must be characterized and distinguished by:
  - Track curvature (tangent vs curve)
- Causes of lateral load variation could include, but are not limited to:
  - Speed
  - Location (geographic)
  - Position Within the Train
  - Track Geometry
  - Vehicle Characteristics
  - Curvature
  - Grade
  - Rail Surface Condition
  - Superelevation
  - Low or High Rail



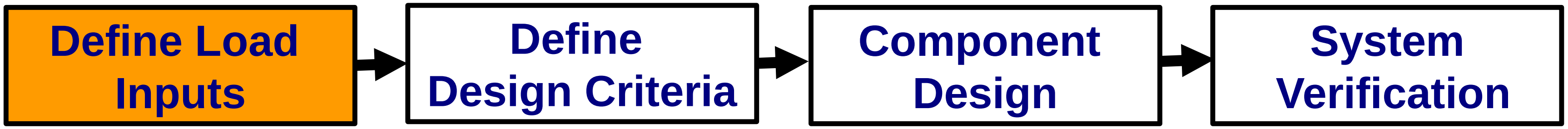
Define Load Inputs → **Define Design Criteria** → **Component Design** → **System Verification**

Lateral Load Wheel Load Distribution



Longitudinal Load Characterization

- No comparable wayside technology to WILD or TPD sites to measure longitudinal load
  - Some IWS can measure longitudinal load
- Longitudinal loads must be characterized and distinguished by:
  - Track curvature (tangent vs curve)
  - Track topography (mountains vs flats)
- Causes of load variation could include, but are not limited to :
  - Speed
  - Temperature
  - Location (geographic)
  - Position Within the Train
  - Track Geometry
  - Vehicle Characteristics
  - Curvature
  - Grade


Define Load Inputs

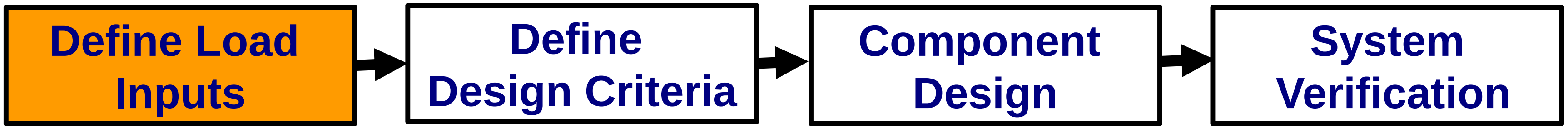
Define Design Criteria

Component Design

System Verification

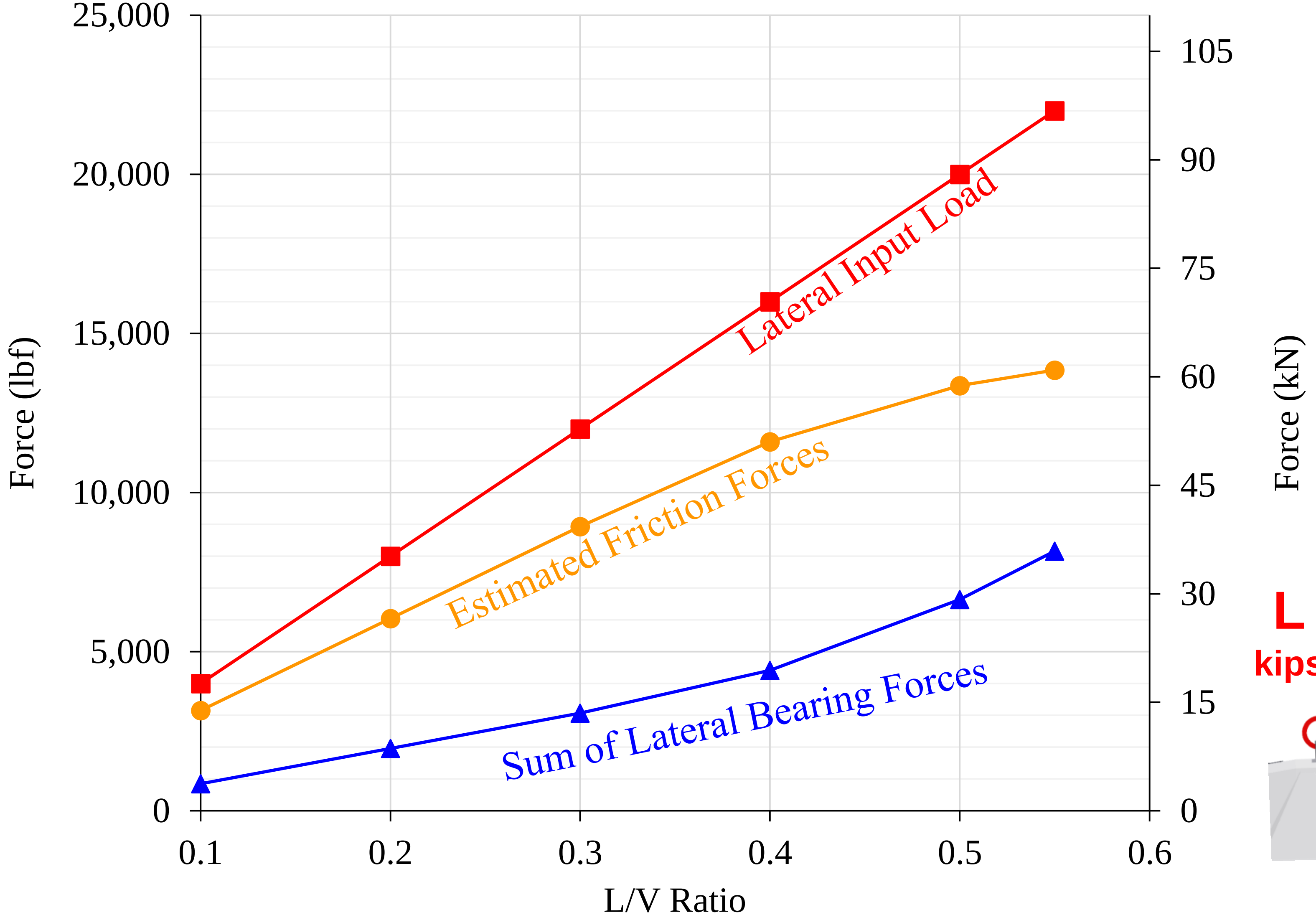
Load Distribution in Fastening System

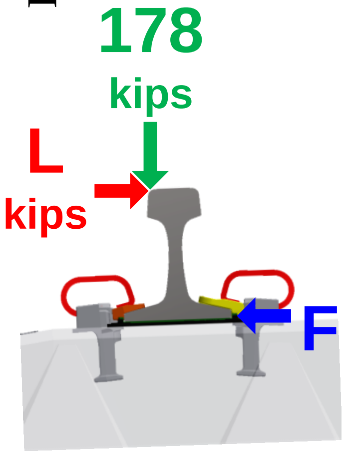
- Determine load transferred to individual component of the system
- Use the load at a specific interface as the design load
- Fastening system and wear dependent
  - As component geometry varies (as a result of design or wear), the load path will vary
- Circular relationship with component design
  - Load distribution guides design of components
  - Component design changes load distribution
- Quantification techniques
  - Laboratory and field experimentation
  - Analytical modeling



Lateral Load Restraint

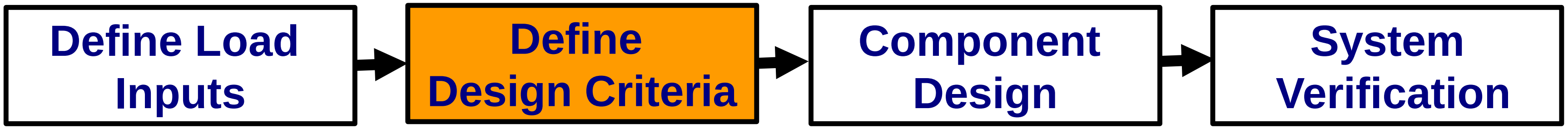
Tangent Track, TLV





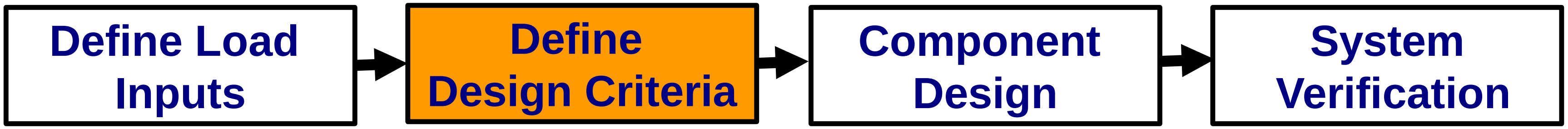
Improving Current Standards

- Recommended practices and standards have areas which can be improved to meet mechanistic design requirements
  - Justify or explain the origination of limit states for tests
    - Maximum allowable moments for concrete crossties (AREMA)
  - Provide limits for all critical properties
    - Lateral rail base displacement limit for insulator
  - Develop a design process for all components
    - Several pad choices are given, but no process for design
- Examining current standards gives clarity to what is missing or what aspects need improvement


Define Load Inputs → **Define Design Criteria** → Component Design → System Verification

Limit State Component Design

- Design component based on failure modes
- Determine value of design criteria for critical fastening system properties
  - Highest value a property can reach that still ensures safe system operation
- Limit state design can be decomposed into three categories of design criteria, each which must have criteria limits defined
  - Material
  - Geometric
  - Assembly
- Provides opportunity to split up design process into smaller manageable pieces
  - E.g. - A project could analyze one specific material property



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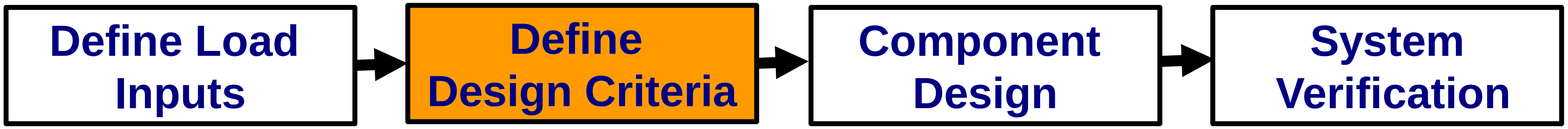
Material Design Criteria

- Define limits for properties of materials used to build components
- Independent of fastening system type and component geometry
- Determine which properties are critical, and the limiting value of the design criteria
- Critical properties to evaluate are:
  - Compressive Strength
  - Tensile Strength
  - Flexural Strength
  - Shear Strength
  - Stiffness
  - Wear Resistance
  - Fatigue
- Example of existing material tests:
  - – ASTM tests regarding material properties of rail pads, described in Ch. 30 section 4.9.1.15 of AREMA



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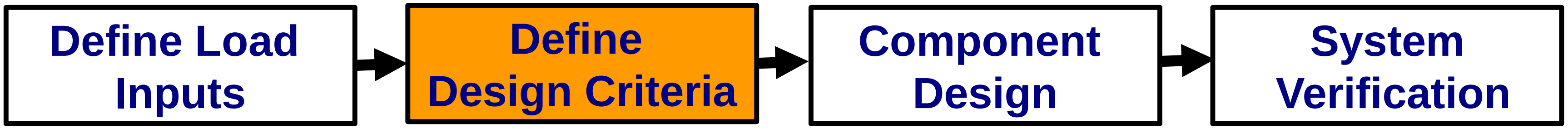
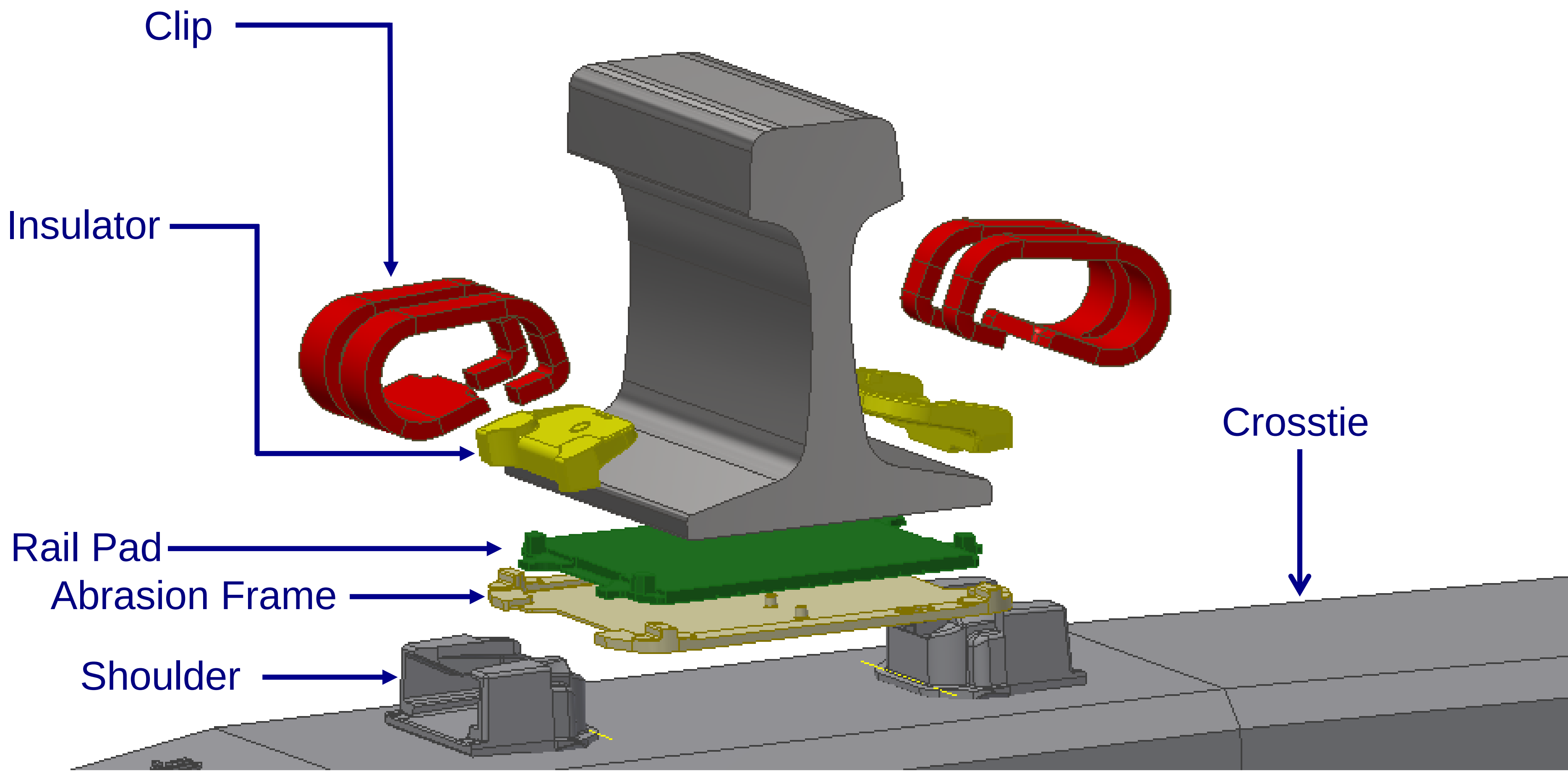
Geometric Design Criteria

- Definite limits for properties dictated by component geometry
- Fastening system dependent
- Critical properties to evaluate are:
    - Compressive Strength
    - Tensile Strength
    - Flexural Strength
    - Shear Strength
    - Stiffness
    - Wear Resistance
    - Fatigue
- Same properties as for material design, but limits will be different
    - Limits based on laboratory and field testing
- No existing examples of geometric design thresholds in AREMA standards



Critical Components

Example: Safelok I fastening system



Clip

Insulator

Rail Pad

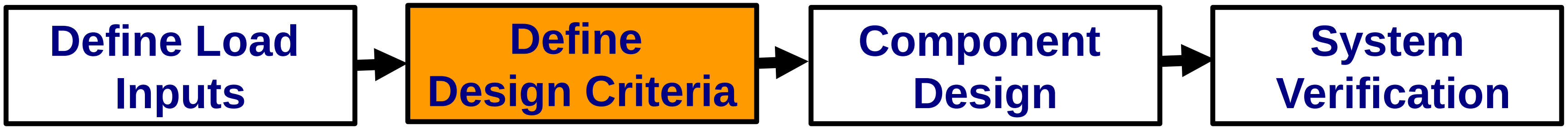
Abrasion Frame

Shoulder

Crosstie

Assembly Design Criteria

- Define the limits of properties of a fully assembled fastening system
- Simplified testing state that eliminates variation due to support conditions
- Critical properties to evaluate include:
  - Contact Pressure
  - Relative Displacement
  - Wear Resistance
- Primary areas of concern are interfaces between components
  - Interfaces will vary with different fastening systems
- Examples of existing assembly tests include:
  - AREMA Test 6
  - Rail Seat Load Index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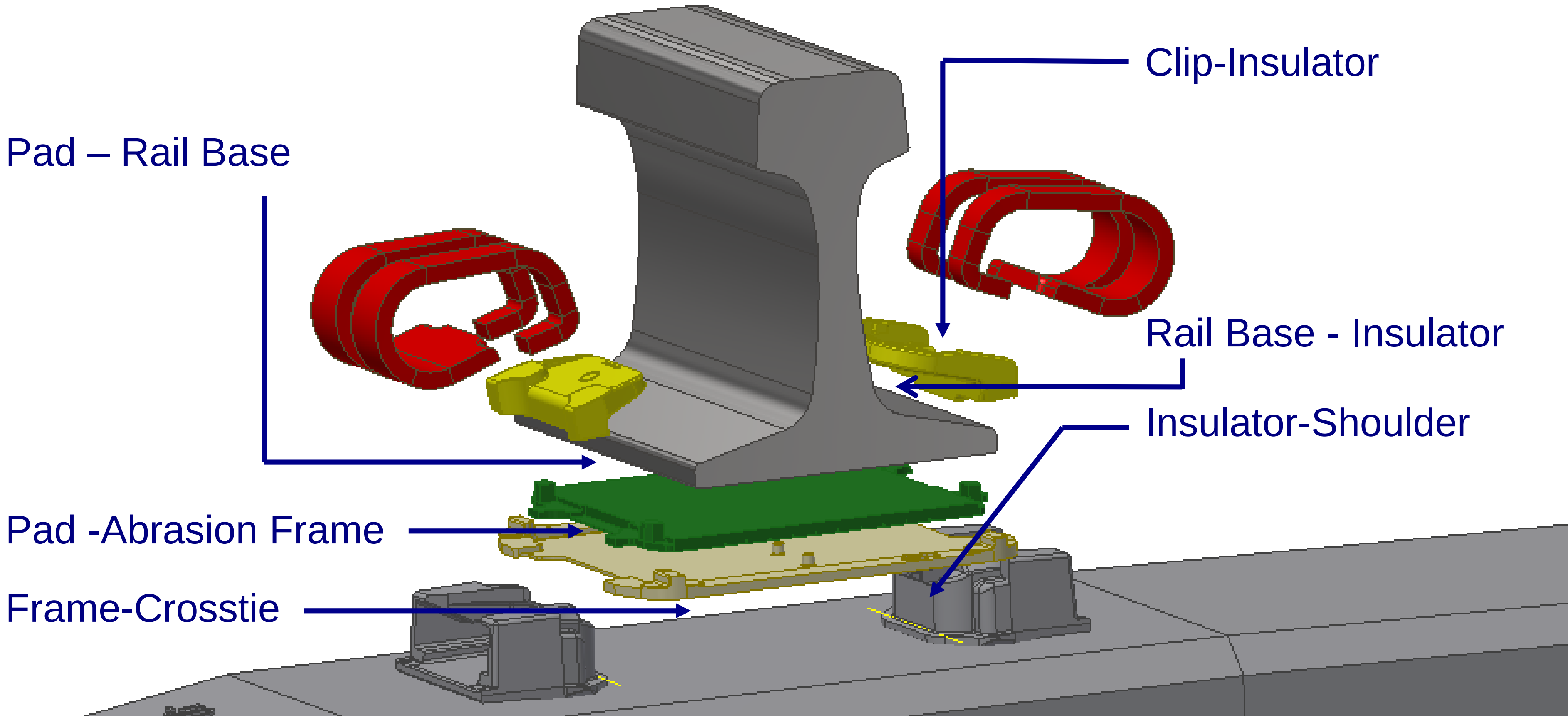
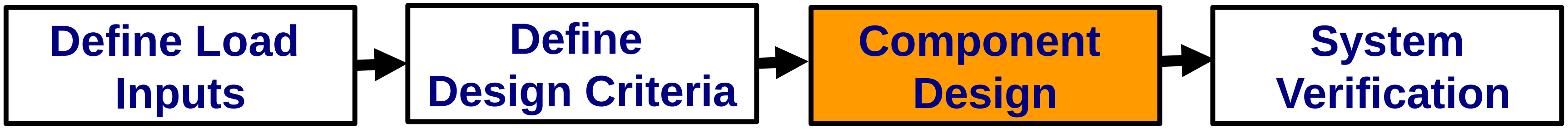
Critical Interfaces

Example: Safelok I fastening system



Component Design Process

1. Select load threshold (low, medium, or high)
2. Complete material design process
    - Compressive Strength
    - Tensile Strength
    - Flexural Strength
    - Shear Strength
    - Stiffness
    - Wear Resistance
    - Fatigue
3. Complete geometric design process
    - Compressive Strength
    - Tensile Strength
    - Flexural Strength
    - Shear Strength
    - Stiffness
    - Wear Resistance
    - Fatigue
4. Complete assembly design process
    - Contact Pressure
    - Relative Displacement
    - Wear Resistance



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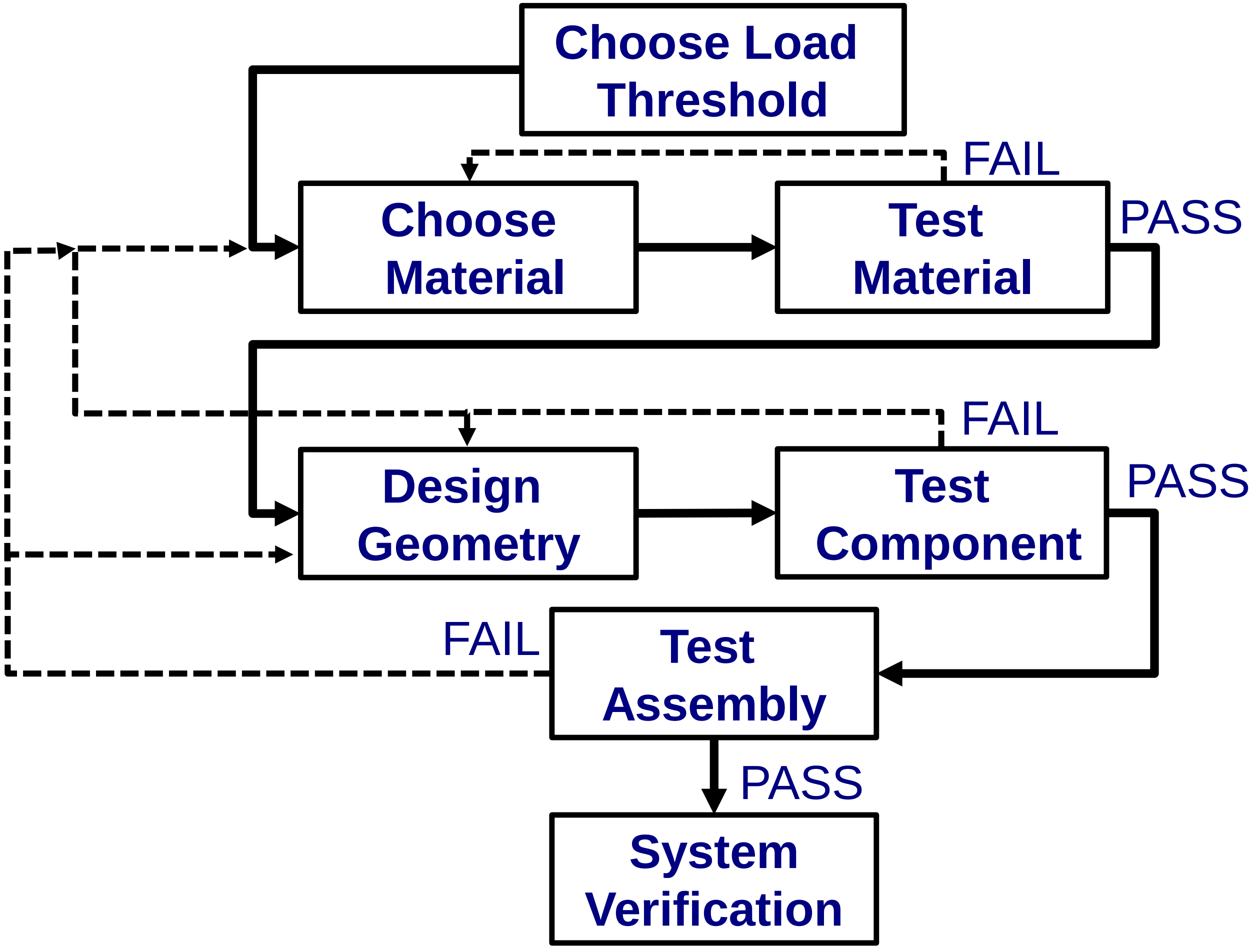
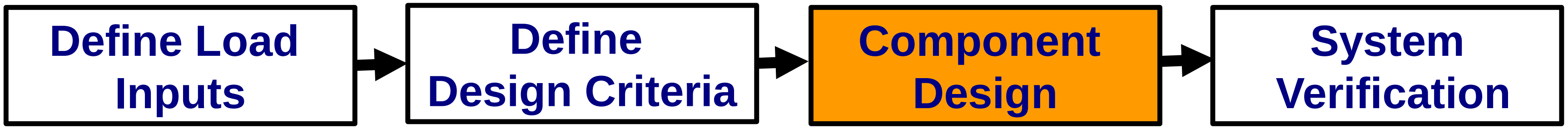
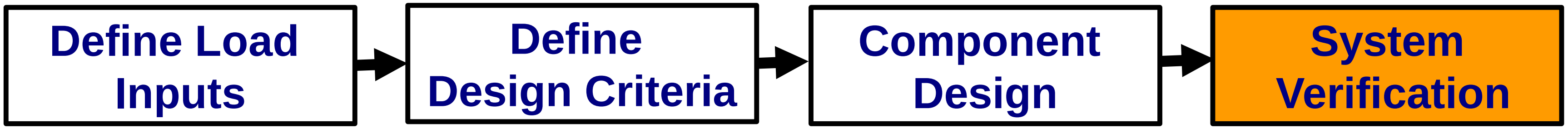




Final System Verification

- Look at overall system response to confirm that design is adequate
- Critical properties to evaluate include:
  - Maximum Ballast Pressure
  - Maximum Subgrade Pressure
  - Total Track Deflection
  - Track Modulus
- Typically involves field testing with varied support conditions
- Initial simulations could be performed with FEM model
  - – Lower cost and more timely than producing new parts
- Evaluate system by installing in track and examine critical properties after appropriate amount of traffic



UIUC Contribution to Mechanistic Design

Field Experimentation

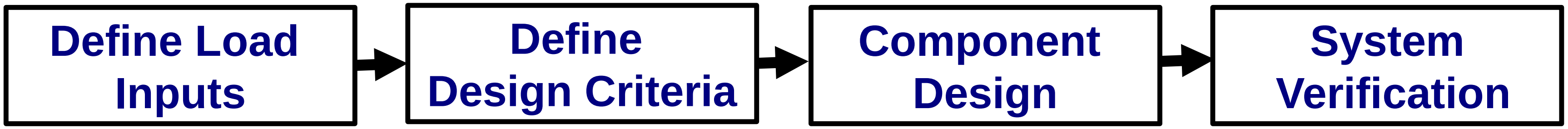
Standards Review

Mining of Existing Data

FEM Model

Lab Experimentation

Analytical Track Design Tool



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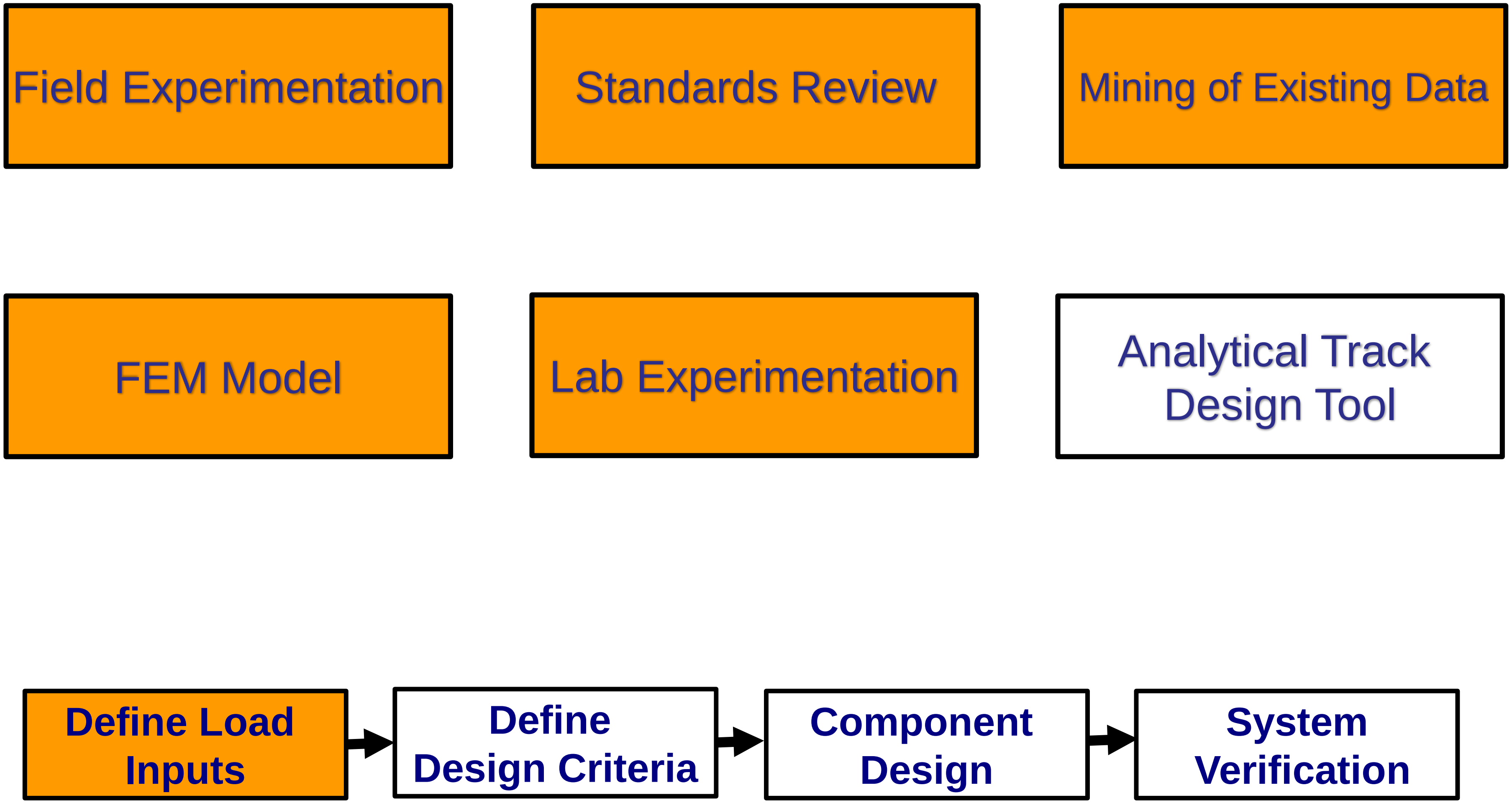

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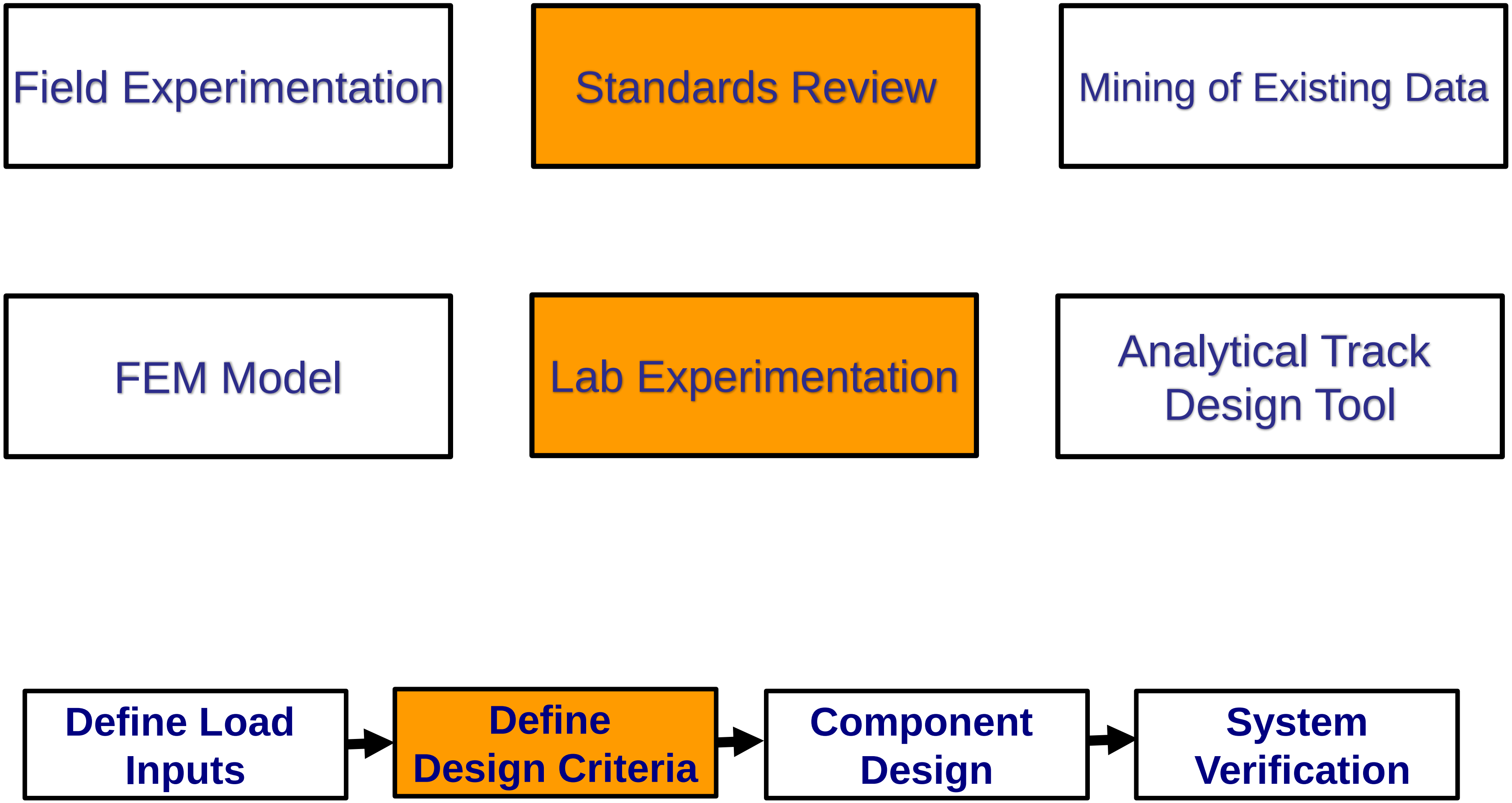

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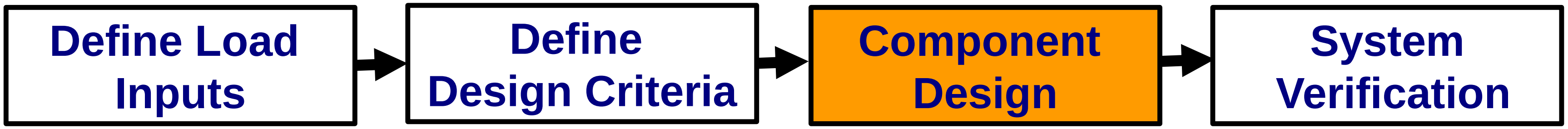

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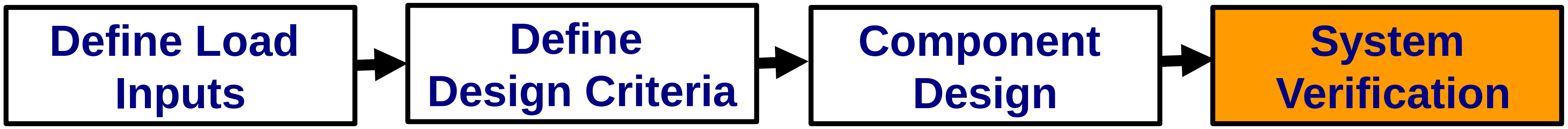

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Conclusions

- Characterizing wheel load distribution of rail traffic will give more realistic values for input loads used to test components and system
- Limit state component design can be used to give greater understanding to what the factor of safety in design is
- Proposed mechanistic design methodology will provide consistent approach even with varying fastening systems
- Framework provides a guide for future research projects to improve the design process

Future Work

- Analyze lateral load data from multiple TPD sites to develop similar load tables to vertical load tables
- Perform more analysis on critical properties, determine if other properties should be included
- Perform literature review to determine existing research on determining values for component properties design criteria
- Include more system level tests, develop ideas for new tests that aren’t currently included in AREMA or other standards

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