Next Generation Automotive Mobility Technology

Innovative n-Wheel Technology Based on an Architectured Cellular Metamaterial

N-Wheel Technologies, Inc.

Ann Arbor, Michigan

www.n-wheel.com

❑ **N**ovel
❑ **N**on-Pneumatic
❑ **N**egative Poisson's Ratio Meta-Material

PART-I

Background

History of Pneumatic Tires

1844 – Vulcanized rubber (Charles Goodyear)

1888 – Pneumatic tires for bicycles (John
　　　　Dunlop)

1890 – Wheel rim (CK Welsh)

1908 – Grooved tires (Frank Seiberling)

1954 – Tubeless tire (Packard)

Charles Goodyear

John Dunlop

Frank Seiberling

1954 Packard Clipper

❑ The current rubber tire technology has been in use for over 70 years
❑ Pneumatic tires widely regarded as the standard for automotive vehicles.

Global Tire Market Forecast

➢ The global tire market is expected to grow significantly, reaching approximately $280 billion by 2024, up from $239 billion in 2019. By 2028, the market is projected to hit $374.51 billion, with a compound annual growth rate (CAGR) of 7.42% (2023–2028).

➢ Key drivers include:

- Increased vehicle production, especially in developing regions.
- Growth in electric and autonomous vehicles.
- Advancements in tire technology and materials.

➢ When combined with the wheel rim market, the total tire-wheel market is even larger, with the wheel rim market alone projected to reach $78 billion by 2028. This estimate excludes related sectors such as tire and rim manufacturing equipment and new assembly lines.

Disadvantages of Pneumatic Tires

- **Susceptibility to Punctures:** Easily punctured by sharp objects, leading to flats and necessary repairs.

- **Vulnerability to Damage:** Prone to damage from impacts like potholes or curbs, causing sidewall issues or blowouts.

- **Maintenance Requirements:** Requires regular air pressure checks and maintenance to prevent poor performance and wear.

- **Temperature Sensitivity:** Air pressure fluctuates with temperature, needing frequent adjustments.

- **Durability:** Shorter lifespan than solid tires due to wear, requiring consistent upkeep.

- **Weight:** Difficult to reduce, affecting fuel efficiency and performance.

- **Cost:** Higher long-term costs due to repairs, replacements, and maintenance.

Non-Pneumatic Tire Technologies

Michelin Tweel (2005)

Bridgestone Airless Tires (2011)

Resilient Technologies (2008)

- Non-pneumatic tires have existed since 2005.
- Leading tire companies are actively developing them.
- Michelin's Tweel is already in mass production.
- GM and Michelin announced plans to equip passenger cars with Uptis in 2024.
- Michelin proclaims the "Second Wheel Revolution" is coming!

Hantai Flexairless Tire (2013)

Advantages of Non-Pneumatic Tires

- **Puncture-Proof:** Non-pneumatic tires resist punctures and flats since they contain no air, making them ideal for rough terrain.
- **Low Maintenance:** No need for air pressure checks or adjustments, reducing upkeep.
- **Durability:** Made from solid materials or advanced composites, they last longer and resist wear.
- **Stability:** Consistent performance unaffected by air pressure, ensuring reliability under varying loads and temperatures.
- **Cost-Effective:** Lower long-term costs due to durability and minimal maintenance.
- **Eco-Friendly:** Often made from recyclable materials, reducing environmental impact.
- **Extreme Performance:** Reliable in harsh conditions where pneumatic tires may fail.
- **Enhanced Safety:** Eliminates blowout risks, improving safety for vehicles and equipment.

Limitations of Current Non-Pneumatic Tire Technologies
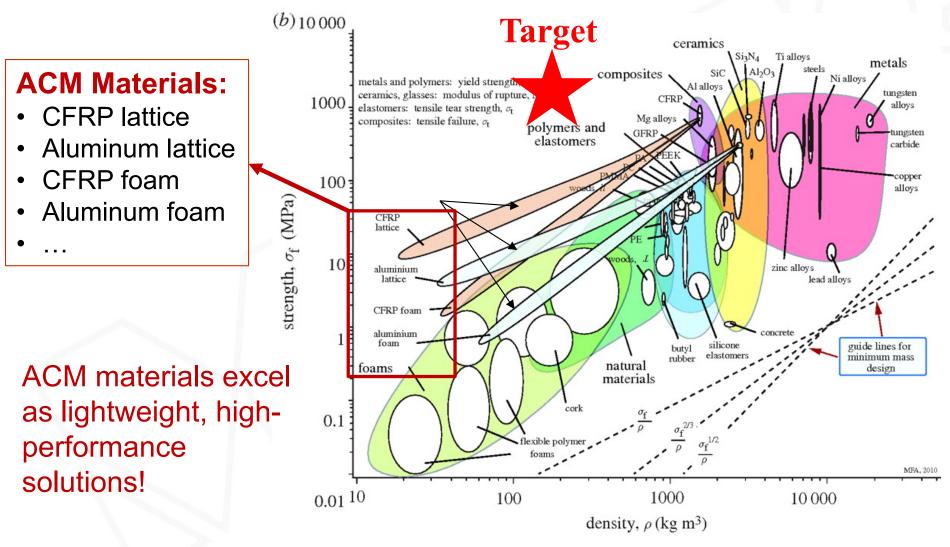
- **Limited Speed and Load Capacities:** Non-pneumatic tires typically have lower speed and load ratings, making them unsuitable for high-speed or heavy-load applications.
- **Reduced Ride Comfort:** The absence of air cushioning leads to less effective shock absorption, resulting in a rougher ride and increased vibrations.
- **Inferior Traction and Handling:** Non-pneumatic tires may underperform in traction and handling compared to pneumatic counterparts.
- **Design and Aesthetic Challenges:** Limited flexibility in design and less appealing aesthetics may influence consumer preferences.
- **Limited Availability and Compatibility:** Non-pneumatic tires are not as widely available and may lack compatibility with many vehicle types, limiting their adoption.
- **Increased Weight:** Heavier construction can negatively impact fuel efficiency and overall vehicle performance.
- **Higher Costs:** Advanced materials and manufacturing processes may result in higher initial costs, which can deter potential buyers.

Developing new and advanced materials is the key to the successful innovation of airless tires!

Lightweight and High-Performance Materials

ACM Materials:
- CFRP lattice
- Aluminum lattice
- CFRP foam
- Aluminum foam
- …

Target

ACM materials excel as lightweight, high-performance solutions!
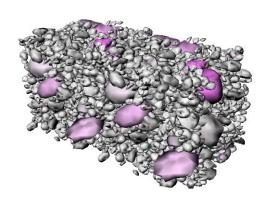
N. A. Fleck, V. S. Deshpande, M. F. Ashby

Tendency of New Material Development
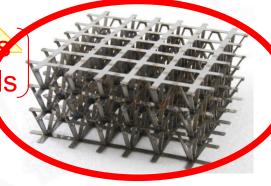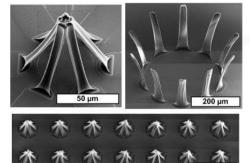
Architectured Cellular Metamaterials (ACM)

Larger-scale
Lattice materials
Cellular materials
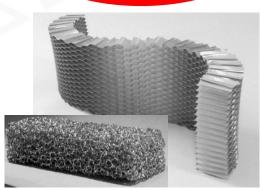
Millimeter

Micro-
Nano-truss

Nano-
Nanotube
Graphene

Metallic foam
Honeycomb
Sandwich

Fiber-reinforced
composites
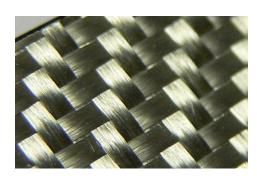
Graphene

Nanotube

Micro-Architectured
Cellular Materials

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Materials to be Architectured in Larger Scale

Architectured Cellular Metamaterial (ACM) Revolution

Solid Materials

Architectured Structures

Composite Materials

ACM Materials

Multi-materials

(Hybrid, Mixed, composite, etc.）

+

Architectured structure

(Lettice, Porous, Honeycomb, etc.)

=

ACM

➡ High-performance, Function-oriented, Lower cost
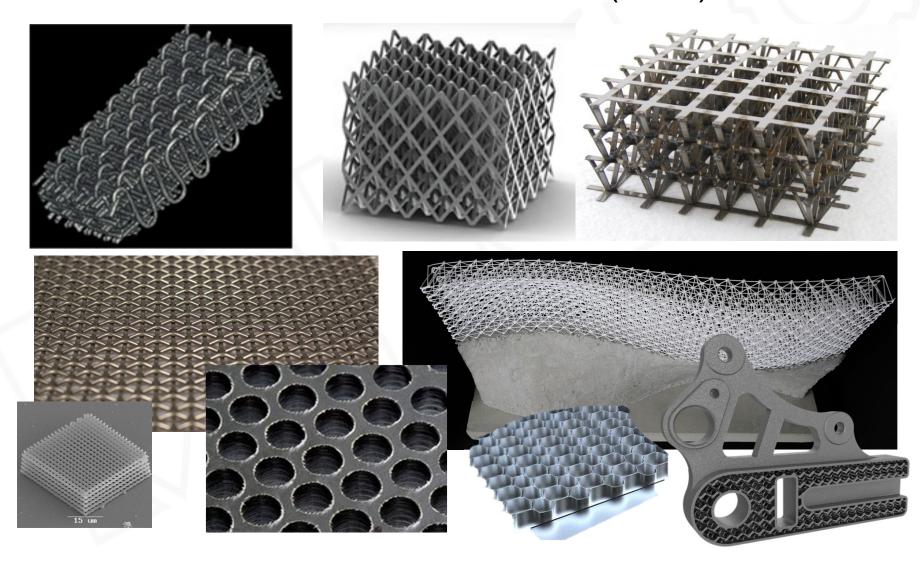
- Architectured Cellular Metamaterials (ACM)

3D Printed ACM Materials

- Architectured Cellular Metamaterials (ACM)
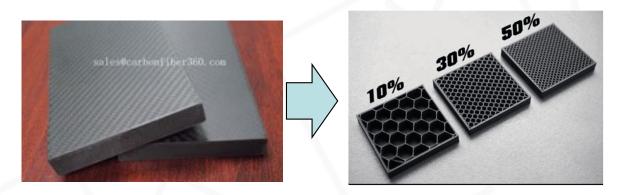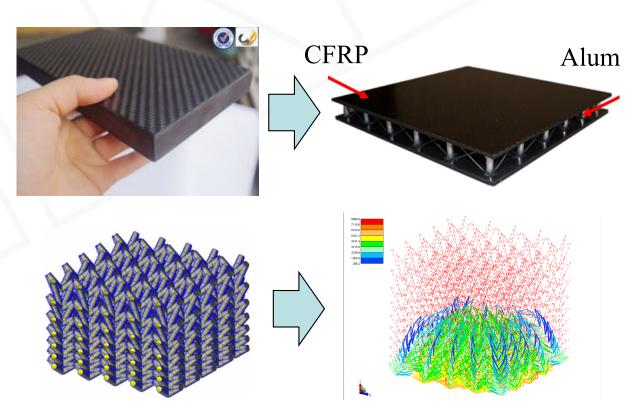
Features of ACM Materials

- **Efficient Usage:** Eliminates wasteful material.

- **Porous-Solid Mix:** Balances structure and performance.

- **Multi-Material:** Combines diverse parent materials.

- **Architectural Design:** Optimized for functionality.

- **Lightweight Performance:** High strength, low weight.

CFRP   Alum

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Three ACM Materials We Developed

Negative Poisson's Ratio Masteries
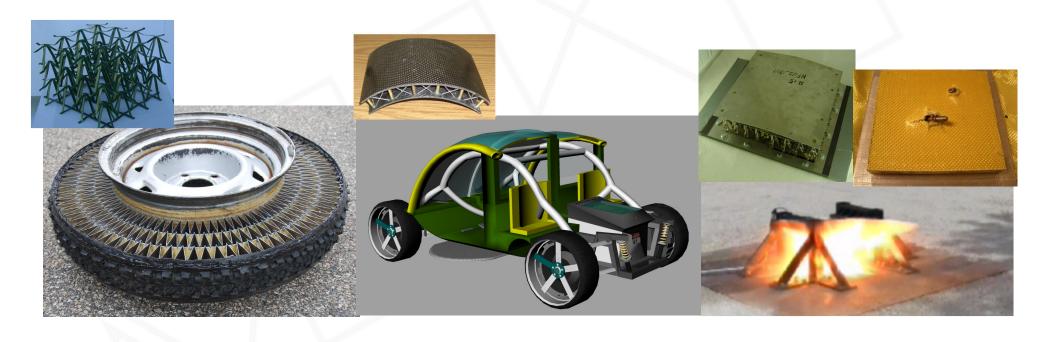
NPR

Biomimetic Tendon-Reinforced Materials

BTR

Advanced Composite Armors

ACA

High-performance & lightweight components

New body structure

Blast & ballistic protection

3D NPR-ACM Material
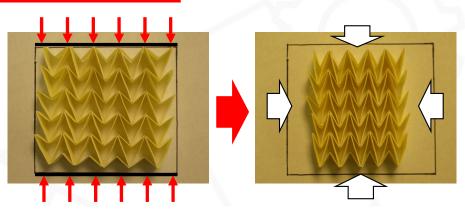
NPR (Negative Poisson's Ratio) Material

U.S. Patent
- **Patent Number:** US 7,910,193 B2
- **Effective Date:** March 22, 2011
- **Other Related Patents**
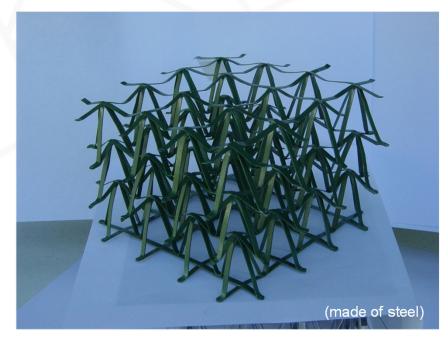
Key Features:
- Shrinks under pressure, expands under tension
- Strengthens with increased pressure
- Exceptional energy absorption
- Customizable functional design
- Unique, irreplaceable advantages
- Wide application potential
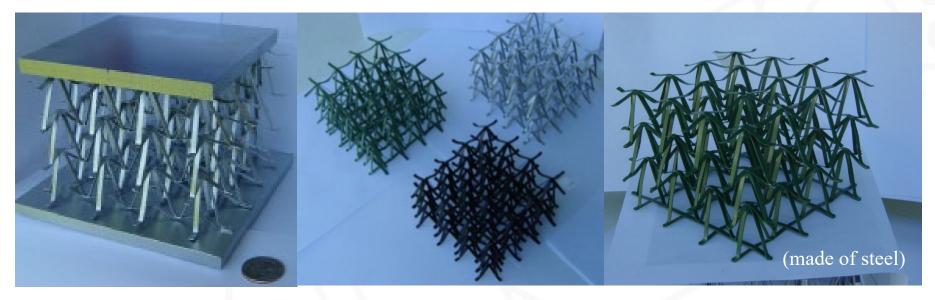
Compressive shrinkage phenomenon

(made of steel)
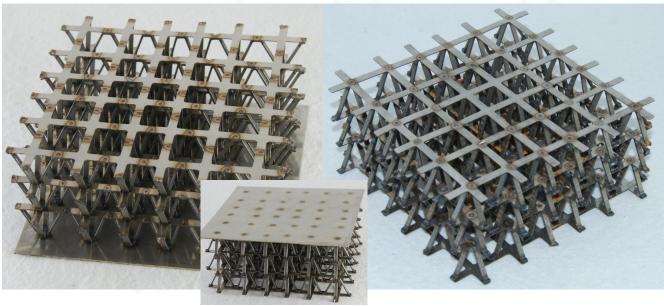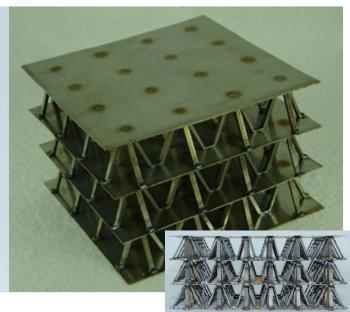
Sample of engineering NPR material

Metallic ACM Developed at MKP Inc.

(made of steel)
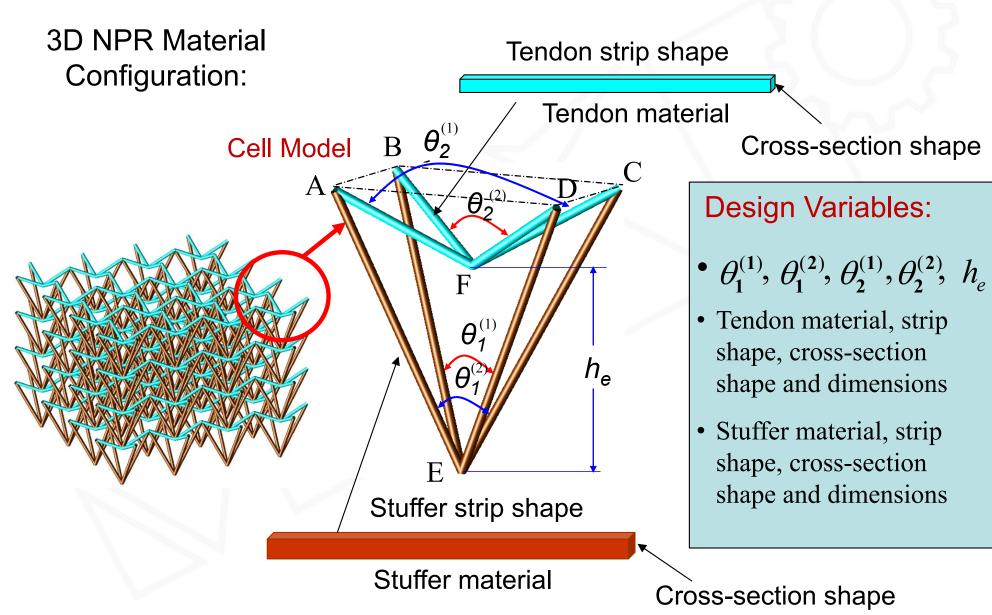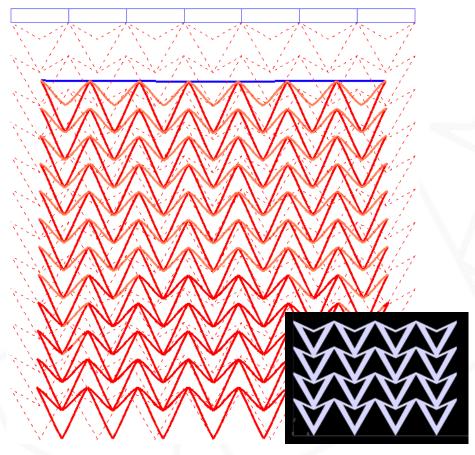
Three-Dimensional NPR Material

3D NPR Material Configuration:

Tendon strip shape

Tendon material

Cross-section shape

Cell Model

B $\theta_2^{(1)}$

A

$\theta_2^{(2)}$

D C

F

$\theta_1^{(1)}$

$\theta_1^{(2)}$

h_e

E

Stuffer strip shape

Stuffer material

Cross-section shape

Design Variables:

- $\theta_1^{(1)}, \theta_1^{(2)}, \theta_2^{(1)}, \theta_2^{(2)}, h_e$
- Tendon material, strip shape, cross-section shape and dimensions
- Stuffer material, strip shape, cross-section shape and dimensions
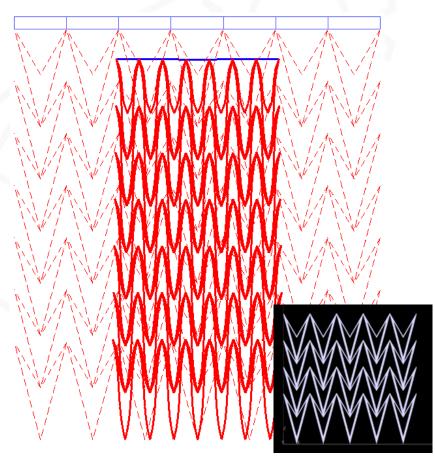
Variability in the Properties of NPR Materials

a) $\theta_1 = 60^{\circ},\ \theta_2 = 120^{\circ}$

Negative Poisson's Ratio = -0.96
Young's Modulus = 1.4e3
Material Density = 36.7%
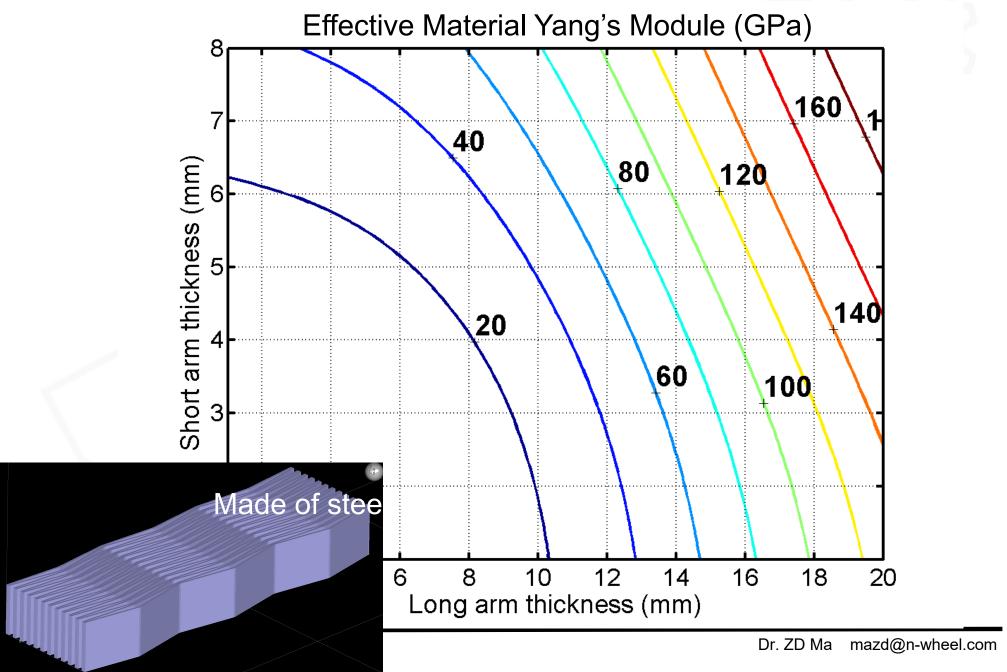
b) $\theta_1 = 30^{\circ},\ \theta_2 = 60^{\circ}$

Negative Poisson's Ratio = -7.4
Young's Modulus = 2.7e3
Material Density = 36.5%

Broad Material Property Coverage

Effective Material Yang's Module (GPa)
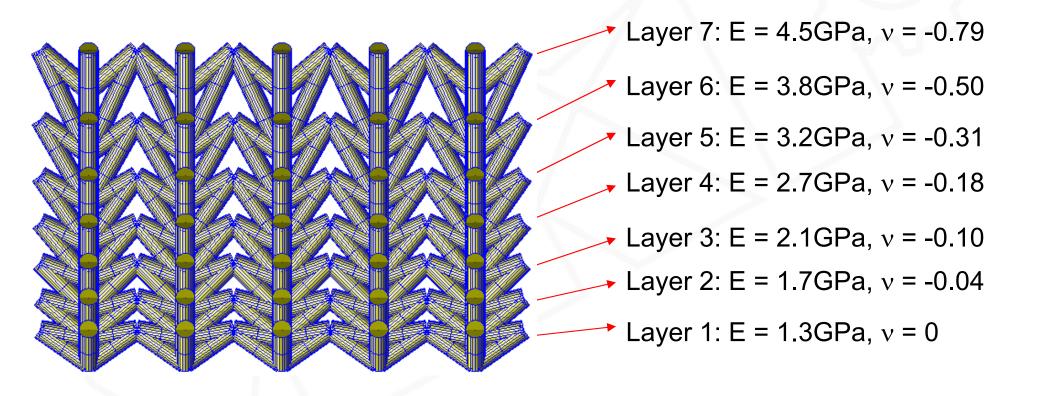
Functionally-Graded Material Design

Layer 7: E = 4.5GPa, ν = -0.79

Layer 6: E = 3.8GPa, ν = -0.50

Layer 5: E = 3.2GPa, ν = -0.31

Layer 4: E = 2.7GPa, ν = -0.18

Layer 3: E = 2.1GPa, ν = -0.10

Layer 2: E = 1.7GPa, ν = -0.04

Layer 1: E = 1.3GPa, ν = 0
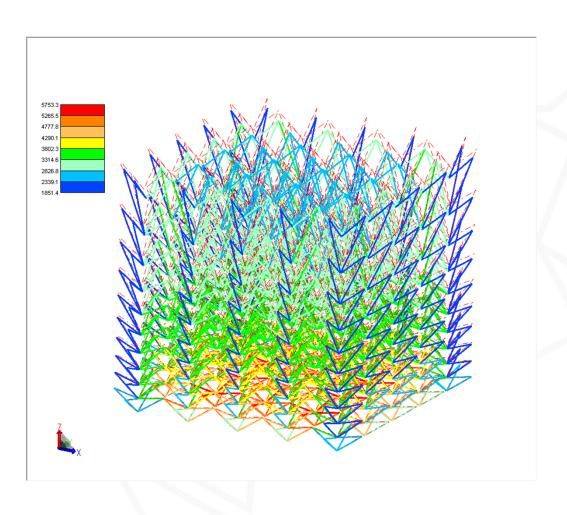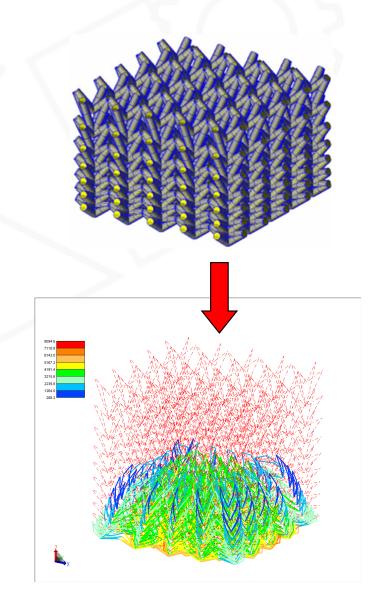
The integrated structure's properties are E = 2.8GPa, ν = -0.24

Animation of Deformed Shape Under a Blast Force
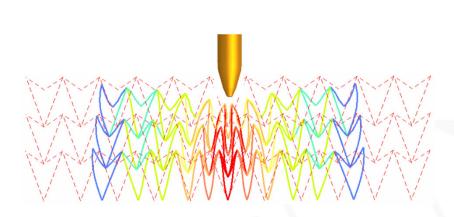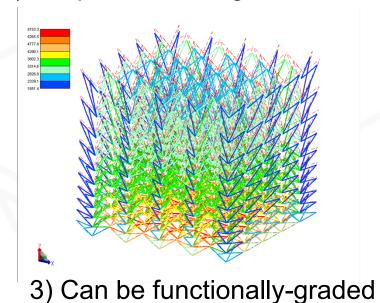
Special Properties of the NPR Material
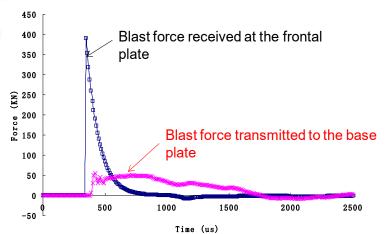
1) Adaptive stiffening under load

Made of steel

2) Broad material property coverage

3) Can be functionally-graded

Blast force received at the frontal plate

Blast force transmitted to the base plate

4) Impact energy absorption

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Potential Applications of the NPR Material

- Lightweight anti-collision energy absorption components
- Bushings, bumpers, mounts, etc.
- NPR non-pneumatic tires
- Anti-explosion energy absorption materials
- Deployable structures
- NPR stents
- …
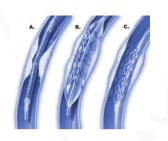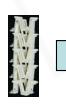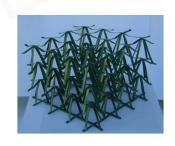
PART-II

Technology Developed
(n-Wheel)
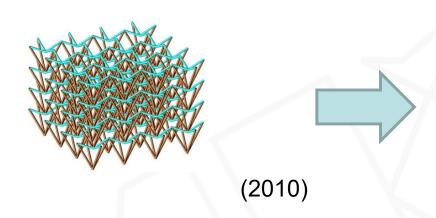
Our New Technology: metaTire™ & n-Wheel™

- In 2010, we developed **metaTire™**, a revolutionary non-pneumatic tire based on our patented **NPR (Negative Poisson's Ratio) metamaterial.** It offers multiple advantages over traditional materials, including **adaptive stiffening under load, superior impact energy absorption, broad material property coverage, and enhanced design flexibility** for diverse applications.

- When integrated with a **wheel rim system**, it becomes **n-Wheel™**, which has been **road-tested** in various vehicles, including an **ATV, TUV, 3.5-ton forklift, and SUV.** More details will be provided in later slides.

- The **metaTire™/n-Wheel™** concept **significantly expands** the design and application possibilities for non-pneumatic tires, surpassing existing solutions.

- The goal of **n-Wheel™** is to deliver **lighter weight, extended tire lifespan, and superior performance** in **drivability, durability, NVH (Noise, Vibration, and Harshness), load capacity, fuel efficiency, and design flexibility**, compared to both **pneumatic and non-pneumatic tires.**

Application to the metaTire™ & n-Wheel™

US patent: 7,910,193

US patent: 7,910,193

(2010)
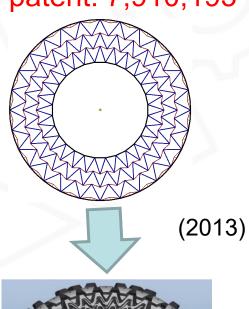
(2013)

Example RUV Application

Physical Prototype

Awarded Patents

Three Major metaTire Concepts
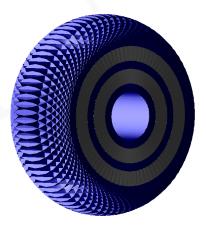
a) Quasi-3D

b) 3D

c) Super-3D

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Design Variations of the N-Wheel

a) Two-layer structure

b) Three-layer structure

metaTire Technology to Replace Pneumatic Tires

Tread: Function-oriented design

Stuffer: High strength, lightweight, fatigue-resistant, low vibration, and low noise material

Tendon: High elasticity, high strength, large deformation, high damping material

- Non-pneumatic, impact-resistant, puncture-free, bulletproof
- Can be manufactured using various methods including Modularized manufacturing
- High speed and high load bearing capacity
- High lateral stiffness

metaTire: Non-Pneumatic Tire

Stuffer: Made of lightweight, high-strength, compressive material: Capable of load-bearing, fatigue resistance, high speed impact, low vibration, low noise, and function-oriented design

Tendon: Made of high elasticity, high damping, tensile material: Impact-resistant, vibration reduction, energy absorption, flexibility, durability, function-oriented design

Tread: Made of high-elasticity with good high-speed and off-road performance, low rolling resistance, function-oriented design material

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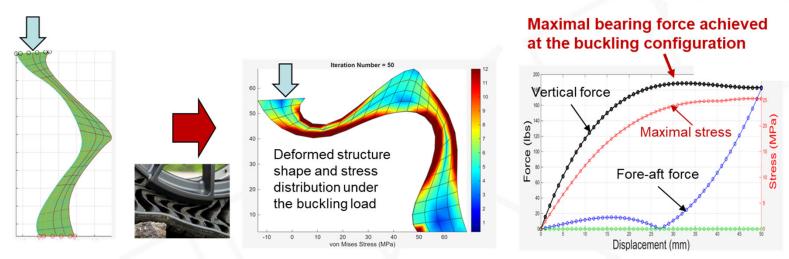
The Necessity of the n-Wheel Technology
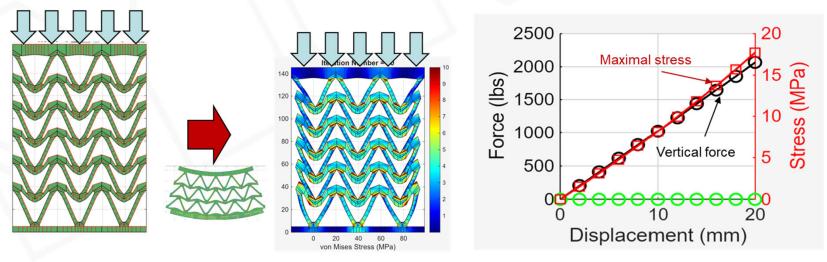
➤ Can overcome the bottlenecks of traditional pneumatic tires/wheels

➤ Can completely replace pneumatic tires/wheels

  – Enhanced negative Poisson's ratio characteristics for superior load-bearing and impact resistance

  – Function-oriented design for ride comfort, smoothness, and reduced NVH (Noise, Vibration, and Harshness)

  – Superior lateral stiffness for better handling and stability

  – Greatly expanded design space for diversified innovative products

➤ Can further revolutionize vehicle structure

➤ Can be easily designed integrated with hub motors

➤ Can integrate various sensors to become smart

➤ Easily achieves active and semi-active control

➤ Can be used for intelligent transportation systems!

N-Wheel Technologies, Inc., USA

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Advantage of NPR Structure Over Beam-like Structure

Maximal bearing force achieved at the buckling configuration

Deformed structure shape and stress distribution under the buckling load

(a) Beam-like structure buckles under excess load
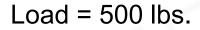
(b) NPR structure is stiffening under the load
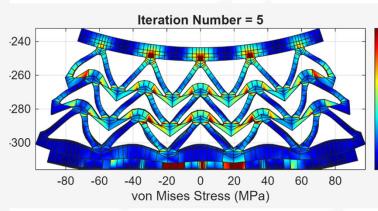
NPR Compares to Honeycomb

NPR

Nonlinear Analysis (Load = 25.4 lbs)

Load = 500 lbs.

Iteration Number = 5

von Mises Stress (MPa)

Stiffening

Honeycomb

Nonlinear Analysis (Load = 19.0 lbs)

Load = 500 lbs.

Iteration Number = 10

von Mises Stress (MPa)

Softening

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(a) Beam-like structure buckles under excess load

(b) NPR structure is stiffening under the load
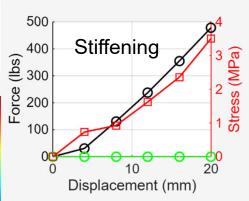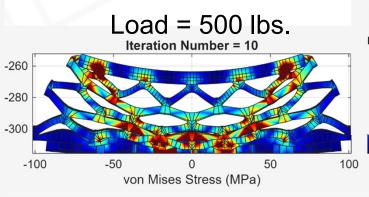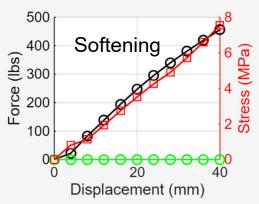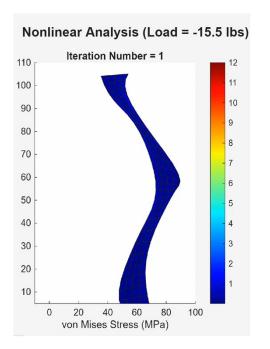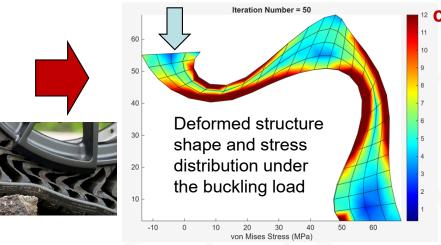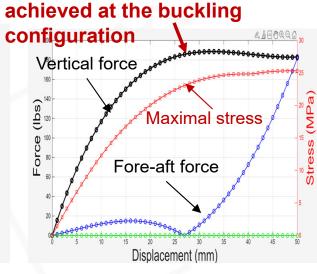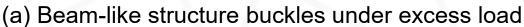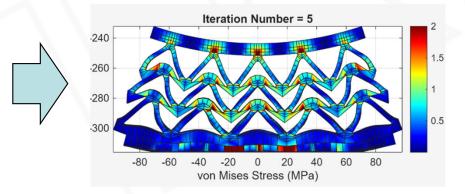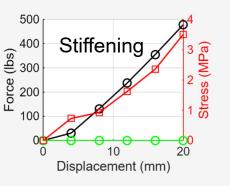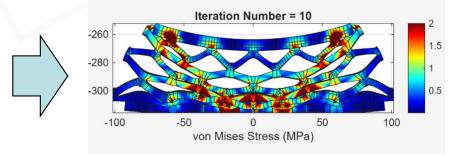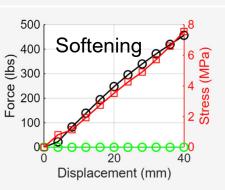
(c) Honeycomb structure is softening under the load

Application Example 1: n-Wheel on RUV

(14 Inch)

(UTV)

(3.5-ton Forklift)

(BJ-40)

Prototypes Developed for the n-Wheel

ATV

RUV

3.5T Forklift

BJ-40a

2014 Beijing International Auto show

BJ-40b

PAJEO

Road Rover

Bicycle
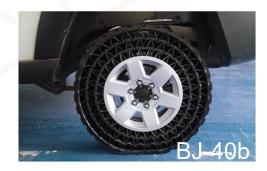
Advantages and Potential of the n-Wheel

Unlocking New Horizons in Mobility and Technology

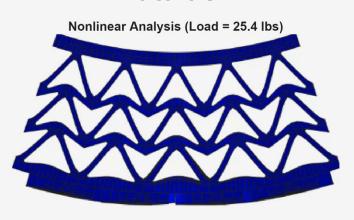- **Load-stiffening NPR characteristics**: Offers tailored performance under varying loading conditions.
- **Adjustable vertical stiffness**: Adapts to load, enhancing ride quality.
- **Functional design flexibility**: Accommodates a wide range of applications.
- **Large design space**: Supports diverse applications and innovations.
- **Superior lateral stiffness**: Improves drivability and vehicle stability.
- **Enhanced braking and ride comfort** and improves NVH (Noise, Vibration, and Harshness) performance.
- **Lightweight and cost-effective**: Reduces vehicle weight and manufacturing costs.
- **Sensor integration-ready**: Supports in-wheel intelligent components like sensors and controls.

PART-III

Supporting Technologies Developed

Core Technologies for the Digital n-Wheel

Core Technologies for the Digital Twin of n-Wheel

1. Multi-Scale Analysis (MSA)

2. Advanced Isogeometric Analysis (AIGA)

3. CAD/CAE/CAM/PLM (C3P) Integration

4. Size, Shape and Topology Optimization (SSTO)

5. Image Processing for Tread NURBS Generation

6. Multi-Level Reduced-Order Modeling (M-ROM)

7. 3D-Printing Pass Optimization and Slicing Process

8. Parameterized, Modularized, User-Friendly Graphic User Interface (PMF-GUI)

Isogeometric Analysis (IGA)

- **NURBS-Based Accuracy:** IGA utilizes NURBS functions to define CAD models as shape functions, ensuring precise geometric representation and eliminating errors, even with minimal parameters.
- **Seamless CAE-CAD Integration:** IGA bridges the gap between Computer-Aided Engineering (CAE) and Computer-Aided Design (CAD), enabling a unified workflow.
- **Manufacturing-Ready Outputs:** Optimization results from IGA are CAD models that are directly ready for manufacturing without additional conversion or adjustments.

NURBS Curve

NURBS Surface

$$C(\xi) = \sum_{i=0}^{nu} R_{i,p}(\xi) \boldsymbol{P}_i$$

$$S(\xi, \eta) = \sum_{i=0}^{nu} \sum_{j=0}^{nv} R_{i,p;j,q}(\xi, \eta) \boldsymbol{P}_{i,j}$$

NURBS Solid

$$V(\xi, \eta, \zeta) = \sum_{i=0}^{nu} \sum_{j=0}^{nv} \sum_{k=0}^{nw} R_{i,p;j,q;k,r}(\xi, \eta, \zeta) \boldsymbol{P}_{i,j,k}$$
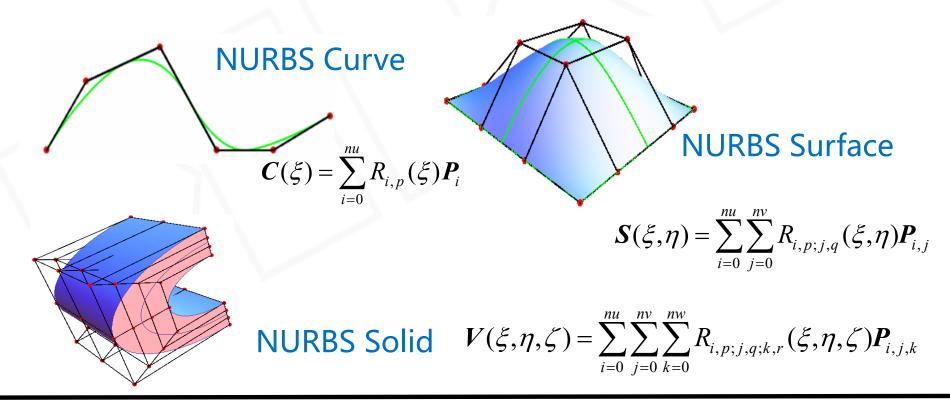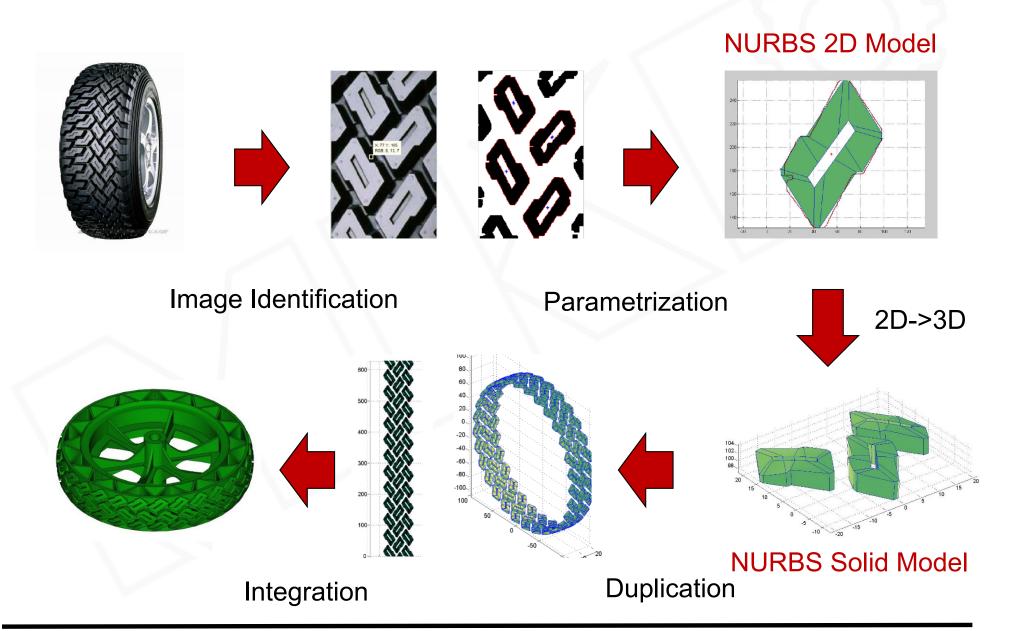
Image Processing & NURBS Generation

NURBS 2D Model

Image Identification

Parametrization

2D->3D

NURBS Solid Model

Integration

Duplication
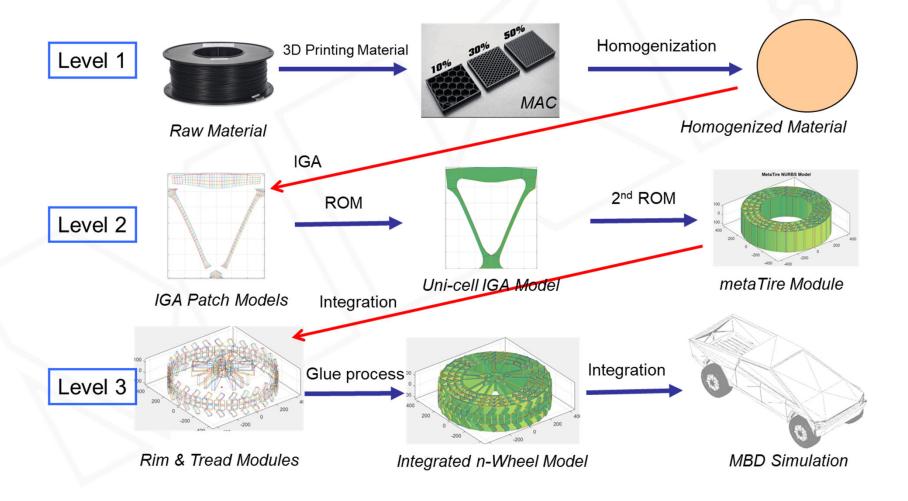
Multi-scale Analysis

$$\varepsilon = \varepsilon_h + \varepsilon_v \qquad \varepsilon_v(y) = \varphi(y)\varepsilon_h$$

Level 1 — Raw Material → 3D Printing Material → MAC → Homogenization → Homogenized Material

Level 2 — IGA Patch Models → ROM → Uni-cell IGA Model → 2nd ROM → metaTire Module

Level 3 — Rim & Tread Modules → Glue process → Integrated n-Wheel Model → Integration → MBD Simulation
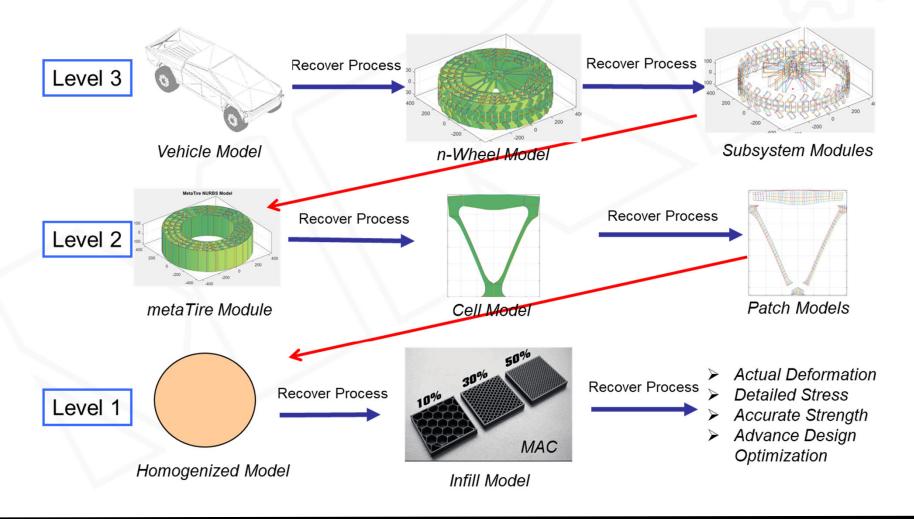
Recover Process of the Multi-scale Analysis

$$\varepsilon = (I + \varphi)\varepsilon_h \qquad \sigma = D^\varepsilon \varepsilon$$

Level 3

Vehicle Model

Recover Process

n-Wheel Model

Recover Process

Subsystem Modules

Level 2

metaTire Module

Recover Process

Cell Model

Recover Process

Patch Models

Level 1

Homogenized Model

Recover Process

Infill Model

MAC

Recover Process

➢ Actual Deformation
➢ Detailed Stress
➢ Accurate Strength
➢ Advance Design Optimization

Topology Optimization

Design Definition

Optimization

Optimized Layout

3D NURBS Model

2D Design

Boundary Identification

Award Winning Technology: Function-Oriented Material Design (FOMD)

FOMD focuses on optimizing material distribution to align with the structural functions of a (vehicle) system, ensuring lightweight design and high performance.

Key Steps:

1. **Define Structural Functions:** Clearly identify the functional roles of a structural element within the (air vehicle) system.

2. **Quantify Objectives and Constraints:** Translate these functions into measurable objectives and constraints for the optimization process.

3. **Optimize Material Distribution:** Utilize topology optimization and related techniques to achieve the most efficient design, balancing lightweight construction and superior performance.

ASME INTERNATIONAL
The American Society of Mechanical Engineers
— Founded 1880 —

DESIGN ENGINEERING DIVISION
VEHICLE DESIGN COMMITTEE

AWARDS THE
BEST PAPER AWARD
TO

Zheng-Dong Ma
Hui Wang
Nopboru Kikuchi
Christophe Pierre
Basavaraju Raju

IN TESTIMONY OF THE HIGH REGARD OF YOUR ASSOCIATES AND THE DEEP APPRECIATION OF THE SOCIETY FOR YOUR VALUED SERVICES IN ADVANCING THE ENGINEERING PROFESSION FOR THE PAPER "Function-Oriented Material Design for Next-Generation Ground Vehicles" at the 2003 ASME International Mechanical Engineering Congress and Exposition
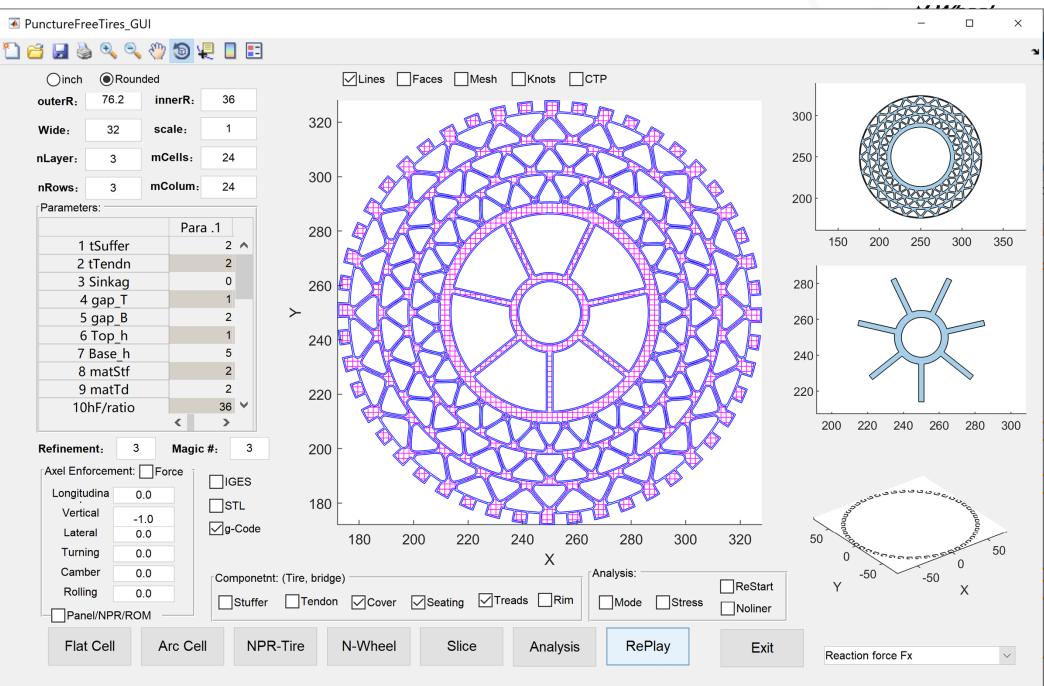
Dr. Bahram Ravani
Division Chair, 2003-2004

November 17, 2003
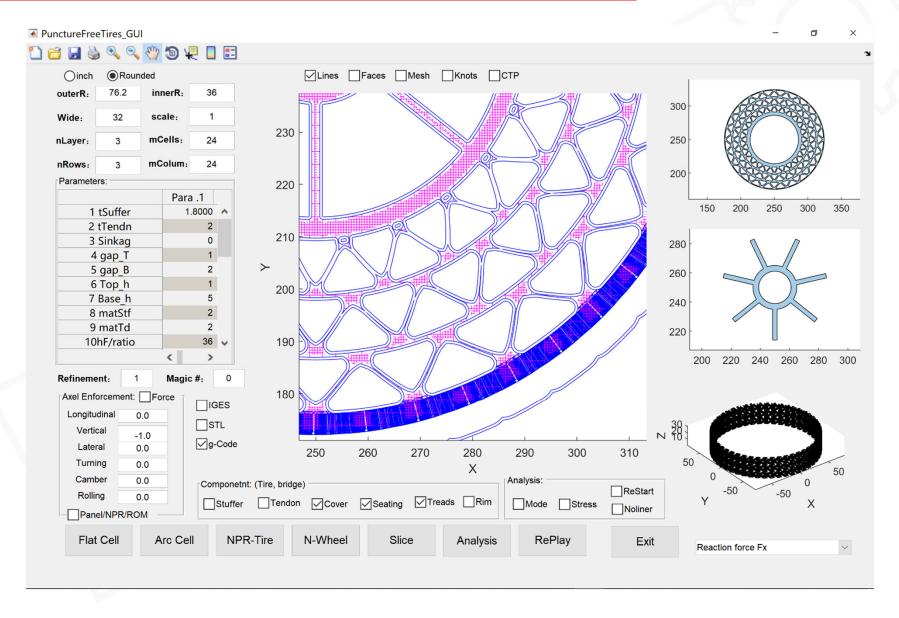
Imbedded Slicer for 3D Printing
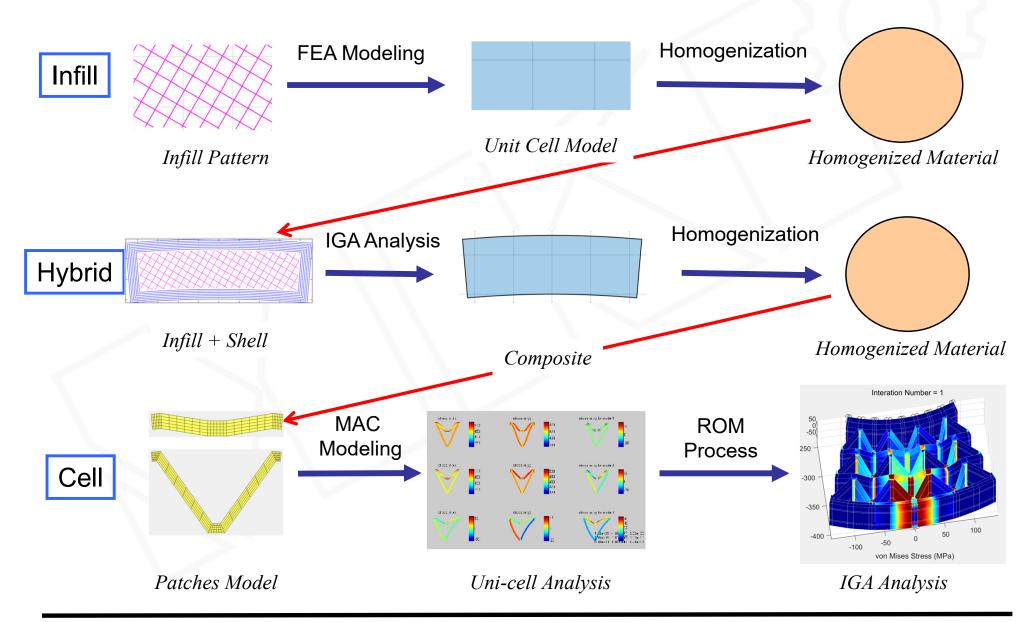
Optimal 3D-Printing Pass Generation

Multi-scale 3D-Printing Infill Analyses

Infill

Infill Pattern — FEA Modeling → *Unit Cell Model* — Homogenization → *Homogenized Material*

Hybrid

Infill + Shell — IGA Analysis → *Composite* — Homogenization → *Homogenized Material*

Cell

Patches Model — MAC Modeling → *Uni-cell Analysis* — ROM Process → *IGA Analysis*
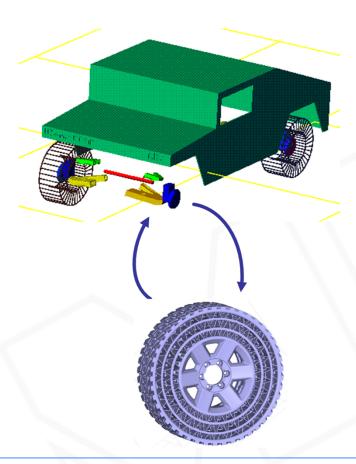
n-Wheel and Vehicle Integration (Next Step)

➤ Developed at The University of Michigan
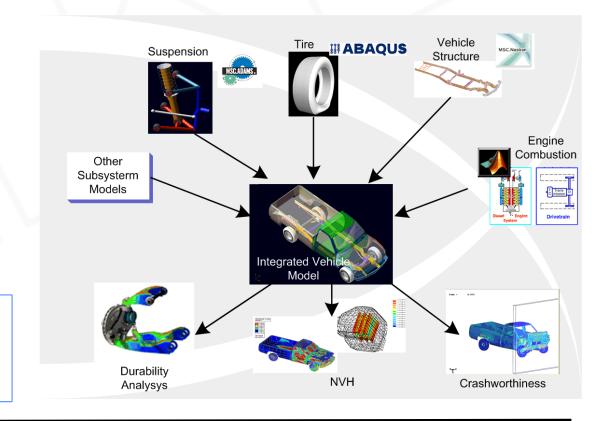
Using distributed simulation functionality, the simulation platform can quickly model vehicle behavior, which is key for modular vehicle design

The simulation platform also provides new and advanced component design capabilities.

Suspension — MSC.ADAMS

Tire — ABAQUS

Vehicle Structure — MSC.Nastran

Other Subsysterm Models

Engine Combustion — Diesel Engine System, Drivetrain, Transmission

Integrated Vehicle Model

Durability Analysys

NVH

Crashworthiness

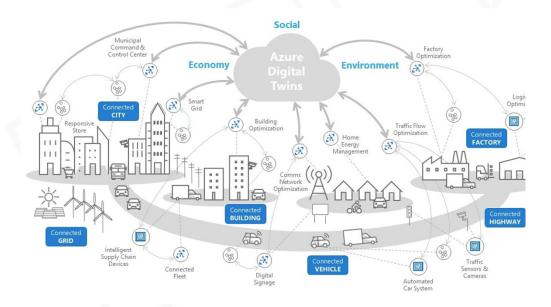# Cloud-Based Distributed Simulation

➢ Developed at The University of Michigan

Proposed Distributed Manufacturing

- Industrial IoT hardware and communication channels are now advanced enough to enable fast, real-time big data processing and interactive networks, supporting distributed manufacturing powered by digital twin technologies.
- Looking ahead, the integration of enhanced 5G technology and the continued evolution of industrial IoT hardware will make digital twins ubiquitous across industries.

PART-IV

Digital n-Wheel

Definition of the Digital Twin for the n-Wheel

- **Self-Contained Digital Model:** A complete virtual representation of the n-Wheel, encompassing all substructure modules and their physical characteristics.
- **Precise Physical Correlation:** Accurately mirrors the geometry, dimensions, and subsystems of the corresponding physical unit.
- **Integrated Performance Data:** Includes all critical physical properties for assessing performance, durability, and cost of the unit and its components.
- **Manufacturing and Process Intelligence:** Provides detailed information on manufacturing, assembly, and related processes.
- **Real-Time Modularity:** Easily decomposable and reassemblable within the virtual space for instantaneous analysis, evaluation, and optimization of the entire unit and its subsystems.
- **Immersive Virtual Interaction:** Offers a realistic user experience through VR technologies, enabling visual, auditory, and tactile interactions in simulated environments like proving grounds.
- **Comprehensive Virtual Testing:** Facilitates robust testing and simulations across various virtual testing platforms.
- **Full Lifecycle Simulation:** Supports end-to-end simulation of the unit's lifecycle, from development to decommissioning.
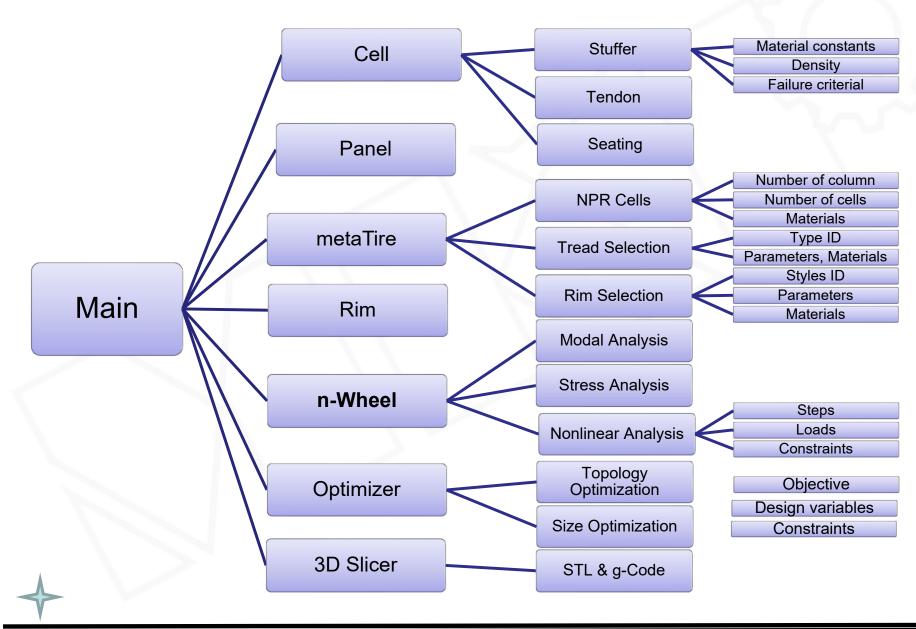
Objective of the Digital n-Wheel

- ➢ Efficient and fast design of various products.
- ➢ Easy to use, simple to understand, usable by ordinary people.
- ➢ Graphical input, parametric, modular.
- ➢ CAD-CAE integrated simulation, design, and optimization.
- ➢ Aesthetic design.
- ➢ Output optimized 3D CAD models directly.
- ➢ Direct connection to CNC machining and 3D printing.
- ➢ Achieve optimized design, lightweight and low cost.
- ➢ Achieve personalized products and customer customization.
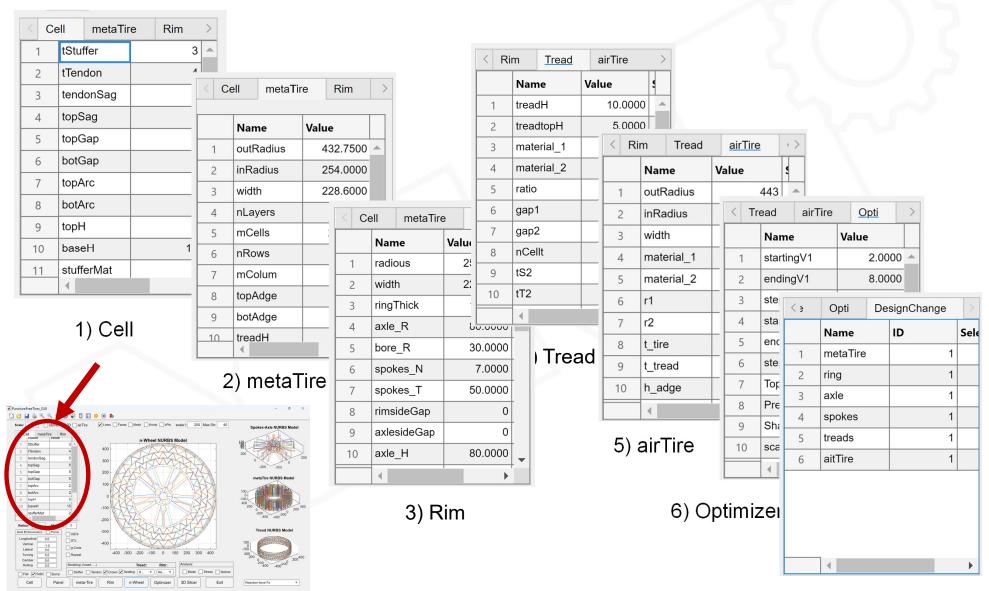- ➢ Realize forward design!

Layout of the Digital n-Wheel

Main
- **Cell**
  - Stuffer
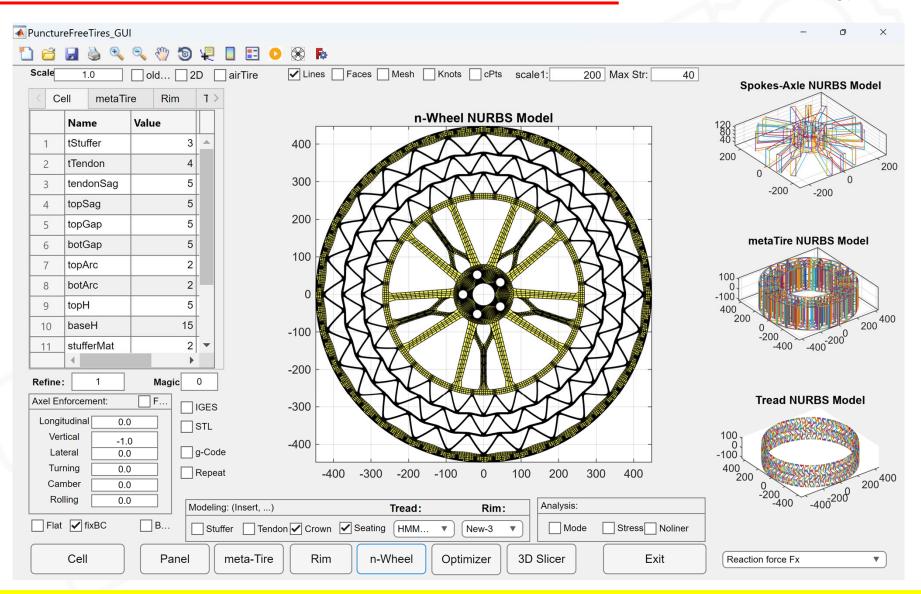   - Material constants
    - Density
    - Failure criterial
  - Tendon
  - Seating
- **Panel**
- **metaTire**
  - NPR Cells
    - Number of column
    - Number of cells
    - Materials
  - Tread Selection
    - Type ID
    - Parameters, Materials
  - Rim Selection
    - Styles ID
    - Parameters
    - Materials
- **Rim**
- **n-Wheel**
  - Modal Analysis
  - Stress Analysis
  - Nonlinear Analysis
    - Steps
    - Loads
    - Constraints
- **Optimizer**
  - Topology Optimization
    - Objective
    - Design variables
    - Constraints
  - Size Optimization
- **3D Slicer**
  - STL & g-Code

Parameterization of the Digital n-Wheel

1) Cell

2) metaTire

3) Rim

4) Tread

5) airTire

6) Optimizer

7) Redesign ID

N-Wheel Technologies, Inc., USA

Dr. ZD Ma   mazd@n-wheel.com
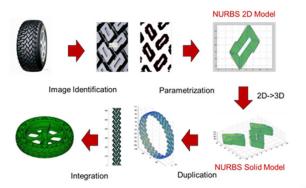
Graphic User Interface of the Digital n-Wheel
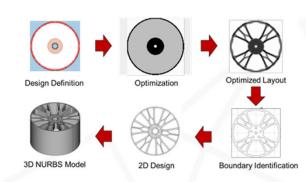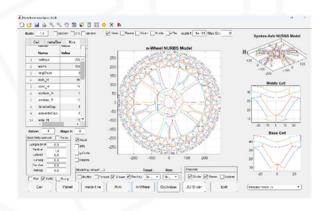
Parametrized, IGA-based, CAD-CAE-CAM integrated, with optimization techniques!

N-Wheel Technologies, Inc., USA
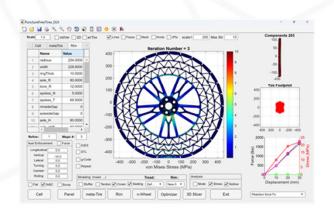
Dr. ZD Ma   mazd@n-wheel.com

Digital n-Wheel Processes

1) Parameter Identification

2) Topology Optimization

3) Full n-Wheel Modeling

1) 75.9 Hz   2) 76.7 Hz   3) 76.8 Hz
4) 76.8 Hz   5) 79.5 Hz   6) 88.3 Hz

4) Modal Analysis
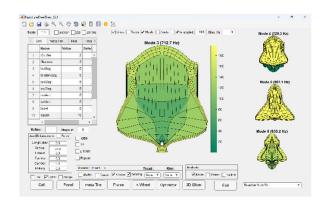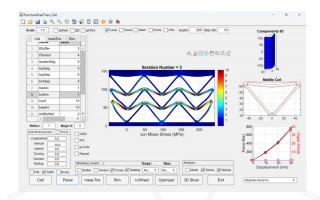
5) Nonlinear Analysis
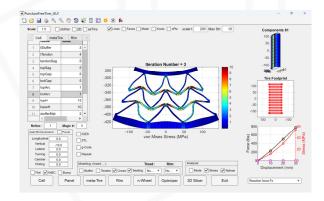
6) 3D-Printing Slicing

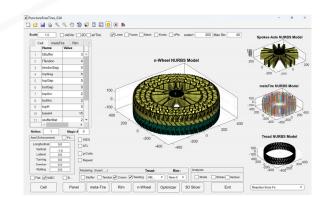# Modeling Options of the Digital n-Wheel
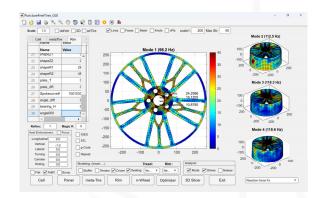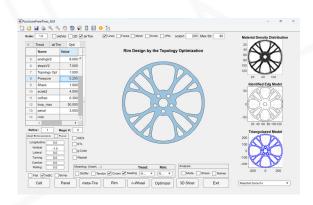
1) Cell

2) Panel

3) metaTire

4) Rim

5) Topology Optimizer

6) Full n-Wheel Design

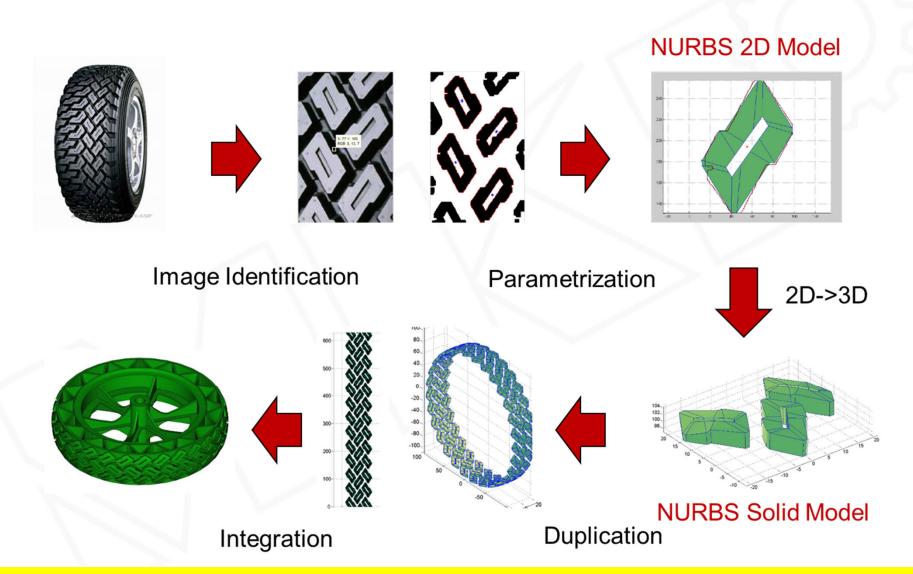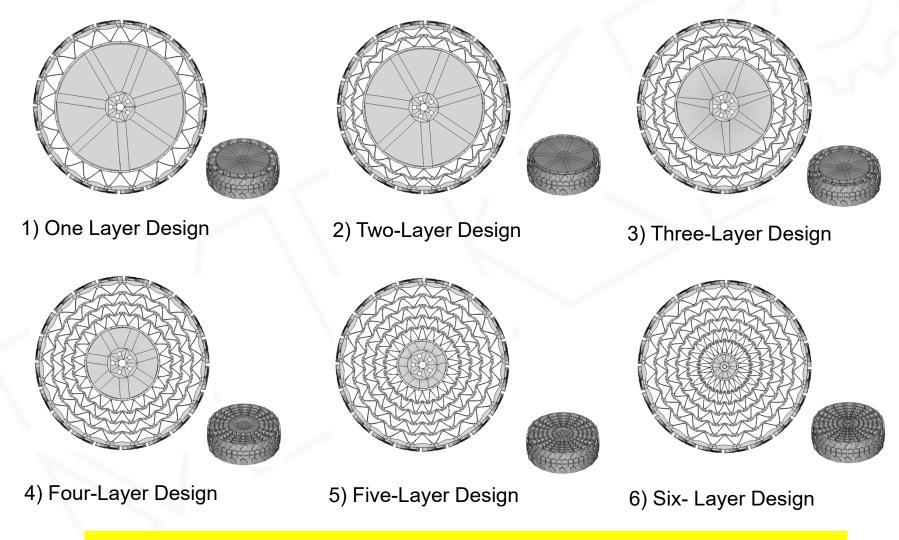| Cell | Panel | meta-Tire | Rim | n-Wheel | Optimizer | 3D Slicer |

Parameter Identification of the Tread

NURBS 2D Model

Image Identification → Parametrization → 2D->3D

NURBS Solid Model

Integration ← Duplication

Photo any existing tread and generate 3D NURBS model automatically for IGA.

Topology Design of the metaTire

1) One Layer Design

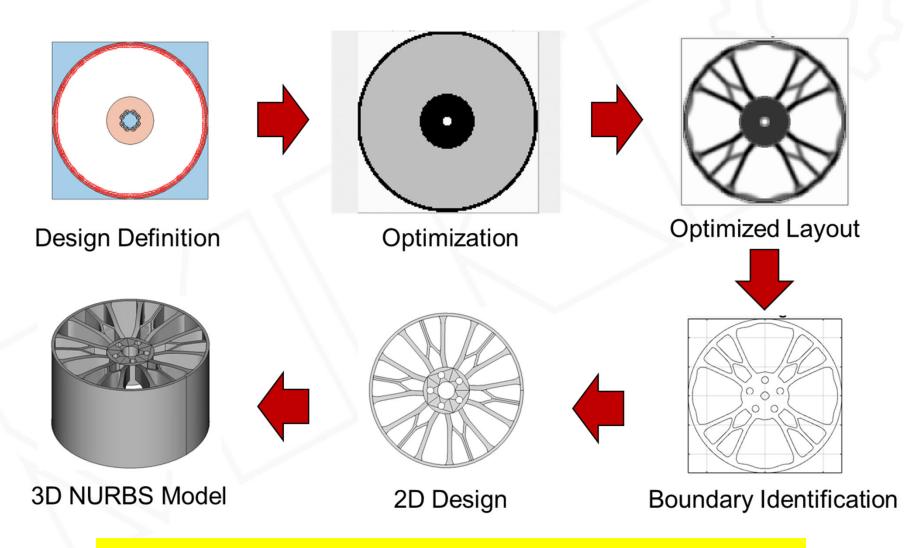2) Two-Layer Design

3) Three-Layer Design

4) Four-Layer Design

5) Five-Layer Design

6) Six- Layer Design

Varied number of layers with varied number of cells in the layer

Topology Optimization of the Rim

Design Definition → Optimization → Optimized Layout → Boundary Identification → 2D Design → 3D NURBS Model
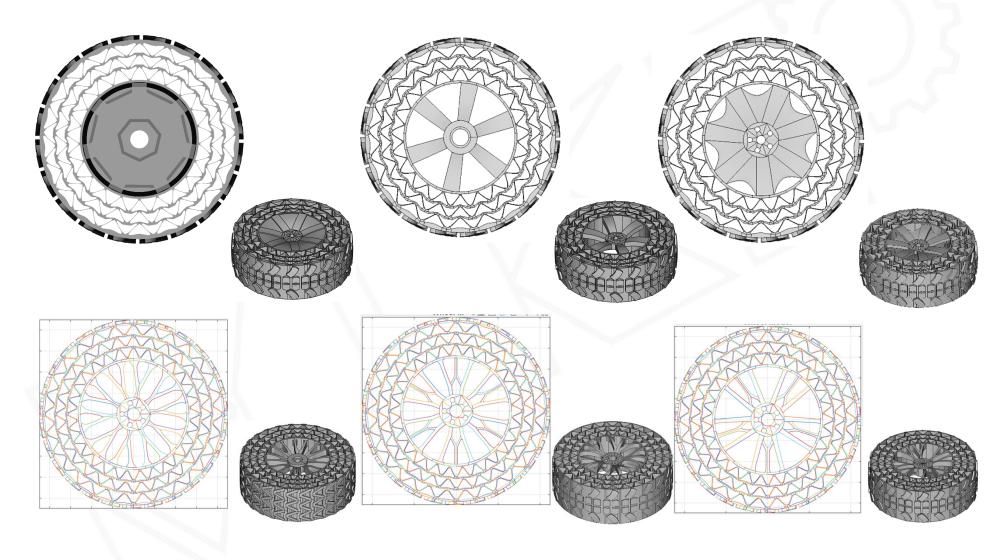
From a blank sheet to optimal layout to 3D NURBS model!

Rim-Integrated n-Wheel Design
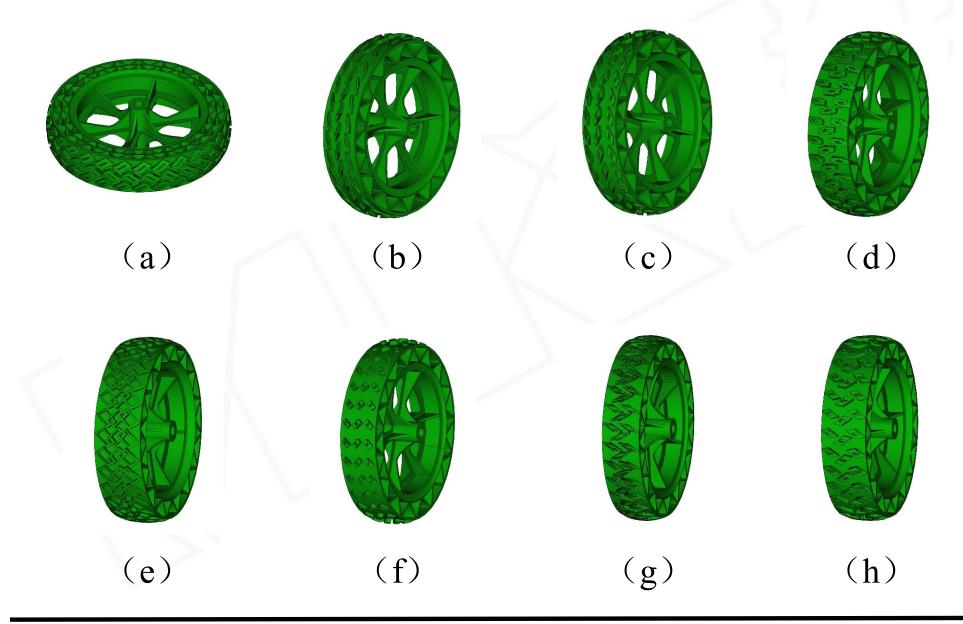
Varied rim types of the n-Wheel design

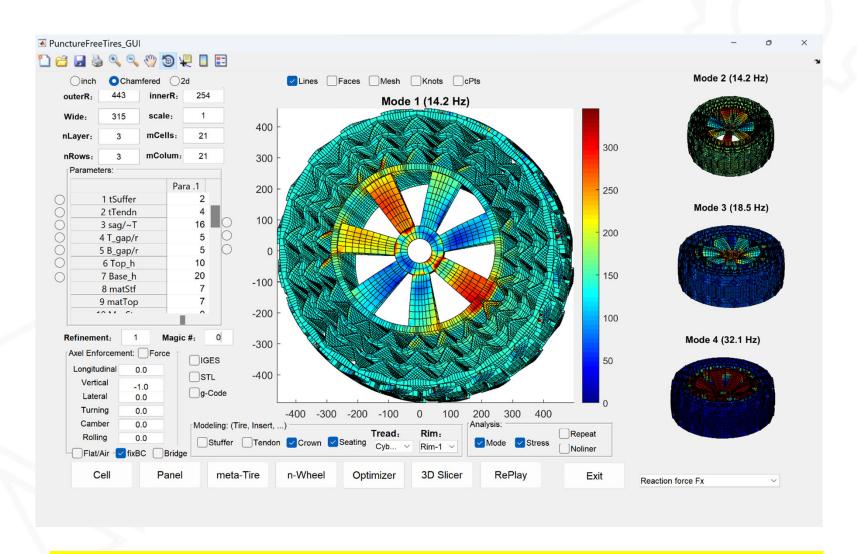# Example Auto-generated Tread Designs

（a）   （b）   （c）   （d）

（e）   （f）   （g）   （h）

Example Modal Analysis

Graphic User Interface of the digital n-Wheel for modal analysis

Comparison of metaTire™ and Rubber Tire

➢ **First 9 modes of metaTire**

1) 75.9 Hz 2) 76.7 Hz 3) 76.8 Hz

4) 76.8 Hz 5) 79.5 Hz 6) 88.3 Hz

7) 88.3 Hz 8) 88.4 Hz 9) 100.0 Hz

➢ **First 9 modes of rubber tire**
(Air Pressure at 36 psi)

1) 15.7 Hz 2) 46.0 Hz 3) 46.8 Hz

4) 84.6 Hz 5) 87.2 Hz 6) 87.3 Hz
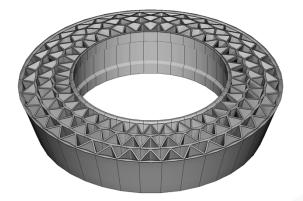
7) 90.0 Hz 8) 97.3 Hz 9) 101.4 Hz

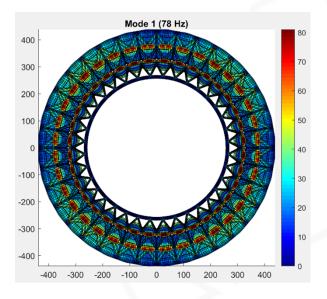**Lower eigenfrequencies of the metaTire are significantly higher than rubber tire**
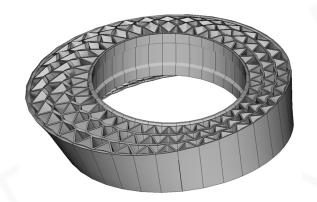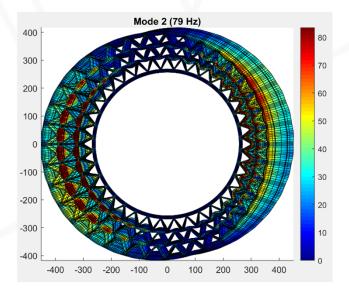
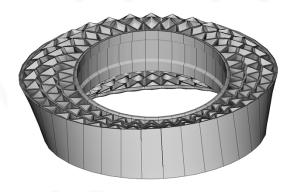# 1ˢᵗ-3ʳᵈ Modes of a NPR Runflat

➢ 2ⁿᵈ Order Model

➢ Modal Stresses:

1) 78 Hz

2) 79 Hz

3) 79 Hz

Dr. ZD Ma   mazd@n-wheel.com
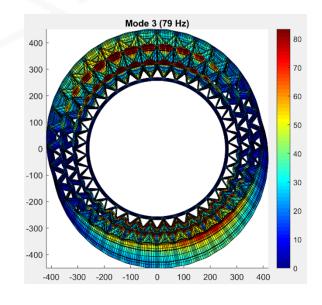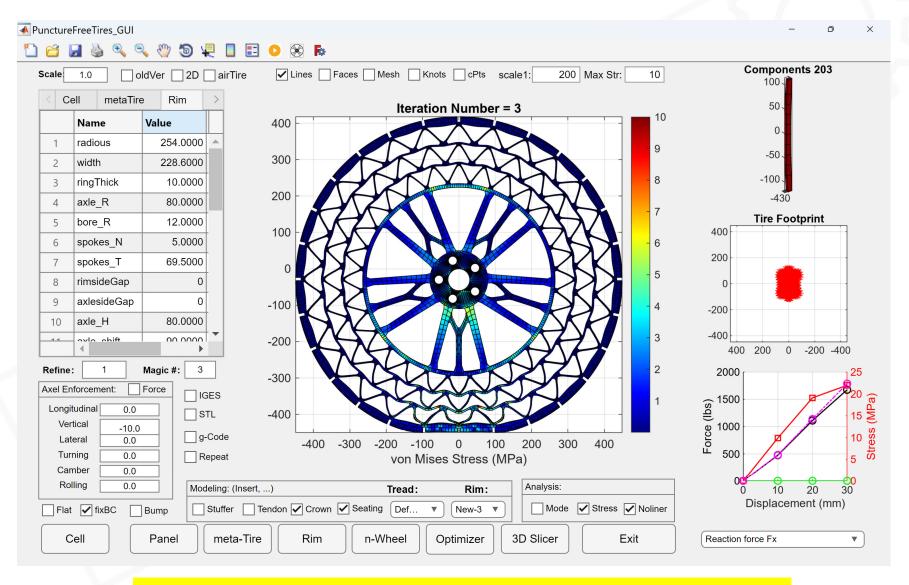
Example Nonlinear Analysis

Parametrized, IGA-based, CAD-CAE-CAM integrated!

N-Wheel Technologies, Inc., USA

Dr. ZD Ma   mazd@n-wheel.com
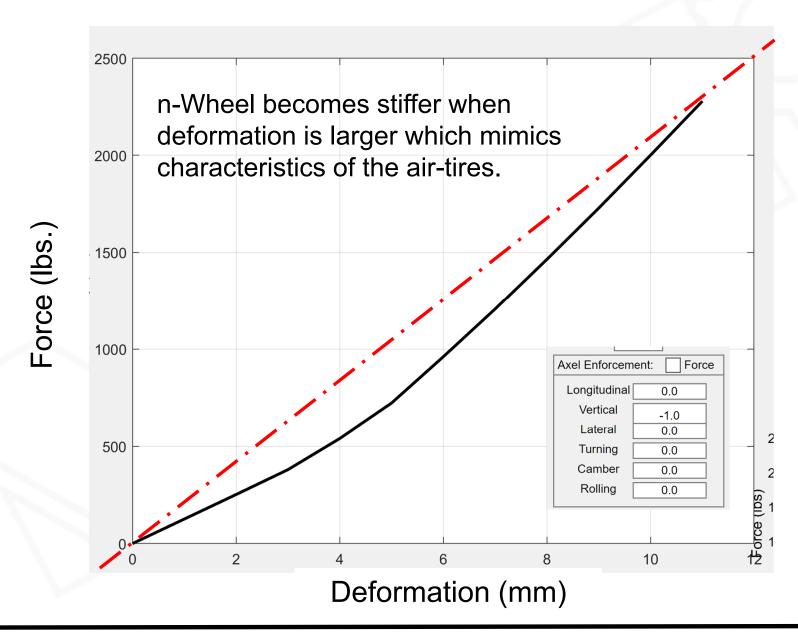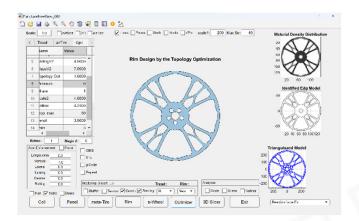
Stiffening Effect of the metaTire™

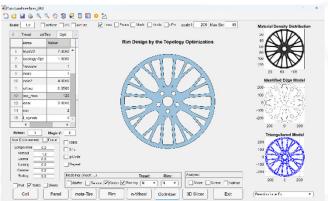n-Wheel becomes stiffer when deformation is larger which mimics characteristics of the air-tires.
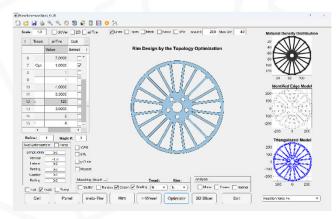
Dr. ZD Ma   mazd@n-wheel.com
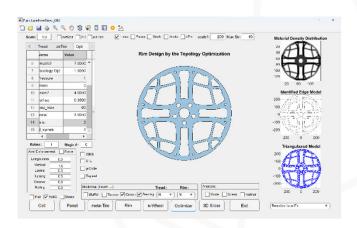
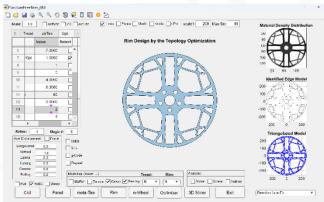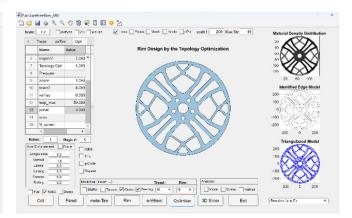# Optimal Designs for Rim Configurations

1) Design A
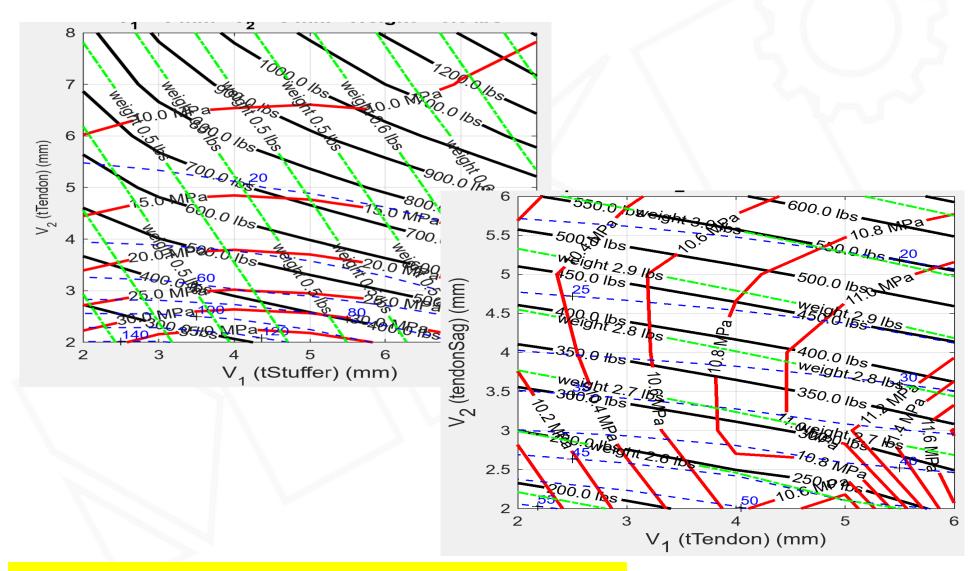

2) Design B

3) Design C

4) Design D

5) Design E

6) Design F

❖ For different loading conditions and weight constraints

Size Optimization of the n-Wheel
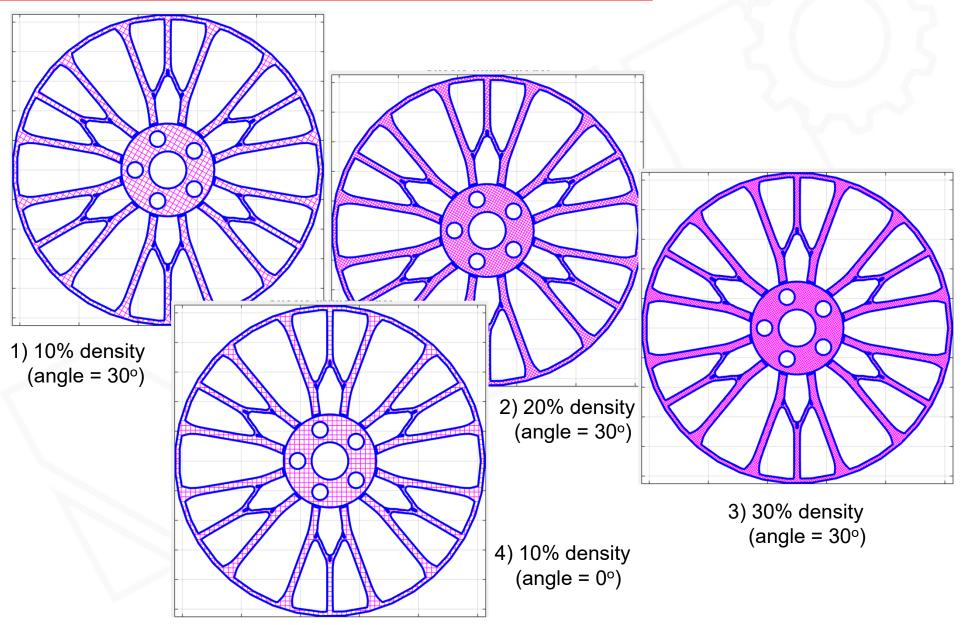

- **All critical design variables are fully optimizable!**
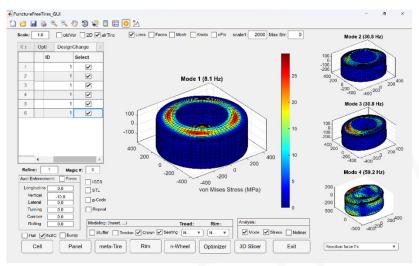
Infill Material Optimization for 3D Printing

1) 10% density (angle = 30°)

2) 20% density (angle = 30°)

3) 30% density (angle = 30°)

4) 10% density (angle = 0°)
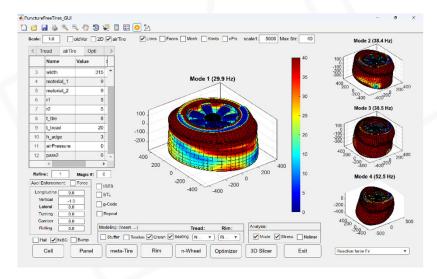
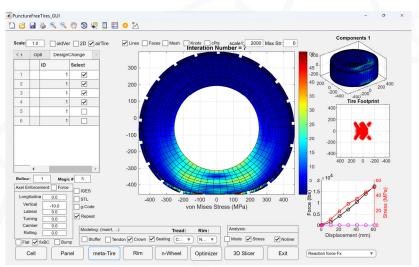# Capable for Designing Pneumatic Tires
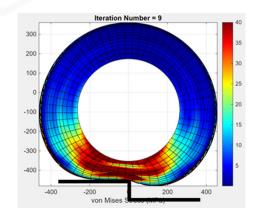
1) Modal analysis of pneumatic tire (36 psi)

3) nonlinear analysis of pneumatic tire with rim

2) Modal analysis of pneumatic tire with rim

• Tire air pressure = 36 psi

4) CAD model of the deformed pneumatic tire

Next Version n-Wheel

Sensors and adaptive control ensure optimal performance in all climates and terrains.

➢ **Features:**
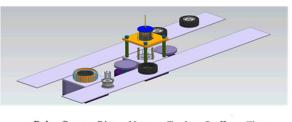
• Variable tread for speed and surface adaptability.

• Reduced rolling resistance for better fuel efficiency.

• Variable stiffness for comfort and noise reduction.
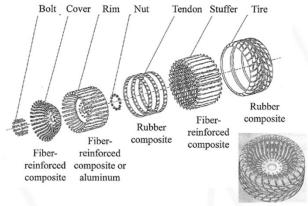
➢ **Benefits:**
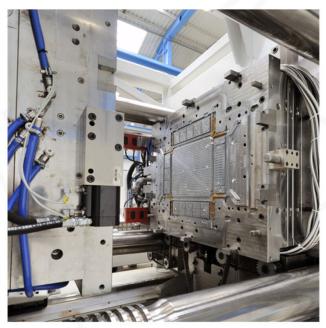
• Simplifies design, lowers costs, and supports green production.

• Powers autonomous driving with intelligent tracking.

Potential Manufacturing Processes

(a) Parts Assembling

b) Injection Molding

c) Future 3D-Printing

PART - V
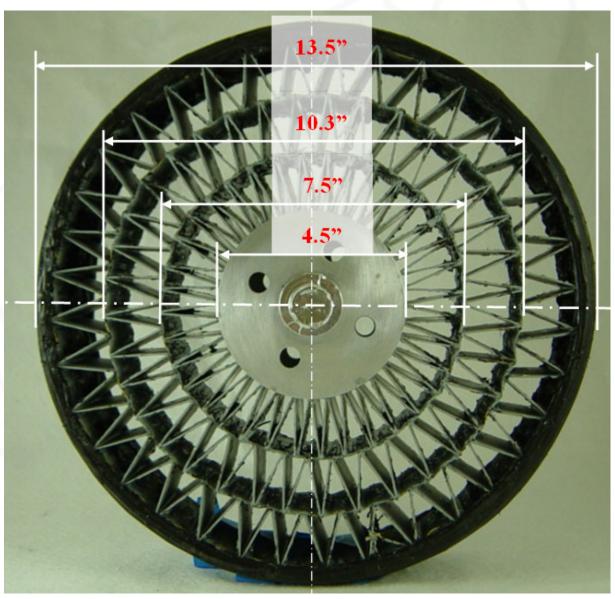
Technology Validation

Comparison with Testing Results

2250 lbs

13.5"

10.3"

7.5"

4.5"

Dr. ZD Ma   mazd@n-wheel.com

Polymaker PolyMide CoPA

TYPE – I

TYPE – V

CoPA Nylon
Sample scale: 0.316
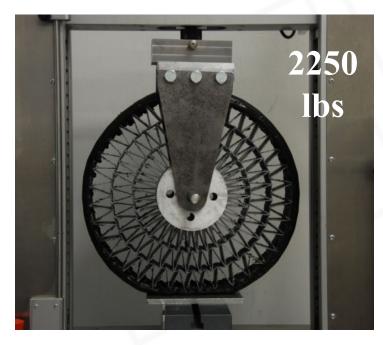
801 Kg

CoPA Nylon
Sample scale: 0.316
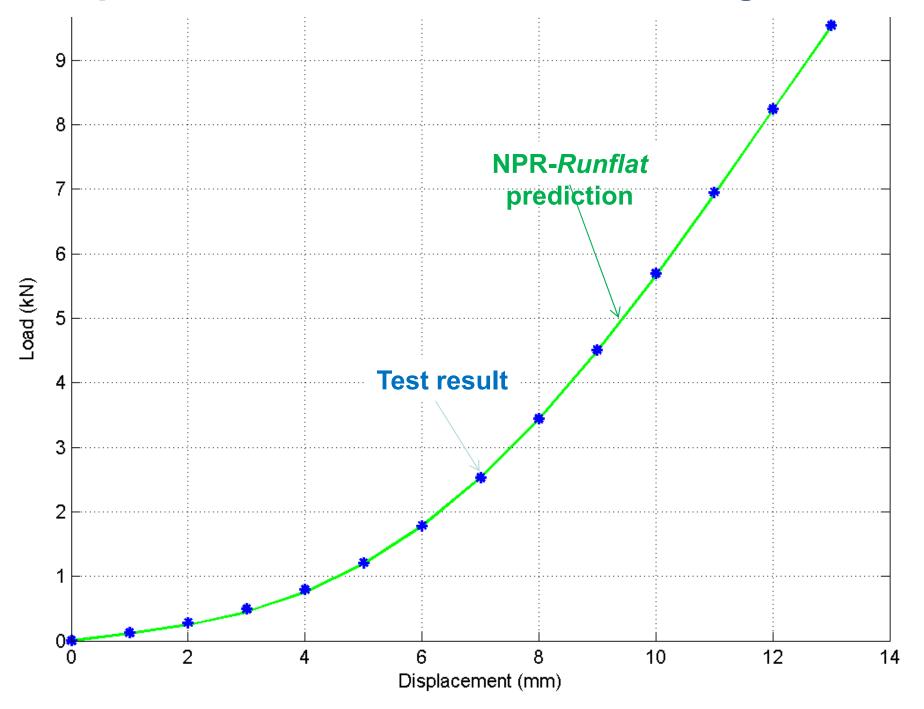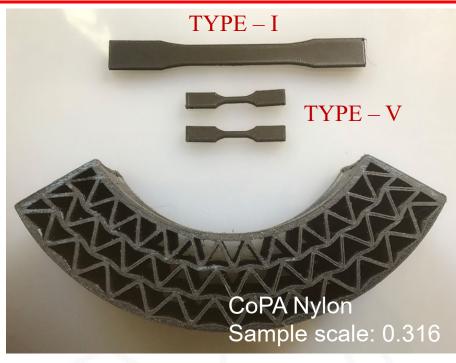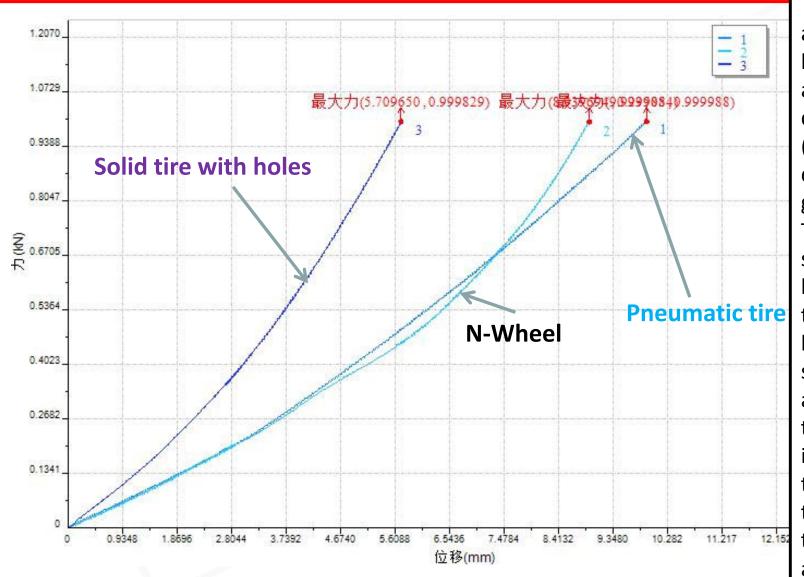
- ➤ Material: Polymaker PolyMide CoPA（Nylon）
- ➤ 3D Printing method: FDM
- ➤ TYPE – I specimen weight: 8 g
- ➤ TYPE – V specimen weight: 1.5 g
- ➤ Calculated material density: 1.0 g/cc
- ➤ Maximum force for TYPE–I: 250.3 Kg
- ➤ Maximum force for TYPE–V: 64 Kg

- ➤ Measured material tensile strength: 60 MPa.
- ➤ Sample scale: 0.316
- ➤ Measured sample weighs: 227 g (convert to the full runflat weight: 47.5 lbs.)
- ➤ Measured force: 801 Kg (no damage) (convert to full runflat load: 17,647 lbs., exceed the required maximum load by 53%)

Dr. ZD Ma   mazd@n-wheel.com

Comparison of N-wheel with Punctured Solid Tire

The vertical axis is the applied force (up to 100 kg) and the horizontal axis is the amount of deformation of the tire (a large amount of deformation indicates a good degree of comfort). The results of this test show that our tires can be more comfortable than the solid tire with holes. The results also show that our tires have a better bearing capacity than conventional inflatable tires because they can harden when the load is heavy. Our tires also have the advantage of lighter weight and cheaper prices than the solid tires.
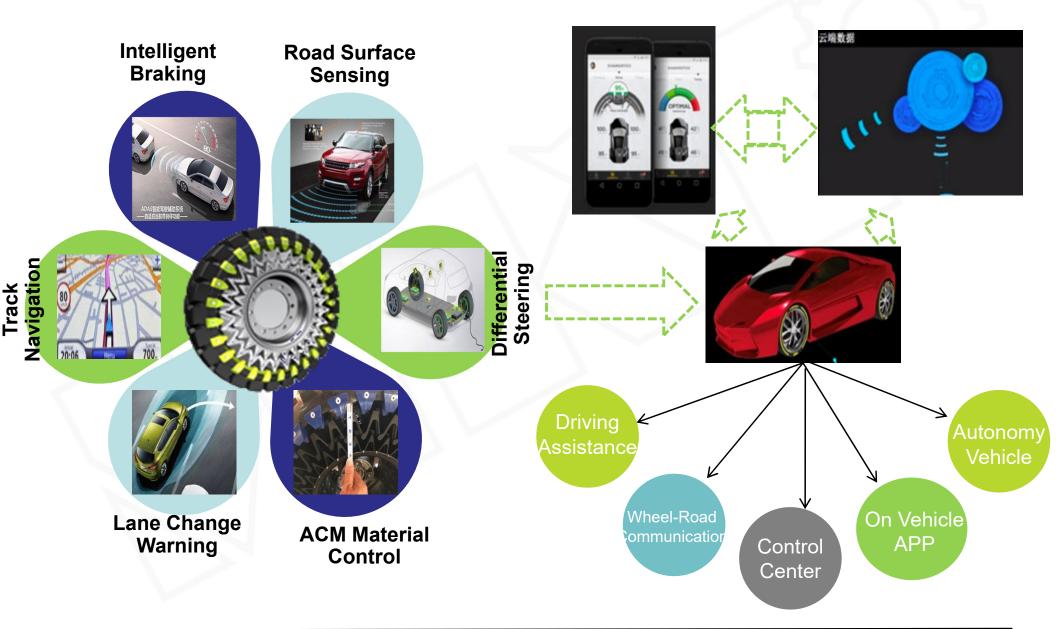
最大力(5.709650 , 0.999829) 最大力(最大力9.499999084 0.999988)

Solid tire with holes

Pneumatic tire

N-Wheel

| 1，Pneumatic tire（45PSI) | 2，N-Wheel | 3，Solid tire with holes |

N-Wheel Technologies, Inc., USA

Dr.

Future of the n-Wheel

➢ A High-performance tire-wheel integrated unit for advanced mobility.

➢ Innovative designs beyond imagination of traditional rubber tires.

➢ Never runflat, puncture-free, and maintenance-free.

➢ Improved vehicle performance in multidisciplinary areas.

➢ Reduced wheel weight and achieving better vehicle mileage.

➢ Function-oriented design for traction, mobility and drivability

➢ Sensor-embedded smart tires for autonomic drives and next generation mobilities.
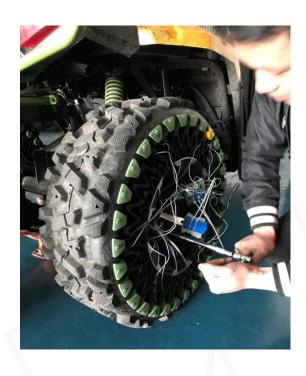
Potential i-Wheel Applications

Intelligent Braking

Road Surface Sensing

Track Navigation

Differential Steering

Lane Change Warning

ACM Material Control

Driving Assistance

Wheel-Road Communication

Control Center

On Vehicle APP

Autonomy Vehicle

云端数据

Intelligent n-Wheels (i-Wheels) Concept
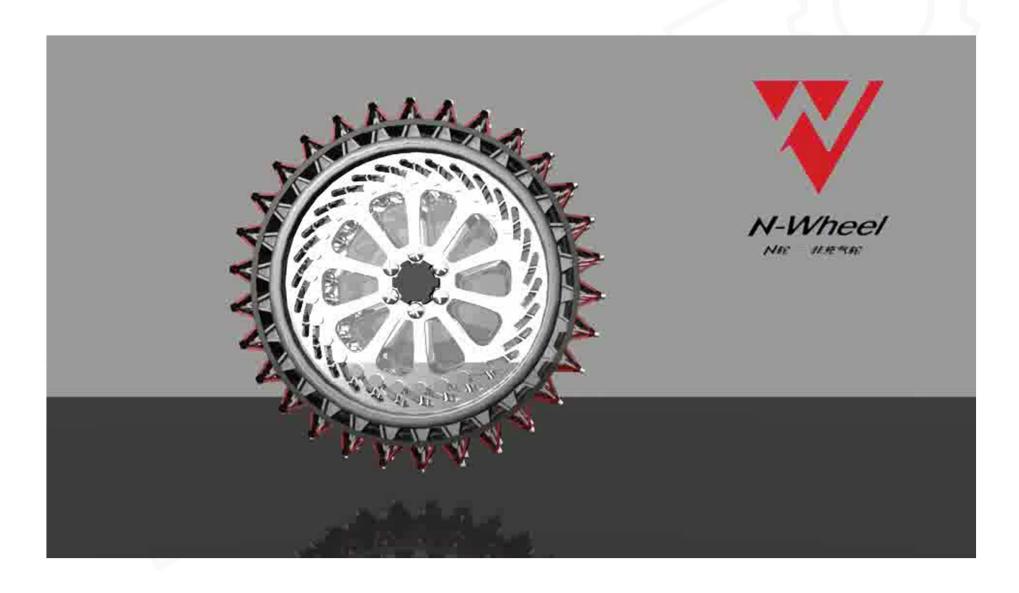
Application for Terrain Identification

n-Wheel with Adaptive Smart Tread
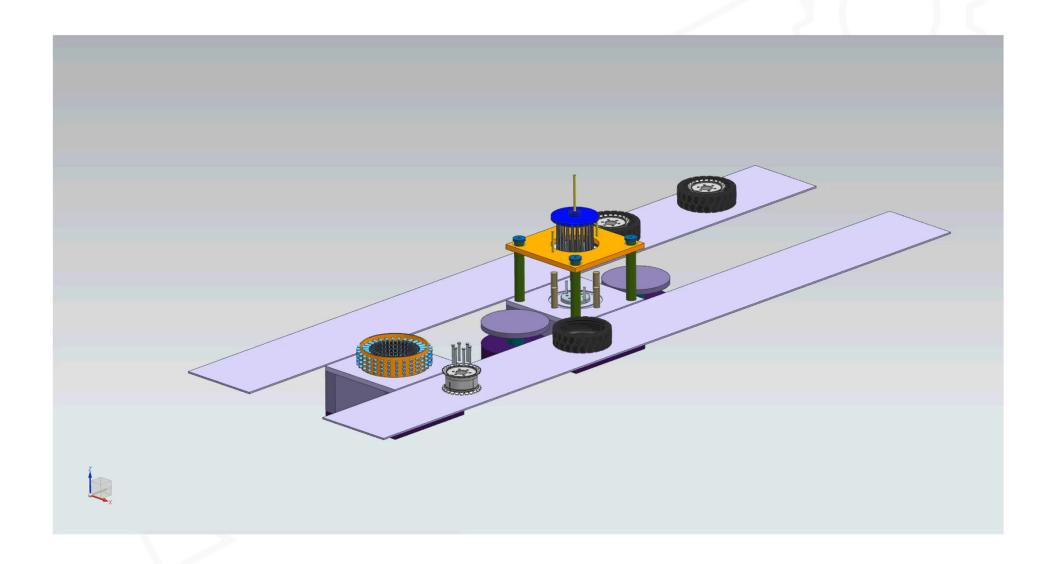
Fully Automated Assembly Line Concept for n-Wheels

Inventor Dr. Z.D. Ma

➢ **Education:**
Ph.D. in Mechanical Engineering, Kyoto University, Japan, 1989

➢ **Professional Positions:**
o Research Scientist Emeritus, University of Michigan
o Fellow, American Society of Mechanical Engineers (ASME)
o Owner, N-Wheel Technologies, Inc. (since 2001)

➢ **Publications & Innovations:**
o Published over 180 high-quality technical articles
o Reached 4,500 citations
o Awarded 12 patents

➢ **Awards & Honors:**
o Recipient of several prestigious international awards
o Outstanding Research Scientist Award, University of Michigan, College of Engineering (2004-2005)

➢ **Research Leadership:**
o Secured and managed research projects totaling over $8 million across various disciplines

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