Target Cascading in Product Development

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Dennis Assanis
Yongsheng Wang
George Delagrammatikas
Overview

• Setting design targets in the early stages of product development
• Mathematical and computational formulation in a simulation-based design environment
• Solution strategy: problem partitioning and coordinated target setting
• The target cascading process in the ARC
• Implementations:
  • Class VI Vehicle *(International 4700 Series)*
  • Class II Vehicle (sports utility vehicle)
• Concluding remarks
Vehicle Mission Specifications

Customer, Corporate and Regulatory goals lead to mission specifications (targets) for a vehicle.

How do we derive actionable design targets from these top level specifications?
Targets Require Compromises!

CAE: Conflicting Targets! But, our department is doing better!

Let’s make the best product! Here are the targets!

Let’s compromise and try to reach decisions rationally and efficiently!
Cascading Targets in a Vehicle Design Hierarchy

Vehicle
- POWERTRAIN
- ELECTRONICS
- BODY
- CHASSIS
- CLIMATE CONTROL

Systems
- GLASS
- BODY-IN-WHITE
- CLOSURE

Subsystems

Components
- JOINTS
- ...
A Formal Process for Model-Based Target Cascading

• Given
  • a set of overall “supersystem” targets
  • models for systems, subsystems and components

• Determine system, subsystem and component targets by
  • partitioning the overall design problem
  • satisfying feasibility/optimality of system, subsystem and component designs
  • achieving overall targets
Two Approaches to Target Cascading

Component Approach

- Supersystem
- System
- Subsystem
- Component

Issues:
- Complexity
- Design availability
- Design freedom

Systems Approach

- Cascade Down
- Rebalance Up

Issues:
- Efficiency
- Design Feasibility
- Common Variables
- Model Availability
Target Cascading as a Systems Engineering Process

Target Cascading enables quick target setting at the early stages of the system design process.
Vehicle Design After Target Cascading

**VEHICLE, SYSTEM, SUBSYSTEM, AND COMPONENT TARGETS**

- **Vehicle Targets**
  - Min. Deviation from Vehicle Targets
    - VEHICLE PARAMETERS

- **System Targets**
  - Min. Deviation from System Targets
    - SYSTEM PARAMETERS

- **Subsystem Targets**
  - Min. Deviation from Subsystem Targets
    - SUBSYSTEM PARAMETERS

- **Component Targets**
  - Min. Deviation from Component Targets
    - COMPONENT PARAMETERS
Target Cascading Hierarchical Structure

Supersystem Optimal Design Model

System Optimal Design Model

Subsystem Optimal Design Model
Generate weakly-connected design subproblems
Model Synthesis: Coordination

Mathematical model

Max \( \mathbf{x} \in \mathbb{R}^n \) \( f_0(\mathbf{x}_0) + \sum_{j=1}^{p} f_j(\mathbf{x}_0, \mathbf{x}_j) \)
subject to:
\( g_0(\mathbf{x}_0) \leq 0 \)
\( h_0(\mathbf{x}_0) \leq 0 \)
\( g_j(\mathbf{x}_0, \mathbf{x}_j) = 0 \)
\( h_j(\mathbf{x}_0, \mathbf{x}_j) = 0 \)

Hierarchical Partition

Solve system problem by solving a set of smaller subproblems concurrently and matching their solutions
A Formal TCP Model: Assumptions and Notation

- Models could be analytical or experimental, quantitative or qualitative. An “approximate” analytical model needs to be generated if not available.
- System/Subsystem hierarchical interaction is similar at all levels.
- System targets $T$ are for system responses $r$.
- System responses $r$ depend on subsystem responses $r_i$ and system variables $x$, i.e., $r = R(r_1, r_2, \ldots, r_N, x)$.
- System models and constraints define the feasible space $S$ of system variables $x$ and subsystem responses $r_i$, i.e., $(r_1, r_2, \ldots, r_N, x) \in S$.
- $x_i$ are the subsystem variables.
- $\tilde{x}_i$ are the subsystem local variables.
- $y_i$ are the subsystem linking variables; so $x_i = (\tilde{x}_i, y_i)$.
- $y$ are the subsystem linking variables, as viewed by the system.
A Formal TCP Model: Problem Statement

Given system targets $T$, determine subsystem targets (responses) $T_i(r_i)$ such that

**At the System Level:**
System targets $T$ are achieved for system responses $r$, where

$$r = R(r_1, r_2, \ldots, r_N, x)$$

and

$$(r_1, r_2, \ldots, r_N, x) \in S \text{ (system feasible design space).}$$

**At the Subsystem $i$ Level:**
Subsystem targets $T_i$ are achieved for subsystem responses $r_i$, where

$$r_i = R_i(r_{i1}, r_{i2}, \ldots, r_{iN}, x_i)$$

and

$$(r_{i1}, r_{i2}, \ldots, r_{iN}, x_i) \in S_i \text{ (subsystem feasible design space).}$$
Minimize \( \tilde{x}_{(i+1)j}, y_{(i+1)j}, y_{(i+2)j}, R_{(i+1)j} \) \( \left\| R_{ij} - R^U_{ij} \right\| + \left\| y_{(i+1)j} - y^U_{(i+1)j} \right\| + \varepsilon_R + \varepsilon_y \)

where \( R_{ij} = r_{ij \leftrightarrow (i+1)j}(R_{(i+1)j}, \tilde{x}_{(i+1)j}, y_{(i+1)j}) \)

subject to

\[ \left\| R_{(i+1)j} - R^L_{(i+1)j} \right\| \leq \varepsilon_R \]
\[ \left\| y_{(i+2)j} - y^L_{(i+2)j} \right\| \leq \varepsilon_y \]
\[ g_{ij \leftrightarrow (i+1)j}(R_{(i+1)j}, \tilde{x}_{(i+1)j}, y_{(i+1)j}) \leq 0 \]
\[ h_{ij \leftrightarrow (i+1)j}(R_{(i+1)j}, \tilde{x}_{(i+1)j}, y_{(i+1)j}) = 0 \]

\( j^{th} \) partition element
\( i^{th} \) level
\( U \): from upper level
\( L \): from lower level
TCP as a Hierarchical Optimization Process

Vehicle Targets

Minimize Deviation between vehicle targets and responses subject to constraints for system responses, subsystem linking variables and vehicle

Minimize Deviation between system targets and responses and between subsystem linking variable targets and variables subject to constraints for subsystem responses, component linking variables and system

Minimize Deviation between subsystem targets and responses and between component linking variable targets and variables subject to constraints for subsystem
An Early TCP Study (Ford)

Vehicle Targets
- Peak Load
- Roll Flexibility
- Force to Body

System Targets
- Durability
  - Ride Frequency
- Dynamics
  - Ride Frequency
- NVH

Toolset:
- Matlab/Adams
- Excel
Target Cascading in the ARC

- TCP introduction
- Model aggregation
- Preliminary implementations
- Application to vehicle systems
  - 21\textsuperscript{st} Century Truck initiative
## ARC TCP Model Matrix

- **Primary relation**  - **Strongest relation**  - **Stronger relation**  - **Weak relation**

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Handling</th>
<th>NVH</th>
<th>Fuel Economy &amp; Emissions</th>
<th>Acceleration Performance</th>
<th>Durability</th>
<th>Weight</th>
<th>Drivability</th>
<th>Ride</th>
<th>Acoustics Signature</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Powertrain</strong> (e.g. Engine, Transmission, Final Drive, ...)</td>
<td>〇(14) ☆(22) ☆(25) 〇(26) 〇(27) ☆(41) ☆(42) ☆(43)</td>
<td>〇(22) 〇(36) 〇(37) 〇(41) 〇(42) 〇(43)</td>
<td>★(14) ★(22) ★(23) ★(24) ★(25) ★(36) ★(37) ★(41) ★(42) ★(43) ★(44)</td>
<td>★(14) ★(22) ★(23) ★(24) ★(25) ★(36) ★(37) ★(41) ★(42) ★(43) ★(44)</td>
<td>〇(22) ★(36) ☆(37)</td>
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<td>〇(22) ★(36) ☆(37)</td>
<td>〇(14)</td>
<td>★(14)</td>
</tr>
</tbody>
</table>

**Model Name:** ARC Models

**Owner/Developer:** Automotive Research Center
# ARC TCP Model Collection

## Model Number

### Area 1

<table>
<thead>
<tr>
<th>Model Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.</td>
<td>M916A1/M870A2 Tractor-Semitrailer in ArcSim</td>
</tr>
<tr>
<td>12.</td>
<td>M916A1/M870A2 Tractor-Semitrailer/Pitch Plane</td>
</tr>
<tr>
<td>13.</td>
<td>M916A1/M870A2 Tractor-Semitrailer/Yaw Roll</td>
</tr>
<tr>
<td>14.</td>
<td>Navistar truck driveline</td>
</tr>
<tr>
<td>15.</td>
<td>Navistar truck vehicle dynamics/Quarter Car</td>
</tr>
<tr>
<td>16.</td>
<td>Navistar truck vehicle dynamics/Pitch plane</td>
</tr>
<tr>
<td>17.</td>
<td>Cherokee/Yaw Roll TruckSim</td>
</tr>
<tr>
<td>18.</td>
<td>Cherokee I TruckSim</td>
</tr>
</tbody>
</table>

### Area 2

<table>
<thead>
<tr>
<th>Model Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.</td>
<td>Bekker's Tire-Soil Model</td>
</tr>
<tr>
<td>22.</td>
<td>Hybrid Electric Powertrain Model</td>
</tr>
<tr>
<td>23.</td>
<td>Iowa Numerical Integration Methods</td>
</tr>
<tr>
<td>24.</td>
<td>Iowa Parallel Computational Model</td>
</tr>
<tr>
<td>25.</td>
<td>Iowa_Powertrain Model</td>
</tr>
<tr>
<td>26.</td>
<td>Virtual Proving Ground Synthetic Environment (NADS)</td>
</tr>
<tr>
<td>27.</td>
<td>Dynamic Terrain Model for Virtual Proving Ground (NADS)</td>
</tr>
<tr>
<td>28.</td>
<td>Virtual Proving Ground Static Terrain Skin Model (NADS)</td>
</tr>
</tbody>
</table>

### Area 3

<table>
<thead>
<tr>
<th>Model Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>31.</td>
<td>Power Flow Model (Pierre)</td>
</tr>
<tr>
<td>32.</td>
<td>Enhanced Homogenization Method (Kikuchi)</td>
</tr>
<tr>
<td>33.</td>
<td>DRAW (Durability Model, CCAD)</td>
</tr>
<tr>
<td>34.</td>
<td>DSO (Durability, CCAD)</td>
</tr>
<tr>
<td>35.</td>
<td>Track/Wheel/Terrain Interaction Model (Ma&amp;Perkins)</td>
</tr>
<tr>
<td>36.</td>
<td>Engine Model Template For Upfront Design (Ma&amp;Perkins)</td>
</tr>
<tr>
<td>37.</td>
<td>Structure/Powertrain Interface Model (Ma)</td>
</tr>
<tr>
<td>38.</td>
<td>Track Models (Perkins&amp;Ma)</td>
</tr>
<tr>
<td>39.</td>
<td>Track/Sprocket Interaction Model</td>
</tr>
</tbody>
</table>

### Area 4

<table>
<thead>
<tr>
<th>Model Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>41.</td>
<td>Diesel Engine System Model (Assanis&amp;Filipi)</td>
</tr>
<tr>
<td>42.</td>
<td>Diesel Engine System – FORTRAN (Assanis&amp;Filipi)</td>
</tr>
<tr>
<td>43.</td>
<td>Diesel Engine Cylinder Model (Assanis&amp;Filipi)</td>
</tr>
<tr>
<td>44.</td>
<td>Neural Net Model for a Centrifugal Compressor (Nelson)</td>
</tr>
</tbody>
</table>

### Area 5

<table>
<thead>
<tr>
<th>Model Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>51.</td>
<td>Bushing Model</td>
</tr>
</tbody>
</table>
## Model Name: Quarter Car Model (Vehicle-System)  
**Owner/Developer:** Kim

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Variables</th>
<th>Responses from Lower Level (e.g. Chassis System)</th>
<th>Responses to Higher Level (e.g. Top Vehicle Design)</th>
<th>Model forms, contents and assumptions (actual software)</th>
<th>Fidelity (High, Medium, or Low)</th>
<th>Computational Cost (Seconds, Hours, or Days)</th>
</tr>
</thead>
</table>
| Road Input to Tire (white noise) | Sprung Mass (w/o Body)  
Unsprung Mass  
Suspension Damping  
Tire Stiffness  
Tire Damping | Body Mass  
Suspension Stiffness | Sprung Mass Acceleration  
Relative Displacement between Sprung and Unsprung Mass | Matlabfiles | Low | Seconds |
Place your analysis model subsystems in the boxes. Indicate the relation of your model to attributes listed using the symbols below.

- ✨ Primary relation
- ★ Strongest relation
- ☆ Stronger relation
- ○ Weak relation

**Model Name**: Quarter Car Model (Vehicle-System)  
**Owner/Developer**: Kim

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Handling</td>
</tr>
<tr>
<td><strong>Chassis</strong></td>
<td>✨</td>
</tr>
<tr>
<td>(e.g. Suspension, Tires, ...)</td>
<td></td>
</tr>
<tr>
<td><strong>Body</strong></td>
<td></td>
</tr>
<tr>
<td>(e.g. Structure, Joints, ...)</td>
<td></td>
</tr>
<tr>
<td><strong>Powertrain</strong></td>
<td></td>
</tr>
<tr>
<td>(e.g. Engine, Transmission, Final Drive, ...)</td>
<td></td>
</tr>
</tbody>
</table>
TCP Implementations

- Class VI Vehicle (*International 4700 Series*) chassis and powertrain targets
- Class II Vehicle (sports utility vehicle) ride and handling targets
Class VI vehicle: International 4700 Series

- **Vehicle Targets:**
  - Fuel consumption
  - Performance: 0-60 mph and 30-50 mph acceleration times
  - Ride: average vertical acceleration
  - Driveability: average horizontal acceleration

- **Models:**
  - Vehicle Level:
    - Vehicle dynamics and powertrain (VESIM-HS)
  - System Level:
    - High-fidelity turbocharged diesel engine (TDES)
    - Planetary gear transmission
    - Detailed suspension
Baseline Vehicle Specs: International 4700 Series

- GVWR: 7950 Kg
- Wheelbase: 3.7 m
- CG Location: 2.2 m from front
- Frontal Area: 5 m²
- Air Drag Coefficient ($C_D$): 0.8
- 4 Speed Automatic Transmission
- Rear Wheel Drive - 4x2
Baseline Engine Specs: International T444E

- V8 DI Diesel
- Turbocharged, Intercooled
- Displacement: 7.3 liters
- Bore: 10.44 cm
- Stroke: 10.62 cm
- Compression Ratio: 17.4
- Electronically controlled HEUI injection system
- Rated Power: 210 HP@2400 rpm
Driving Cycle Used to Estimate Vehicle Targets

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Velocity (MPH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-60</td>
<td>60</td>
</tr>
<tr>
<td>50-50</td>
<td>50</td>
</tr>
<tr>
<td>30-50</td>
<td>30</td>
</tr>
</tbody>
</table>

- Speed command
- Actual speed

0-60 time
30-50 time

Time (sec)
Vehicle System Integration

Vehicle Dynamics

Traction Force

Engine

Drivetrain

Exhaust Gas

Air

Intercooler

ICM

EM

IM

TC

Trns

DS

PS

D
Model Hierarchy for TCP

Vehicle Level (VESIM-HS)

Engine

Drivetrain

Vehicle Dynamics

System Level

High fidelity, phenomenological

Planetary gear transmission

Suspension kinematics
Model Hierarchy for TCP

Vehicle Dynamics and Powertrain

Engine
- TDES
  - displacement, turbocharger, fuel control
- engine map

Transmission
- Planetary Gear
  - gear geometry
- gear ratios

Suspension
- Suspension Kinematics
  - coil-spring stiffness, geometry
  - stiffness, damping unsprung mass

fuel economy, performance, ride & driveability

engine map scaling parameters
Vehicle Level: Engine Model in VESIM

- Look-up table for engine output torque as a function of fuel input and speed
- Includes fuel injection controller and engine dynamics
- Look-up tables are generated using the high fidelity simulation TDES
Vehicle Level:
Drivetrain Model in VESIM

Flexible Propshafts
Flexible Driveshaft

TC
Trns
D-R

- Quasi-Static
- Lookup Tables
- Flexible Shafts
- Gear Inertias
- Gear Ratios
- Blending Functions
- Shift Logic

Wheel Hub

Equal Torque
Gear Inertias
Vehicle Level: Vehicle Dynamics Model in VESIM

- Nonlinear pitch plane model (3 DOF)
- Aerodynamic and rolling resistance losses
- Linear spring/damper suspension
- Nonlinear tire traction forces
System Level:
High-Fidelity Engine Model (TDES)

- Zero-Dimensional model of engine in-cylinder processes
- Engine and turbocharger dynamics

- **Response/Target**
  - Engine torque map

- **Design Variables**
  - Displacement (stroke)
  - Turbocharger size
  - Fuel control (HS governing)
System Level: Planetary Gear Transmission Model

- **Responses/Targets**
  - 4 Gear ratios

- **Design Variables**
  - Input Planetary
    - Sun diameter
    - Reaction Diameter
  - Reaction Planetary
    - Sun diameter
    - Reaction Diameter

- **Kinematics**
  - Gear geometry

Diagram:

- 1-2 Band Clutch
- Input Planetary
- Second Clutch
- First Clutch
- Reaction Planetary
- To Final Drive
System Level: Kinematics Suspension Model

- **Responses/Targets**
  - Vertical linear stiffness
  - Unsprung mass

- **Design Variables**
  - Coil spring stiffness
  - Geometry

- **Double A-arm**
- **3D nonlinear kinematics**
- **Linear coil spring**
- **Bushings**
Vehicle Level Target Achievement: Emphasis on Ride Quality

Responses (Target-Value)/Target

- Baseline
- Final

- Forward Acceleration
- Fuel Consumption
- 0-60mph Acceleration Time
- 30-50mph Acceleration Time

OVERDESIGN
UNDERDESIGN
## System Level Cascaded Targets

<table>
<thead>
<tr>
<th>System</th>
<th>Response</th>
<th>Vehicle Target Emphasis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ride</td>
</tr>
<tr>
<td>Suspension</td>
<td>Suspension Compliance (μm/N)</td>
<td>2.399</td>
</tr>
<tr>
<td></td>
<td>Axle Front Mass (kg)</td>
<td>200</td>
</tr>
<tr>
<td>Transmission</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; Gear Ratio</td>
<td>3.796</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt; Gear Ratio</td>
<td>1.835</td>
</tr>
<tr>
<td></td>
<td>3&lt;sup&gt;rd&lt;/sup&gt; Gear Ratio</td>
<td>1.2877</td>
</tr>
<tr>
<td></td>
<td>4&lt;sup&gt;th&lt;/sup&gt; Gear Ratio</td>
<td>1.0067</td>
</tr>
<tr>
<td>Engine</td>
<td>Rated RPM</td>
<td>2400</td>
</tr>
<tr>
<td></td>
<td>Torque Scale</td>
<td>0.95</td>
</tr>
</tbody>
</table>
Model-Based Target Cascading

Benefits

• Eliminate...
  • many design iterations
  • late changes and avoidable compromises

• Produce an early design that...
  • allows concurrency in the development of individual systems, subsystems, and components
  • provides support to management decisions using CAE capabilities
Thanks!!