Development of High Power Density Driveline for Vehicles

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Argonne National Laboratory
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Project ID # VSS058

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Overview

Timeline

- Start date - October 2010
- End date - FY2015
- Percent complete – 15%

Budget

- Total project funding
  - DOE share – 470K
  - Contractor share – 120K (in-kind)
- Funding
  - FY 11 – 170K
  - FY12 – 300K

Barriers

- Barriers addressed
  - Constant Advances in Technology
  - Computational models, design and simulation methodologies
  - Risk Aversion
  - Cost

Partners

- Interactions/ collaborations
  - Wedeven Associates, Inc.
  - Afton Chemical Corp.
  - Castrol – BP Corp.
Project Description and Relevance

- The main goal of DOE-VTP is the reduction of petroleum use in transportation. Such reduction is accompanied by other benefits.
  - Emissions, economic, environmental, ....

- Significant fuel savings possible through weight reduction in all classes of vehicles.

- Numerous analyses suggests 2 to 5% reduction in fuel consumption by 10% reduction in vehicle weight.
  - An increasingly necessary approach to fuel savings

Calculated Fuel savings in gasoline and diesel vehicles

<table>
<thead>
<tr>
<th></th>
<th>NEDC ICEV-G</th>
<th>NEDC ICEV-D</th>
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</thead>
<tbody>
<tr>
<td>Compact Class</td>
<td>-2.6 %</td>
<td>-3.5 %</td>
</tr>
<tr>
<td>Mid-Size Class</td>
<td>-1.9 %</td>
<td>-2.7 %</td>
</tr>
<tr>
<td>SUV</td>
<td>-2.4 %</td>
<td>-2.6 %</td>
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</table>
Project Objective and Relevance

- Weight reduction in vehicles must be accomplished without sacrificing safety, reliability and durability.

- Based on weight vehicles distribution, systems where significant weight reduction can be achieved are identified.
  - DOE currently have programs for weight reduction in structure and engine – light weight materials.

- Driveline system constitutes about 20% of the vehicle’s weight.
  - Opportunity for weight reduction.
Project Objective and Relevance

- **Objective**: The ultimate objective of this project is to enable significant vehicle weight reduction through the reduction in size and weight of the driveline systems such as transmission, axle.

- The driveline size reduction to be achieved by developing materials, surface and lubrication technologies for increasing the power density of the systems.
  - Can enable downsizing of power-train system without loss of performance
  - Further improvement in fuel savings

<table>
<thead>
<tr>
<th></th>
<th>% Improvement in Fuel Economy</th>
<th>% Weight Reduction</th>
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</thead>
<tbody>
<tr>
<td>EPA Combined (Metro-Highway) Drive Cycle</td>
<td>Passenger Vehicle</td>
<td>Truck</td>
</tr>
<tr>
<td></td>
<td>Base Engine</td>
<td>Downsized Engine</td>
</tr>
<tr>
<td>Gasoline</td>
<td>0.33%</td>
<td>0.65%</td>
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<tr>
<td>Diesel</td>
<td>0.39%</td>
<td>0.63%</td>
</tr>
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</table>
Technical Approach/Goals

- Vehicle driveline systems – transmission, axles consist of planetary gear systems and bearings.

- In order to reduce the size of the planetary gear system, high power density gearing and bearings will be required.
  - High severity of contact in gears and bearing
  - Reliability and durability issues
    - Wear; scuffing; and contact fatigue (pitting)

Goal: Develop and evaluate integrated materials, surface and lubricant technologies needed to enable HPD driveline
Technical Approach

In order to establish materials, surface and lubricant technologies target and goals, analyses must be conducted to:

- Determine gear contact kinematics for gearbox with different levels of size reduction in a planetary gear system
- Determine impact of new contact parameters on gearbox reliability and durability
  - Wear, scuffing and contact fatigue (pitting) life reduction

Evaluate performance of some of the existing materials, surface (texture, coatings, treatments.....), and lubricant technologies and their combinations to mitigate reliability and durability issues of high power density (HPD) gearbox.

Develop and evaluate appropriate surface and lubricant technologies as needed to simultaneously enhance wear, scuffing and contact fatigue life of gears and bearings.

- Often contradictory
FY 11: Accomplishments

- Conducted gear kinematics analysis to determine impact of size reduction on contact stresses, surface velocities in planetary gear system
- Effect on gear reliability and durability evaluated
  - Scuffing, wear and contact fatigue life reduction

<table>
<thead>
<tr>
<th>Size reduction (%)</th>
<th>Scuffing life reduction (%)</th>
<th>Contact fatigue life reduction (%)</th>
<th>Wear life reduction (%)</th>
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<tr>
<td>5</td>
<td>5.2</td>
<td>28.9</td>
<td>5.2</td>
</tr>
<tr>
<td>10</td>
<td>11.1</td>
<td>50.4</td>
<td>11.1</td>
</tr>
<tr>
<td>15</td>
<td>17.6</td>
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<td>20</td>
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<td>81.8</td>
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<tr>
<td>50</td>
<td>100</td>
<td>99.0</td>
<td>100</td>
</tr>
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</table>
FY 12 Accomplishment: Test methodology for gear Contact

Independent control of surface velocities allows evaluation of tribological phenomena at meshing gear teeth.
- Frictional behavior
- Failure and damage mechanisms

1. Contact configuration: Ball vs. Disk
2. Contact stress: 2.1 to 2.2 GPa
3. Temperature: 75 °C
4. Percent Sliding: 40%
FY 12 Accomplishment: Test methodology for gear Contact

Life-limiting Surface Failure Modes

- Scuffing & Severe Wear
- Wear & Micro-pitting (near-surface distress)
- Wear

Slide to Roll Ratio (S/R)

0.5

Lub film thickness / surface roughness ratio (h/σ)

Anti-wear attributes

Long Life

EHD film-forming capability

Load carrying attributes

Schematic of life-limiting surface failure modes (boundaries are postulated)
FY 12 Accomplishment: Wear Life Improvement

- Thin-film tribological coatings and lubricant formulation with anti-wear additives are two technologies commonly used for wear life improvement
  - Integration of both can be a viable pathway to achieve wear life requirement for HPD gearbox
- Evaluated friction and wear performance of coatings and lubricants

### Coatings Evaluated

<table>
<thead>
<tr>
<th>Coatings</th>
<th>Deposition method</th>
<th>Type</th>
<th>Thickness (µm)</th>
<th>Manufacture Hardness (Hv)</th>
<th>Nano Hardness (GPa)</th>
<th>Roughness (nm)</th>
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<tbody>
<tr>
<td>4118-Steel</td>
<td>none</td>
<td>No layer</td>
<td>0</td>
<td>850</td>
<td>7</td>
<td>19</td>
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<tr>
<td>DLC-1</td>
<td>PACVD</td>
<td>multilayer</td>
<td>1.9</td>
<td>1200-1500</td>
<td>12-15</td>
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<td>DLC-2</td>
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<td>1000-1500</td>
<td>10-15</td>
<td>133</td>
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<tr>
<td>DLC-3</td>
<td>PACVD</td>
<td>multilayer</td>
<td>3.5</td>
<td>1500-3000</td>
<td>16</td>
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<tr>
<td>CrN</td>
<td>PVD</td>
<td>monolayer</td>
<td>5.0</td>
<td>800-1100</td>
<td>10</td>
<td>16</td>
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<tr>
<td>CrSiCN</td>
<td>PVD</td>
<td>monolayer</td>
<td>3.4</td>
<td>2700-3000</td>
<td>29</td>
<td>6.6</td>
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<tr>
<td>AlTiN</td>
<td>PVD</td>
<td>bilayer</td>
<td>2.4</td>
<td>3500</td>
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<tr>
<td>TiB₂</td>
<td>PVD</td>
<td>monolayer</td>
<td>1.9</td>
<td>3650</td>
<td>34.37</td>
<td>30</td>
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<tr>
<td>TiCN</td>
<td>PVD</td>
<td>monolayer</td>
<td>0.9</td>
<td>4000</td>
<td>39</td>
<td>49</td>
</tr>
<tr>
<td>TiN</td>
<td>PVD</td>
<td>monolayer</td>
<td>3.7</td>
<td>3000</td>
<td>29-30</td>
<td>87</td>
</tr>
</tbody>
</table>

### Lubricants Evaluated

- **PAO10**: synthetic basestock (no additives)
- **PAO4+Additives**: synthetic basestock + 2.5wt. % ZDDP + 2.5 wt. % MoDTC
- **Synthetic A**: optimized for friction control
- **Synthetic B**: optimized for wear protection
FY 12 Accomplishment: Wear Life Improvement

Friction and wear testing for coating and lubricants

- Reciprocating sliding contact roller-on-flat configuration
- Friction continuously monitored.

**Test Parameters**

- Load: 150N $\sigma_{\text{mean}}=0.33$ Gpa. $\sigma_{\text{max}}=0.42$ Gpa.
- Speed: 0.5 Hz (ave. speed: 1cm /s)
- Stroke length: 10 mm
- Duration: 180 minutes
- Temperature: 100°C
FY 12 Accomplishment: Wear Life Improvement

Friction Results for tests with model lubricants

- In unformulated basestock lubricant, some coatings reduced friction
- In oils with additives, friction was higher for almost all the coatings
FY 12 Accomplishment: Wear Life Improvement

Friction Results for tests with fully formulated lubricants

- In fully formulated lubricants, friction is higher in tests with the coatings
- Different levels of tribochemical interaction between coatings and oil additives

Coatings reduced the effectiveness of oil additives in terms of friction
FY 12 Accomplishment: Wear Life Improvement

Wear Results for tests with different lubricants and coatings

- Minimal wear observed on the flat specimens
- Wear measured on the roller specimen

Note the difference in scale of the two Figures

Coatings must be selected wisely for wear life improvement in gears
FY 12 Accomplishment: Effect of coatings on lubrication regime transition

- Transition in lubrication regime was assessed by a step speed increase protocol in unidirectional sliding

Some coatings are beneficial for fluid film lubrication, others are not. Opportunity for integration of coating and lubricant technologies for optimal tribological performance.
Collaborations

- **Wedeven Associates, Inc. (industry):**
  - Development of test methodology for gear teeth contacts
  - Evaluation and analysis of materials and lubricant technologies

- **Afton Chemical Corp. (industry):**
  - Development of lubricant additives for coatings to ensure adequate wear, scuffing and contact fatigue life
  - (Possible CRADA talk between ANL and Afton in progress).

- **Other Potential Collaborators:**
  - DOE Wind Energy Program
    - Leverage efforts on wind turbine gearbox reliability projects
  - Other agencies with programs and projects on gearbox technology development
  - Castrol –BP corp.
  - Many OEM willing to provide guidance, but not formally.
    - Keenly interested in the progress and outcome of work
Proposed Future Work

- Continue tribological performance evaluation of coating and lubricant systems with appropriate test methodologies.
  - Wear, Scuffing and Contact fatigue life.
  - Mechanism studies of tribochemical interactions between coatings and oil additives.

- In collaboration with industrial partner (WAI), identify and evaluate material attributes and technologies for HPD gearing.

- In collaboration with lubricant industrial partners, identify and/develop additives that can synergistically work with coatings in terms of wear, scuffing and contact fatigue performance, especially under severe contact conditions.

- Continue continuous dialogue and feed back from pertinent OEM
Summary

- Significant weight reduction and consequent fuel savings and emissions reduction can be achieved in all transportation vehicle platforms by reducing the size and weight of the driveline system.
  - Can enable downsizing of powertrain system, resulting in more fuel savings.

- In order to reduce the size and weight of driveline systems without loss of transmitted power, high power density gearbox will be required.
  - Analyses showed the need to significantly increase the wear, scuffing and contact fatigue life.

- Appropriate test methodology was developed to adequately evaluate performance of candidate technologies under gear contact kinematics.

- Initial performance evaluation of thin-film coatings and lubricant additives show promise to simultaneously increase in wear, scuffing and contact fatigue life.

- Integrated materials, surface and lubricant technologies will be needed to enable the development of a reliable and durable high power density driveline systems for transportation vehicles.
Supplemental Slides

- Provides some information on the structure of coatings evaluated and assessment of tribochemical interaction between coatings and lubricant additives.
Some coatings cross-sections

DLC-1

DLC-2

DLC-3

TiN

TiB₂

AlTiN

TiCN
Interaction of coatings and lubricant additives
One lubricant and several coatings

Steel

- Extensive tribofilm formation

TiN

- Tribofilm formation

TiCN

- Tribofilm formation and minimal metal transfer
- Minimal chemical interaction and no damage

TiB₂

- Tribofilm formation and extensive surface damage

AlTiN

- Extensive metal transfer

Lubricant: Synthetic A

CrN

- Tribofilm formation

CrSiCN

- Some tribofilm formation and metal transfer

DLC-1

- Minimal interaction—some coating densification

DLC-2

- Chemical interaction—coating damage

DLC-3

- Minimal chemical interaction and no damage
Interaction of coatings and lubricant additives
CrSiCN coating with different lubricants

Synthetic B
- Some metal transfer
- Tribofilm patches
- No surface damage

Synthetic A
- Extensive metal transfer
- No tribofilm formation
- Surface damage - delamination

PAO with no additives
Interaction of coatings and lubricant additives
Several lubricants and several coatings

Lubricant: Synthetic A

Lubricant: Synthetic B

Lubricant: PAO4+ZDDP+MoDTC

Steel  TiN  TiB₂